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CLIMATE CHANGE, ECONOMIC GROWTH, AND HEALTH

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Abstract: This paper studies the interplay between climate, health, and the economy in a stylized world with four heterogeneous regions, labeled 'West' (cold and rich), 'China' (cold and poor), 'India' (warm and poor), and 'Africa' (warm and very poor). We introduce health impacts into a simple integrated assessment model where both the local cooling effect of aerosols as well as the global warming effect of CO2 are endogenous, and investigate how those factors affect the equilibrium path. We show how some of the important aspects of the equilibrium, including emission abatement rates, health costs, and economic growth, depend on the economic and geographical characteristics of each region.

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1 Introduction

The worldwide increase of CO2 emissions has caused an increase in the concentration of CO2 (and other greenhouse gases) in the atmosphere, and this has led to higher temperatures on Earth through the greenhouse effect: global warming. The greenhouse effect is, however, not the only pollution effect. Producers and consumers create dirt and this dirt enters the atmosphere as aerosols. The aerosol particles reflect sunlight so that less sunlight falls onto the Earth and the Earth becomes cooler: local dimming. There are thus two opposite effects. Moreover, the greenhouse effect is global whereas the aerosol effect is (primarily) local. If one region produces more CO2 then we all suffer, but if one region produces more aerosols, only that region is affected. The statistical evidence for the two pollution effects was recently investigated by Magnus *et al.* (2010).

Since aerosols have a cooling effect, one might think that producing more aerosols is a useful tool to counter global warming. But aerosols also have a negative effect: they cause more people to suffer from lung and other respiratory diseases. The literature on the effects of air pollution on health has been evaluated by the WHO (2000, 2006), and there is little doubt that a significant link exists between short-term exposure to sulphur dioxide and asthma (Bates *et al.*, 1990; Galán *et al.*, 2003; O'Connor *et al.*, 2008). More aerosol emissions thus cause more people to be ill, and all such aerosol-induced diseases are labeled 'asthma' in this paper.

While air pollution causes more asthma, an increase in temperature will also lead to more diseases, such as malaria. A higher temperature affects the number of people at risk for malaria, and hence also the number of malaria patients (Martens *et al.*, 1997; Githeko *et al.*, 2000; van Lieshout *et al.*, 2004; Pascual *et al.*, 2006). All temperature-induced diseases are labeled 'malaria'.

We thus distinguish between two types of pollution (CO2 and aerosols) with different effects on climate, and between two associated diseases. In addition, climate change has an impact on the natural and human environment (IPCC, 2007), and this causes economic costs through three channels. First, climate change affects productivity directly. For example, flooding and storms cause drinking water to be scarce, and therefore reduce crop productivity, thus harming the population and damaging the economy. Second, climate change increases the number of sick people (malaria), reduces the labor force, and hence the amount of output. Third, more diseases will increase health care and prevention costs, so that less money is available for consumption and investment.

In this paper we propose a simple climate-economy model, based on the Nordhaus and Yang (1996) RICE model, in which the interrelations between pollution, climate, health, and the economy can be studied. Our model is an integrated assessment model with multiple regions. Our main analysis takes place in a highly stylized world with four regions: 'West' (cold and rich), 'China' (cold and poor), 'India' (warm and poor), and 'Africa' (warm and very poor). The region labeled 'West' represents North America, European Union, and Japan; the region labeled 'India' represents not only India, but also Pakistan, Indonesia, and Latin America; 'China' represents mainly China; and 'Africa' only Africa. Each region maximizes its own welfare (and thus chooses its policy instruments optimally), taking into account its own specific geographical and economic characteristics and its own regional damages from CO2 and aerosols. The four regions are connected to each other only through the accumulation of CO2 in the global atmosphere. Hence, more CO2 emission from one region may cause damages in other regions. In this stylized world we examine how climate change affects health and production in each of the regions. Industrial regions tend to be crowded and hence vulnerable to health risks of exposure to aerosols. Warm regions are vulnerable to temperature-related diseases. We investigate how equilibrium levels of abatement of both emission types are related to the geographical and economic characteristics of each region, we examine how much health costs associated with CO2 and aerosols each region has to carry, and we discuss how global CO2 accumulation contributed by a specific region affects other regions.

Recently, the links between air pollutants and greenhouse gases and the impact on human health through these links have received much attention (Swart *et al.*, 2004; EEA, 2004). Such studies typically consider a global cooling effect of aerosols to partially offset global warming, and hence they do not contain the *local* dimming effects which we study and which lead to differences in economic behavior. Some studies also emphasize the ancillary benefits of reduced air pollution (Burtraw *et al.*, 2003; Aunan *et al.*, 2007; Bahn and Leach, 2008; Bollen *et al.*, 2009). Strategies to reduce greenhouse gas emissions would thus decrease air pollutants as well. The magnitude of this co-benefit influences abatement strategies in each region, and thus affects global climate as well. We investigate the effect of these co-benefits on an equilibrium regional level of abatement of CO2 and aerosols. Pittel and Rübbelke (2008) suggest that ancillary benefits of climate policy may provide incentives for developing countries to participate in an international agreement on climate change. However, if we take account of local dimming through air pollutants, then the co-benefit of climate policy for developing countries (with typically high temperatures and hence many temperature-related diseases) will be reduced. Bahn and Leach (2008) examine the welfare and growth effects of climate change mitigation policies, incorporating the cooling effect and health effects of sulphur dioxide emissions in an overlapping generations model. They examine the inter-generational effects of policies, but not the intra-temporal effects. In contrast, we consider multiple regions and local health effects of climate change in a Nash game framework, thus illustrating regional disparities in climate, economics, and health. Moreover, we analyze how the inter-temporal resource allocation differs among regions responding to varying rates of social time preference.

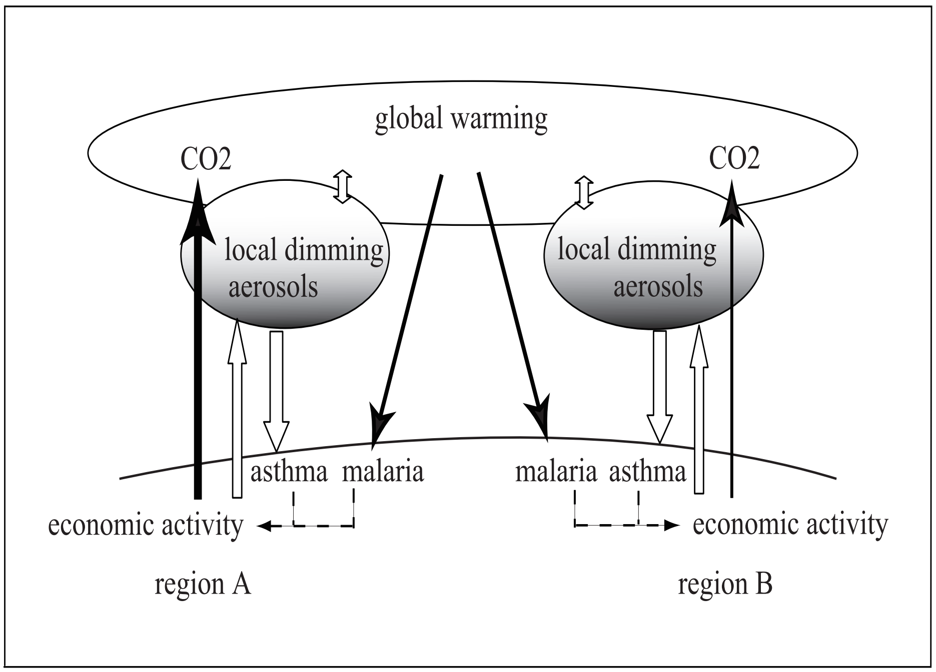

Figure 1: Interactions between the economy, temperature, and health

Some aspects of our model are summarized in Figure 1. Region A has large CO2 emissions relative to region B, but about the same amount of aerosol emissions. The aerosols cause asthma and also reduce the greenhouse effect. The resulting global warming affects both regions in the same way (since CO2 concentration is global) and causes malaria. The diseases cause less people to work and hence reduce economic activity.

The paper is organized as follows. In Section 2 we present the economy-climate model of our stylized world. In Section 3 we examine the first-order conditions of the welfare-maximizing problem under local economic and climate restrictions. Section 4 presents the results based on the warm-cold rich-poor divide in our stylized world. The robustness of our results is studied in Section 5. Section 6 concludes.

2 The model

Our stylized world consists of J regions which we consider over T periods. One period is ten years. At the beginning of period t there are $N_{j,t}$ inhabitants of region j, identical apart from the fact that some work while others don't, some are healthy while others are ill, and some are 'at risk' while others are not. The healthy workers constitute the labor force $L_{j,t}$. People living in different regions may be different.

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

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

where $K_{j,t}$ denotes the capital stock in region j at the beginning of period t, $d_{j,t}$ represents temperature-induced damage, and $\psi_{j,t}$ is technological efficiency. All stocks are measured at the beginning of the period. Temperature $Z_{j,t}$ enters our model through three channels. The first channel is that if temperature deviates from the 'optimal' temperature $Z_{j,t} = Z_j^*$ (the temperature in 1900), then damage occurs resulting in a reduction of output. Following Nordhaus (2008) we specify damage $d_{j,t}$ as

$$d_{j,t} = \gamma_j (Z_{j,t} - Z_j^*)^2 \qquad (\gamma_j > 0). \tag{2}$$

Capital is accumulated through

$$K_{j,t+1} = (1-\delta_j^k) K_{j,t} + I_{j,t} \qquad (0 < \delta_j^k < 1), \tag{3}$$

where $I_{j,t}$ denotes investment and δ_j^k is the depreciation rate of capital (assumed constant over time). Different regions may have different depreciation rates. The labor force $L_{j,t}$ is defined as a proportion ω_j (constant over time) of the healthy people in the region:

$$L_{j,t} = \omega_j (N_{j,t} - D_{j,t}),$$

where $D_{j,t}$ denotes the number of people with some disease. There are two diseases — one caused by temperature (say malaria), the other by aerosols (say asthma). The two diseases are not mutually exclusive, but they are independent. Denoting the fraction of the population suffering from the two diseases by $s^{(1)}_{j,t}$ and $s^{(2)}_{j,t}$, respectively, we have

$$D_{j,t} = (s^{(1)}_{j,t} + s^{(2)}_{j,t} - s^{(1)}_{j,t} s^{(2)}_{j,t}) N_{j,t},$$

and hence

$$L_{j,t} = \omega_j (1 - s^{(1)}_{j,t})(1 - s^{(2)}_{j,t}) N_{j,t} \qquad (0 < \omega_j < 1). \tag{4}$$

Demand side: In each region j and period t, the income generated by GDP can be spent in four ways:

$$Y_{j,t} = C_{j,t} + I_{j,t} + A_{j,t} + H_{j,t}, \tag{5}$$

namely consumption C, investment I, abatement cost A, and health cost H. Consumption yields instantaneous welfare through (16), investment increases the capital stock and future production through equations (1) and (3), abatement of pollution reduces emissions through equation (10), and health cost (12) covers the prevention and treatment of diseases.

Pollution: Each region pollutes by emitting CO2 (c) and aerosols (a). CO2 has a global (instantaneous) effect, while aerosols have a local effect. More CO2 leads to global warming, more aerosols lead to local dimming. Emissions $E^c_{j,t}$ (for CO2) and $E^a_{j,t}$ (for aerosols) are defined by

$$E^c_{j,t} = e^c_{j,t} Y_{j,t}, \qquad E^a_{j,t} = e^a_{j,t} Y_{j,t} \tag{6}$$

with

$$\begin{pmatrix} e^c_{j,t} \\ e^a_{j,t} \end{pmatrix} = \begin{pmatrix} \sigma^{cc}_{j,t} & \sigma^{ca}_{j,t} \\ \sigma^{ac}_{j,t} & \sigma^{aa}_{j,t} \end{pmatrix} \begin{pmatrix} 1 - \mu^c_{j,t} \\ 1 - \mu^a_{j,t} \end{pmatrix}, \tag{7}$$

where $\mu^c_{j,t}$ and $\mu^a_{j,t}$ denote the abatement fractions for CO2 and aerosols, respectively, and the $\sigma_{j,t}$ are technical parameters.

We note the inclusion of two cross-influences $\sigma^{ca}_{j,t}$ and $\sigma^{ac}_{j,t}$. The idea that a policy to reduce one type of pollutant has an effect on another type of pollutant was well summarized by Swart *et al.* (2004) who state that many of the traditional air pollutants and greenhouse gases have common sources; that they interact chemically and physically in the atmosphere; and that they cause a variety of intertwined environmental effects at the local, regional, and global scale. Empirical evidence that a policy to reduce CO2 (through μ^c) affects aerosol emissions (and hence that $\sigma^{ac} > 0$) was provided by Cifuentes *et al.* (2001) in a study of four large cities (Mexico City, New York City, Santiago, and São Paulo); and by Bell *et al.* (2007). The opposite effect (that is, the question whether $\sigma^{ca} > 0$) is ambiguous: a policy on reducing aerosols (through μ^a) may or may not affect CO2 emissions.

Aerosols are generated in the process of fossil fuel combustion. Hence, activities that would reduce carbon emissions could also reduce aerosol emissions, thus improving the local air quality as a secondary benefit. These co-benefits are typically not incorporated in climate policy analyses and they deserve more attention (Nemet *et al.*, 2010). The co-benefit is likely to be especially large in developing countries, and this feature is captured by assuming that the technical parameter $\sigma_{j,t}^{ac}$ is positive for all regions and larger in poor regions. More precisely, we shall assume a stable relationship between carbon emissions and aerosol emissions, and specify $\sigma_{j,t}^{ca}$ and $\sigma_{j,t}^{ac}$ as

$$\sigma_{j,t}^{ca} = \chi_j^{ca}\sigma_{j,t}^{aa}, \qquad \sigma_{j,t}^{ac} = \chi_j^{ac}\sigma_{j,t}^{cc},$$

for some constants χ_j^{ca} and χ_j^{ac}. Notice that if χ_j^{ca} and χ_j^{ac} are small, then

$$\begin{aligned} E_{j,t}^c &= (1-\chi_j^{ca}\chi_j^{ac})\sigma_{j,t}^{cc}(1-\mu_{j,t}^c)Y_{j,t} + \chi_j^{ca}E_{j,t}^a \\ &\approx \sigma_{j,t}^{cc}(1-\mu_{j,t}^c)Y_{j,t} + \chi_j^{ca}E_{j,t}^a, \end{aligned}$$

and, similarly,

$$E_{j,t}^a \approx \sigma_{j,t}^{aa}(1-\mu_{j,t}^a)Y_{j,t} + \chi_j^{ac}E_{j,t}^c.$$

The first term in each equation represents the amount of emission which comes directly from production, while the second term captures the possibility that carbon and aerosol emissions can be a byproduct of each other. So the parameter χ_j^{ca} may be interpreted as a fraction of aerosol-emitting sources which also emit carbon dioxide as a byproduct. Similarly, χ_j^{ac} is a fraction of carbon-emitting sources which also emit aerosol.

Global CO2 concentration is given by

$$M_t = \sum_{j=1}^{J} M_{j,t}, \tag{8}$$

where

$$M_{j,t+1} = (1-\delta^c)M_{j,t} + \zeta^c E_{j,t}^c \qquad (0 < \delta^c < 1). \tag{9}$$

Here, δ^c denotes the depreciation rate of CO2 (rate of removal from atmosphere), and ζ^c the degree of contribution of CO2 emissions to accumulation. Some care is required in interpreting equation (9). The quantity $M_{j,t}$ keeps track of the accumulated amount of CO2 emitted by region j. Since CO2 spreads rapidly around the globe, it can *not* be interpreted as a concentration in region j. It is added here to keep account of the total pollution damage caused by region j.

Abatement: Extending the often-used abatement cost function from one type of emission (as for CO2 in Nordhaus, 2008) to two types of emission (CO2 and aerosols), we write

$$A_{j,t} = a_{j,t} Y_{j,t}, \tag{10}$$

where

$$a_{j,t} = \alpha_j^c (\mu_{j,t}^c)^{\xi_j^c} + \alpha_j^a (\mu_{j,t}^a)^{\xi_j^a} \tag{11}$$

and the exponents ξ_j^c and ξ_j^a are chosen greater than one, so that abatement is convex in $\mu_{j,t}^c$ and $\mu_{j,t}^a$.

Health: We are interested in the health impact of climate change and air pollution. People will get ill from time to time and we shall consider health costs explicitly. All health costs are distributed evenly over the population and everybody has the same consumption net of average health costs. Health expenditures consist of the costs of prevention and treatment. It will be useful to introduce the concept of *population at risk*. As shown by van Lieshout *et al.* (2004), the population at risk of malaria increases as temperature increases. Let $r_{j,t}^{(1)}$ and $r_{j,t}^{(2)}$ denote the proportion of the population that is at risk for disease 1 (malaria) and 2 (asthma), respectively. This is the group that receives preventive health care. Since prevention will not be completely successful, illnesses occur. A sick person receives medication, will be ill for one period, and will then be healthy again (but may of course fall ill again). Health expenditures are given by

$$H_{j,t} = \left(h_{j,t}^{(1)} + h_{j,t}^{(2)} \right) N_{j,t}, \tag{12}$$

where

$$h_{j,t}^{(1)} = p_{j,t}^{(1)} r_{j,t}^{(1)} + q_{j,t}^{(1)} s_{j,t}^{(1)}, \qquad h_{j,t}^{(2)} = p_{j,t}^{(2)} r_{j,t}^{(2)} + q_{j,t}^{(2)} s_{j,t}^{(2)},$$

$p_{j,t}^{(1)}$ and $p_{j,t}^{(2)}$ denote the prevention costs for someone at risk, and $q_{j,t}^{(1)}$ and $q_{j,t}^{(2)}$ are the treatment costs per patient. We specify the proportion of malaria and asthma patients in the population as

$$s_{j,t}^{(1)} = (1 - u_j^{(1)}) r_{j,t}^{(1)}, \qquad s_{j,t}^{(2)} = (1 - u_j^{(2)}) r_{j,t}^{(2)},$$

where $0 < u_j^{(1)} < 1$ and $0 < u_j^{(2)} < 1$ denote the success rates of prevention. Then,

$$h_{j,t}^{(1)} = \theta_{j,t}^{(1)} r_{j,t}^{(1)}, \qquad h_{j,t}^{(2)} = \theta_{j,t}^{(2)} r_{j,t}^{(2)}, \tag{13}$$

where

$$\theta_{j,t}^{(1)} = p_{j,t}^{(1)} + (1 - u_j^{(1)}) q_{j,t}^{(1)}, \qquad \theta_{j,t}^{(2)} = p_{j,t}^{(2)} + (1 - u_j^{(2)}) q_{j,t}^{(2)}.$$

We next specify the two fractions of people at risk by

$$r_{j,t}^{(1)} = \frac{\beta_j^{(1)} \left(Z_{j,t}/\kappa_j^{(1)} \right)^{\eta_j^{(1)}}}{1 + \left(Z_{j,t}/\kappa_j^{(1)} \right)^{\eta_j^{(1)}}}, \qquad r_{j,t}^{(2)} = \frac{\beta_j^{(2)} \left(\nu_{j,t} E_{j,t}^a/\kappa_j^{(2)} \right)^{\eta_j^{(2)}}}{1 + \left(\nu_{j,t} E_{j,t}^a/\kappa_j^{(2)} \right)^{\eta_j^{(2)}}} \tag{14}$$

for the two diseases malaria and asthma, respectively. The parameter $\nu_{j,t}$ in $r_{j,t}^{(2)}$ is a concentration parameter, measuring how concentrated the population is in region j and time t. Since aerosols are (mostly) a local phenomenon, it makes a difference whether the population is spread out over the whole region or is concentrated in a few urban areas.

We see that temperature enters our model not only through the production function, but also through the health cost function and the available labor force (both via $s^{(1)}$). Notice that $\partial r^{(1)}/\partial Z \geq 0$ and $\partial r^{(2)}/\partial E^a > 0$. The second impact (more aerosols, more asthma) is reasonable, but the first (higher temperature, more malaria) requires some explanation. In Africa one expects a rise in temperature to cause more diseases, but in Siberia a rise in temperature would result in a milder climate and possibly less diseases. We shall assume here that a rise in temperature has no effect on malaria until it reaches a benchmark; a further increase then results in more malaria.

Climate: The temperature equation is inspired by Nordhaus (2008):

$$\begin{aligned} Z_{j,t+1} = {} & \tau_{0,j} + \tau_{1,j} Z_{j,t} + \tau_2 \log(M_t) \\ & + \tau_{3,j} E_{j,t}^a + \tau_{4,j} \log(1 + \tau_{5,j} E_{j,t}^a) \end{aligned} \tag{15}$$

In the Nordhaus model, however, the radiative forcing of aerosols is given exogenously. It is made endogenous here based on Harvey *et al.* (1997). For further details see Appendix A.2.

Temperature is thus dynamically determined by its own past, but also by the concentration of carbon dioxide and the emission of aerosols. More CO2 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: Each region maximizes its own welfare W_j, defined by total discounted utility:

$$W_j = \sum_{t=0}^{T} \frac{N_{j,t} \log(C_{j,t}/N_{j,t})}{(1+\rho_j)^t}, \tag{16}$$

where ρ_j is the discount rate for region j.

3 Welfare maximization

We wish to maximize welfare (16) under the economy and climate restrictions (1)–(15). We first condense the restrictions to one resource constraint,

$$\begin{aligned}\Psi^k_{j,t} = Y_{j,t} - C_{j,t} + (1-\delta^k_j)K_{j,t} - K_{j,t+1}\\ - a_{j,t}Y_{j,t} - (h^{(1)}_{j,t} + h^{(2)}_{j,t})N_{j,t} = 0,\end{aligned}$$

together with two dynamic constraints:

$$\Psi^m_{j,t} = \zeta^c E^c_{j,t} + (1-\delta^c)M_{j,t} - M_{j,t+1} = 0,$$

and

$$\begin{aligned}\Psi^\tau_{j,t} = \tau_{0,j} + \tau_{1,j}Z_{j,t} + \tau_2 \log\left(M_{j,t} + \sum_{i\neq j} M_{i,t}\right)\\ + \tau_{3,j}E^a_{j,t} + \tau_{4,j}\log\left(1+\tau_{5,j}E^a_{j,t}\right) - Z_{j,t+1} = 0.\end{aligned}$$

Each region maximizes its own welfare under local restrictions. The regions are linked only through (8): $M_t = \sum_{j=1}^J M_{j,t}$. We are seeking the Nash equilibrium in this finite perfect-information game, and this is what our GAMS program does.

We write the Lagrangian for region j as

$$\mathcal{L}_j = \sum_{t=0}^T \frac{N_{j,t}\log(C_{j,t}/N_{j,t})}{(1+\rho_j)^t} + \sum_{t=0}^T \left(\lambda^k_{j,t}\Psi^k_{j,t} + \lambda^m_{j,t}\Psi^m_{j,t} + \lambda^\tau_{j,t}\Psi^\tau_{j,t}\right),$$

where the $\lambda_{j,t}$ $(t = 0,\dots,T)$ denote Lagrangian multipliers. We need to differentiate with respect to:

$$C_{j,t}, \mu^c_{j,t}, \mu^a_{j,t} \qquad (t = 0,\dots,T)$$

and

$$K_{j,t}, M_{j,t}, Z_{j,t} \qquad (t = 1,\dots,T+1),$$

based on starting values $K_{j,0}$, $M_{j,0}$, and $Z_{j,0}$.

In order to find the first-order conditions, we first write the model in differential form. This gives

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

and

$$(dL_{j,t}) = \frac{\partial L_{j,t}}{\partial r^{(1)}_{j,t}}\frac{\partial r^{(1)}_{j,t}}{\partial Z_{j,t}}(dZ_{j,t}) + \frac{\partial L_{j,t}}{\partial r^{(2)}_{j,t}}\frac{\partial r^{(2)}_{j,t}}{\partial E^a_{j,t}}(dE^a_{j,t})$$

for output and labor, and

$$\begin{aligned}(dK_{j,t+1}) = {} & (1-a_{j,t})(dY_{j,t}) - (dC_{j,t}) + (1-\delta^k_j)(dK_{j,t}) \\ & - \frac{\partial a_{j,t}}{\partial \mu^c_{j,t}} Y_{j,t}(d\mu^c_{j,t}) - \frac{\partial a_{j,t}}{\partial \mu^a_{j,t}} Y_{j,t}(d\mu^a_{j,t}) \\ & - \theta^{(1)}_{j,t} \frac{\partial r^{(1)}_{j,t}}{\partial Z_{j,t}} N_{j,t}(dZ_{j,t}) - \theta^{(2)}_{j,t} \frac{\partial r^{(2)}_{j,t}}{\partial E^a_{j,t}} N_{j,t}(dE^a_{j,t}),\end{aligned}$$

$$(dM_{j,t+1}) = (1-\delta^c)(dM_{j,t}) + \zeta^c(dE^c_{j,t}),$$

and

$$(dZ_{j,t+1}) = \tau_{1,j}(dZ_{j,t}) + \frac{\partial Z_{j,t+1}}{\partial M_t}(dM_{j,t}) + \frac{\partial Z_{j,t+1}}{\partial E^a_{j,t}}(dE^a_{j,t})$$

for the three dynamic equations, where

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

and

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

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. We have

$$\begin{pmatrix} 1 & -\phi^{yl}_{j,t} \\ \phi^{ly}_{j,t} & 1 \end{pmatrix} \begin{pmatrix} dY_{j,t} \\ dL_{j,t} \end{pmatrix} = \begin{pmatrix} 0 & 0 & \phi^{yk}_{j,t} & -\phi^{y\tau}_{j,t} \\ \phi^{lc}_{j,t} & \phi^{la}_{j,t} & 0 & -\phi^{l\tau}_{j,t} \end{pmatrix} \begin{pmatrix} d\mu^c_{j,t} \\ d\mu^a_{j,t} \\ dK_{j,t} \\ dZ_{j,t} \end{pmatrix}$$

and hence

$$(dY_{j,t}) = \frac{1}{1+\phi^{yl}_{j,t}\phi^{ly}_{j,t}} \begin{pmatrix} \phi^{yl}_{j,t}\phi^{lc}_{j,t} & \phi^{yl}_{j,t}\phi^{la}_{j,t} & \phi^{yk}_{j,t} & -(\phi^{y\tau}_{j,t} + \phi^{yl}_{j,t}\phi^{l\tau}_{j,t}) \end{pmatrix} \begin{pmatrix} d\mu^c_{j,t} \\ d\mu^a_{j,t} \\ dK_{j,t} \\ dZ_{j,t} \end{pmatrix}, \tag{17}$$

where

$$\phi^{yl}_{j,t} = \frac{\partial Y_{j,t}}{\partial L_{j,t}}, \quad \phi^{yk}_{j,t} = \frac{\partial Y_{j,t}}{\partial K_{j,t}}, \quad \phi^{y\tau}_{j,t} = -\frac{\partial Y_{j,t}}{\partial d_{j,t}} \frac{\partial d_{j,t}}{\partial Z_{j,t}},$$

and

$$\phi^{ly}_{j,t} = -\frac{\partial L_{j,t}}{\partial r^{(2)}_{j,t}} \frac{\partial r^{(2)}_{j,t}}{\partial E^a_{j,t}} e^a_{j,t}, \quad \phi^{lc}_{j,t} = -\frac{\partial L_{j,t}}{\partial r^{(2)}_{j,t}} \frac{\partial r^{(2)}_{j,t}}{\partial E^a_{j,t}} \sigma^{ac}_{j,t} Y_{j,t},$$

$$\phi^{la}_{j,t} = -\frac{\partial L_{j,t}}{\partial r^{(2)}_{j,t}} \frac{\partial r^{(2)}_{j,t}}{\partial E^a_{j,t}} \sigma^{aa}_{j,t} Y_{j,t}, \quad \phi^{l\tau}_{j,t} = -\frac{\partial L_{j,t}}{\partial r^{(1)}_{j,t}} \frac{\partial r^{(1)}_{j,t}}{\partial Z_{j,t}}.$$

Since $\phi^{yl}_{j,t}\phi^{ly}_{j,t} > 0$, any output change caused by a marginal change in $\mu^c_{j,t}$, $\mu^a_{j,t}$, $K_{j,t}$, or $Z_{j,t}$ is scaled down through the interaction between output and labor.

The first-order conditions can now be written as (for $t = 0, \ldots, T$):

$$\lambda^k_{j,t} = \frac{1}{(1+\rho_j)^t (C_{j,t}/N_{j,t})} \tag{18}$$

and

$$\begin{pmatrix} \pi^{cm}_{j,t} & \pi^{c\tau}_{j,t} \\ \pi^{am}_{j,t} & \pi^{a\tau}_{j,t} \end{pmatrix} \begin{pmatrix} \lambda^m_{j,t} \\ \lambda^\tau_{j,t} \end{pmatrix} = -\lambda^k_{j,t} \begin{pmatrix} \pi^{ck}_{j,t} \\ \pi^{ak}_{j,t} \end{pmatrix} \tag{19}$$

together with a system of three dynamic equations (for $t = 1, \ldots, T$):

$$\begin{pmatrix} \lambda^k_{j,t-1} \\ \lambda^m_{j,t-1} \\ \lambda^\tau_{j,t-1} \end{pmatrix} = \begin{pmatrix} \pi^{kk}_{j,t} & \pi^{km}_{j,t} & \pi^{k\tau}_{j,t} \\ 0 & \pi^{mm}_{j,t} & \pi^{m\tau}_{j,t} \\ \pi^{\tau k}_{j,t} & \pi^{\tau m}_{j,t} & \pi^{\tau\tau}_{j,t} \end{pmatrix} \begin{pmatrix} \lambda^k_{j,t} \\ \lambda^m_{j,t} \\ \lambda^\tau_{j,t} \end{pmatrix}, \tag{20}$$

and the terminal conditions

$$\lim_{t\to\infty} \lambda^k_{j,t} K_{j,t} = \lim_{t\to\infty} \lambda^m_{j,t} M_{j,t} = \lim_{t\to\infty} \lambda^\tau_{j,t} Z_{j,t} = 0,$$

requiring that the shadow values of more capital, more CO2 concentration, and higher temperature vanish asymptotically. Together with the three constraints $\Psi^k_{j,t} = \Psi^m_{j,t} = \Psi^\tau_{j,t} = 0$ this gives us nine equations with nine unknowns, namely $C_{j,t}$, $\mu^c_{j,t}$, $\mu^a_{j,t}$, $K_{j,t+1}$, $M_{j,t+1}$, $Z_{j,t+1}$, $\lambda^k_{j,t}$, $\lambda^m_{j,t}$, and $\lambda^\tau_{j,t}$, for $t = 0, \ldots, T$. To find the values of the π coefficients is somewhat tedious, and is relegated to Appendix B.

Condition (18) says that for every region j and in every period t the shadow value of the resource constraint equals the present value of marginal utility (both are equal to the shadow value of capital). Condition (19) equates marginal benefit to marginal cost of CO2 and aerosol reduction in region j. The marginal benefit of carbon abatement thus consists not only of the reduced carbon concentration, but also of the air quality co-benefits. The improvement of air quality causes temperature to increase, and this partly offsets the effectiveness of carbon abatement. Hence, the marginal cost of carbon abatement includes the cost of temperature increase as a result of air quality improvement as well as the direct abatement cost. Similarly, the marginal cost of aerosol abatement includes not only the abatement cost, but also the indirect cost of temperature increase due to local dimming.

The three dynamic equations (20) provide the evolutions of the shadow prices of capital stock, CO2 concentration, and temperature, respectively. The evolution of the shadow price of capital ($\lambda^k_{j,t-1}$) is composed of three terms: the net marginal return on capital stock accumulation ($\pi^{kk}_{j,t}\lambda^k_{j,t}$), which includes capital depreciation, aggregate health cost of asthma due to additional output and hence additional aerosols, and net marginal return on output after abatement expenditures; the marginal return on CO2 accumulation ($\pi^{km}_{j,t}\lambda^m_{j,t}$); and the marginal return on a change in temperature ($\pi^{k\tau}_{j,t}\lambda^\tau_{j,t}$). An additional unit of capital gives more output in the subsequent periods, but also more aerosol emission and thus higher health costs. This decreases the shadow value of capital. At the same time, the lower cost of carbon emission ($-\pi^{km}_{j,t}\lambda^m_{j,t} > 0$) due to less labor, and the local dimming effect ($\pi^{k\tau}_{j,t} < 0$) increase the shadow value of capital.

Substituting (18) and (19) into (20) yields the Keynes-Ramsey rule:

$$\frac{(1+\rho_j)(C_{j,t}/N_{j,t})}{C_{j,t-1}/N_{j,t-1}} = \pi^{kk}_{j,t} - \left(\pi^{km}_{j,t}\ ,\ \pi^{k\tau}_{j,t}\right)\begin{pmatrix}\pi^{cm}_{j,t} & \pi^{c\tau}_{j,t}\\ \pi^{am}_{j,t} & \pi^{a\tau}_{j,t}\end{pmatrix}^{-1}\begin{pmatrix}\pi^{ck}_{j,t}\\ \pi^{ak}_{j,t}\end{pmatrix},$$

requiring that the marginal rate of substitution between consumption today and consumption tomorrow is equal to the physical marginal rate of substitution. We note that the Keynes-Ramsey rule for the Nash equilibrium only internalizes climate change damage occurring domestically, because negative climate change externalities to neighboring regions are not taken into account into the shadow price of CO2.

The second dynamic equation in (20) provides the evolution of the shadow price of CO2 concentration ($\lambda^m_{j,t-1}$), as the sum of the net value of CO2 concentration in the next period ($\pi^{mm}_{j,t}\lambda^m_{j,t}$) and the marginal value of temperature with respect to CO2 adjusted by the shadow price of temperature ($\pi^{m\tau}_{j,t}\lambda^\tau$).

¿From the third dynamic equation in (20) we see that the evolution of the shadow price of temperature ($\lambda^\tau_{j,t-1}$) depends on three effects of a change in temperature: the additional aggregate health costs of malaria and asthma ($\pi^{\tau k}_{j,t}\lambda^k_{j,t}$); the marginal return on a change in temperature due to additional CO2 concentration ($\pi^{\tau m}_{j,t}\lambda^m_{j,t}$); and the direct (through the temperature equation) and indirect (through output and aerosols) effect ($\pi^{\tau\tau}_{j,t}\lambda^\tau_{j,t}$). The magnitude of the first effect ($\pi^{\tau k}_{j,t}$) varies considerably across regions. The adverse impact of malaria is larger in warm regions, which means a lower $\pi^{\tau k}_{j,t}$, and thus a higher shadow cost of temperature. In cold regions, which have no malaria, a reduction of output due to the direct effect of temperature decreases the health cost of asthma. The higher value of $\pi_{j,t}^{\tau k}$ decreases the shadow cost of temperature. However, increasing temperature decreases output and corresponding aerosol emission. As a result, less dimming (brightening) increases the local temperature.

4 The warm-cold rich-poor divide

We shall consider a world consisting of four regions, characterized by only two features, namely whether the region is warm or cold and whether the people are rich, poor or very poor. We denote these four regions by 'West', 'China', 'India', and 'Africa', respectively. More precisely, we define:

- cold rich ('West'): European Union, North America, Japan;
- cold poor ('China'): China, Eastern Europe;
- warm poor ('India'): India, Pakistan, Bangladesh, Indonesia, Rest of Asia, Middle East, Latin America; and
- warm very poor ('Africa'): Africa.

There is also a warm rich region, for example Australia, but this region is small and will be ignored.

	West	China	India	Africa
Income	high	low	middle	very low
Econ. growth	moderate	high	high	moderate
Population	small	middle	large	small
Temperature	low	low	high	high
Pop. density	high	low	low	low
Carbon emission	large	middle	middle	small
Aerosol emission	large	large	large	small
Abatement cost	high	middle	middle	low
Health cost	high	middle	middle	low

Table 1: Characterization of the four regions

Some characteristics of the four regions are presented in Table 1. The division of the world based on temperature and wealth only is obviously very stylized, but it captures the essence of our story. Our parameters are calibrated such that they correspond closely to the true geographical areas; see Appendix A. The four-region model with the calibrated parameter values (the 'benchmark' model) is our principal tool for analysis. There is of course considerable uncertainty about the calibrated parameter values, and we shall investigate the sensitivity of our results to parameter uncertainty in Section 5. The main purpose of our analysis is to illustrate the link between global and local climate change, and examine how this link affects economic behavior in heterogeneous regions.

	2005	2055	2105	2005	2055	2105
	Output			*Consumption per capita*		
West	34.065	69.679	113.398	2.728	5.151	8.292
China	3.400	8.392	16.157	0.161	0.392	0.784
India	7.117	24.843	51.638	0.173	0.432	0.848
Africa	0.883	3.522	6.371	0.069	0.172	0.315
	Global carbon emission			*Carbon concentration*		
Global	7.584	11.798	15.138	809.4	1047.5	1393.8
	Malaria patient rate			*Asthma patient rate*		
West	0.000	0.000	0.000	0.109	0.066	0.050
China	0.000	0.000	0.000	0.062	0.061	0.063
India	0.045	0.061	0.093	0.059	0.071	0.074
Africa	0.338	0.366	0.391	0.018	0.028	0.027
	Carbon abatement			*Aerosol abatement*		
West	0.005	0.161	0.223	0.000	0.325	0.452
China	0.000	0.075	0.108	0.000	0.097	0.139
India	0.000	0.154	0.228	0.000	0.144	0.205
Africa	0.000	0.068	0.090	0.000	0.059	0.092

Table 2: Selected results of the four-region benchmark model

Some selected results from our benchmark model are summarized in Table 2. Along the equilibrium path, output and per capita consumption will continue to increase in every region. While West remains the largest economic power throughout the 100-year time horizon, the growth rates of output and consumption are both larger in the other three regions. Developing countries grow at a faster pace than developed countries, because of our assumptions on initial output and technology efficiency. The growth rates of per capita consumption in India and Africa are, however, relatively small compared to their output growth rates, especially in the first fifty years. Output in these two regions will grow rapidly, but per capita consumption will not grow as rapidly. This is primarily because the number of people who are at risk of or suffer from diseases will rise, and thus a non-negligible fraction of resources must be used for prevention and treatment.

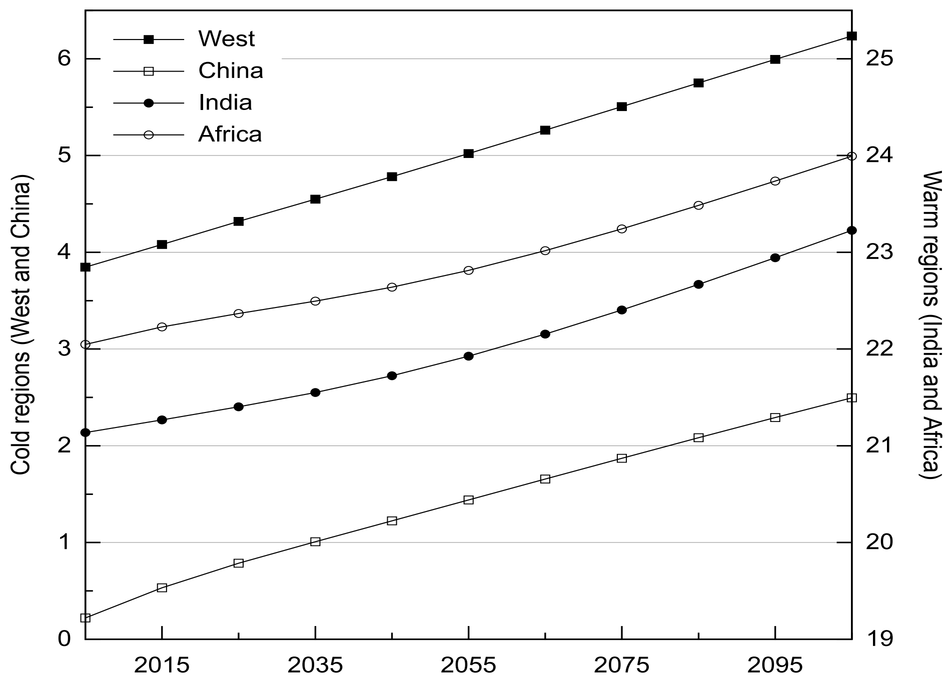

Figure 2: Regional mean temperatures, 2005–2105

The expected increase of malaria patients in warm regions is obviously due to the temperature change caused by global warming. Global carbon emission will continue to rise and the level of carbon concentration will be significantly increased by the end of this century. Consequently, the mean temperature in each region will be two to three degrees higher in 2105 than in 2005 (Figure 2). Since the risk of malaria depends on regional temperature, an increase in regional temperature will increase the number of malaria patients, which in turn implies higher health cost. Notice that this is only the case in India and Africa, because there is no malaria in cold regions. In the cold regions (West and China), temperature change will cause damage only through direct productivity loss. The relatively slow growth of per capita consumption in warm regions is partly due to this asymmetric structure of climatic damage.

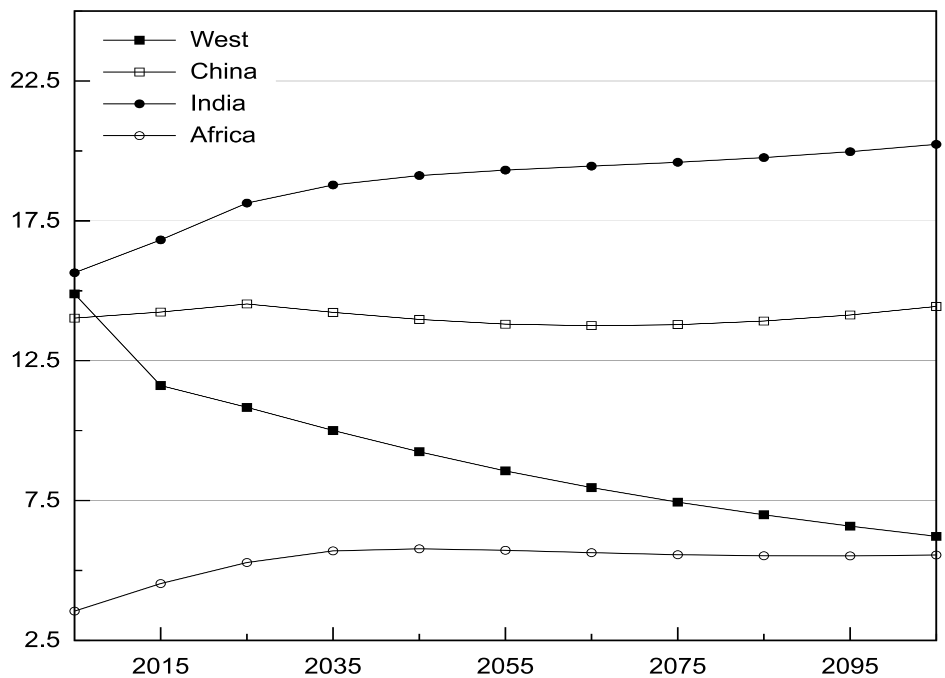

Figure 3: Aerosol emission, 2005–2105

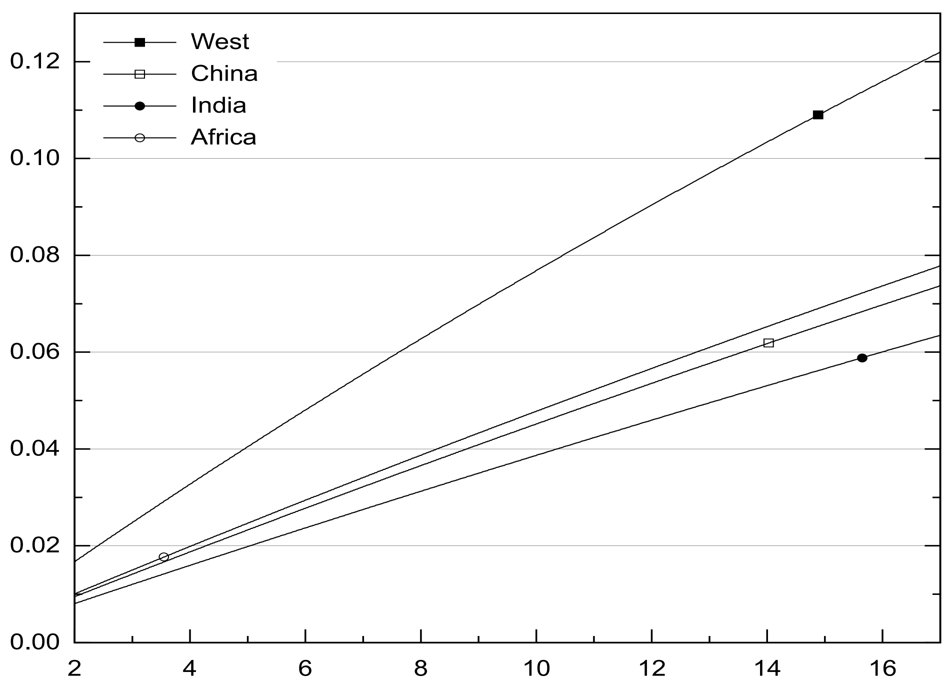

Figure 4: Asthma patient rate as a function of aerosol emission

In warm regions, not only the number of malaria patients but also the number of asthma patients will increase. This contrasts with the situation in cold regions, where the fraction of the population suffering from asthma will decrease or at least stabilize. The sharp reduction of asthma patients in West follows from a rapid improvement of air quality (Figure 3), caused by the fact that West is more vulnerable to air pollution and thus more willing to abate aerosol emission. This is not the case for the other three regions. Figure 4 shows that the slope of the asthma function, representing the vulnerability to air pollution, is almost the same for China, India, and Africa, but steeper in West. The four initial states are indicated in the figure. However, only India and Africa will continue to increase their aerosol emission in the coming decades.

This is the part of our model where the endogenous local dimming effect becomes important. In our model, regional temperature is determined not only by the level of carbon concentration, but also by the amount of local aerosol emission, which is endogenous and individually controlled by each region. Improvement of air quality reduces asthma, but it also intensifies the damage caused by global warming because the aerosols reduce the amount of sunlight reaching the Earth. Since warm regions will suffer more from a rise in temperature, they will be reluctant to promote policies that reduce aerosols. This is why aerosol emission in India and Africa will continue to rise while China will manage to stabilize the level of emission. The impact of local dimming can be seen in the equilibrium regional temperature (Figure 2). Temperatures in India and Africa exhibit a moderate increase compared with those in West and China. This indicates that warm regions control regional temperature at the cost of air quality. India and Africa will thus be required to pay more for preventing and treating asthma.

The increase of asthma patients actually matters, especially for Africa. To clarify this point we plot the development over time of the share of asthma health cost in total output (Figure 5). In the long run, the economic cost associated with asthma in each region become less important due to economic growth. But in the short run, Africa will have to keep allocating a constant portion of its disposable income to treating asthma, while the burden of asthma in the other three regions declines. As a result, consumption in Africa will be suppressed by aerosol-induced health cost. Since the increase of asthma patients is a necessary byproduct of Africa's policy to counteract rising temperature, one can view this as an indirect cost of global warming.

The carbon and aerosol abatement rates chosen by each region deserve more careful interpretation. Our benchmark results show that while West abates carbon emission at the highest rate in the near future, India is likely to exert an even higher carbon abatement rate in the long run. Recall that

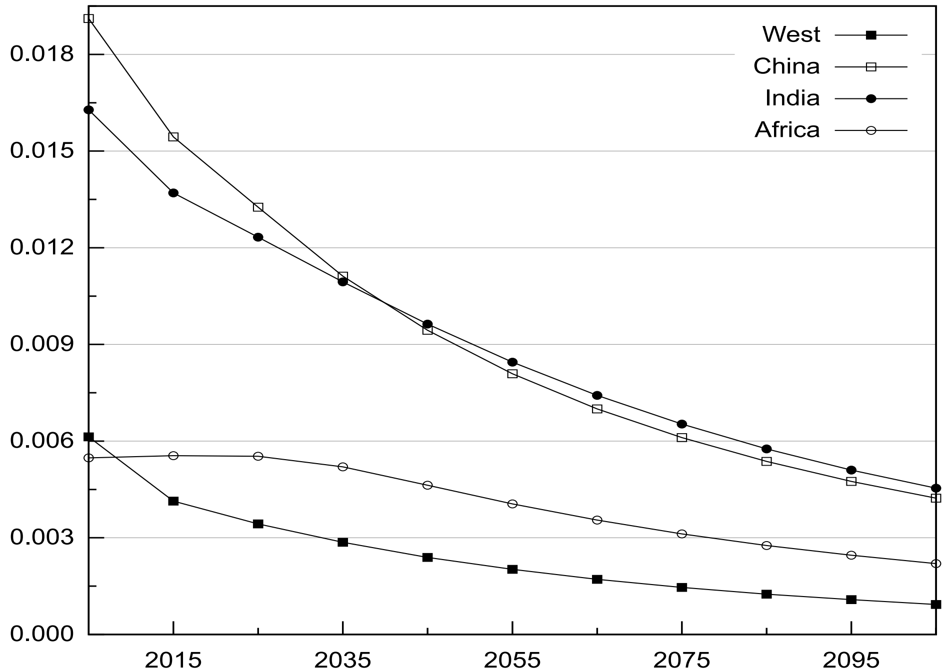

Figure 5: Share of asthma health cost in output, 2005–2105

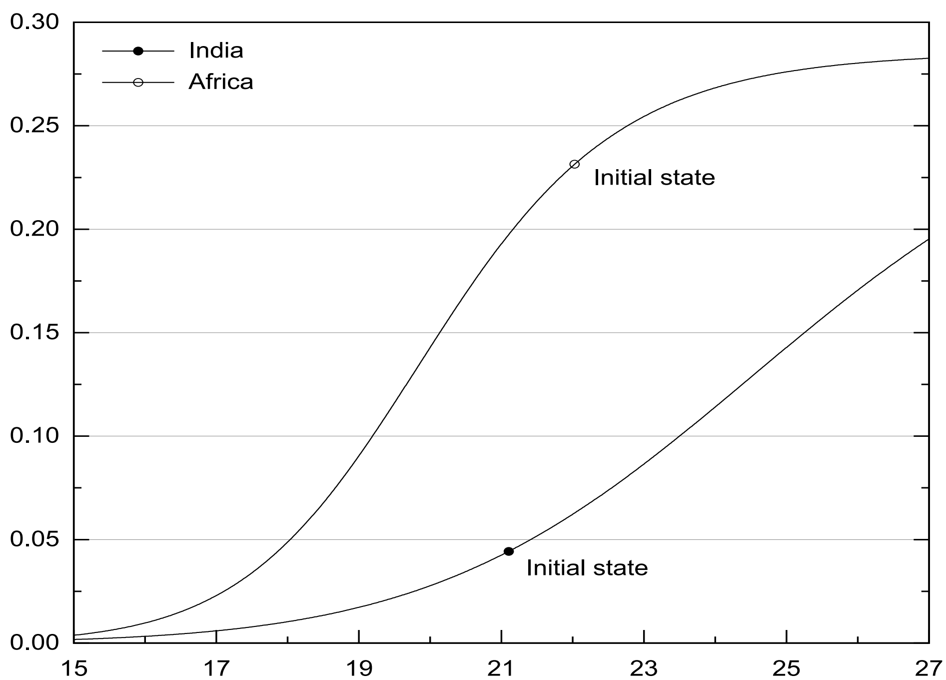

Figure 6: Malaria patient rate as a function of temperature

what we call 'India' is in fact a huge region that covers the entire warm area on the globe other than Africa. This region thus includes countries which are located at the edge of the current distribution of malaria (van Lieshout *et al.*, 2004). Hence it is India which will be the first to suffer if the malaria-endemic area is expanded. This feature is captured in our model by assuming that the malaria function for India is locally convex (Figure 6). Therefore, marginal damage of malaria expansion is large in this region and will be even larger as the regional temperature increases. The cost of carbon abatement is therefore more likely to be paid off in the long run.

Africa is another region which will suffer from the intensification of malaria. The marginal damage of temperature change will be large, but the equilibrium level of carbon abatement will be small in Africa. To explain this we note first that additional damage from temperature increase through malaria expansion in this region is relatively small. Since Africa is already highly malaria-endemic, there is little room left for further expansion of the malaria-endemic area (van Lieshout *et al.*, 2004). In our model, the malaria function for Africa is locally concave in order to capture this feature (Figure 6). The marginal damage of an increase in temperature is thus smaller in Africa than in India. In other words, Africa is less willing to abate carbon emission compared with India as far as malaria is concerned. This point alone, however, does not provide a complete explanation, because the carbon abatement in Africa is even smaller than in China, where there is no additional damage from malaria.

This brings us to the second point: endogenous local dimming. Recall that each region can control regional temperature either by reducing carbon emission or by increasing (or not reducing) aerosol emission. Considering that the latter option can only be chosen with the side effect of increasing the number of asthma patients, it might seem that the first option is always more attractive. However, the second option can be a better way of slowing down the rise of regional temperature. Global warming is a public bad, and hence the marginal benefit from additional mitigation efforts is limited. This is especially the case in Africa. As is shown in Figure 7, Africa is the smallest contributor to global warming. This means that the global trend of increasing temperature is given as an almost complete externality to this region. Hence, as long as global warming is mostly beyond control, increasing aerosol emission is a reasonable way of controlling temperature even though it is accompanied by air pollution. In fact, the equilibrium level of aerosol abatement in Africa is very low, which indicates that this region controls temperature by increasing aerosol emission rather than by reducing carbon emission.

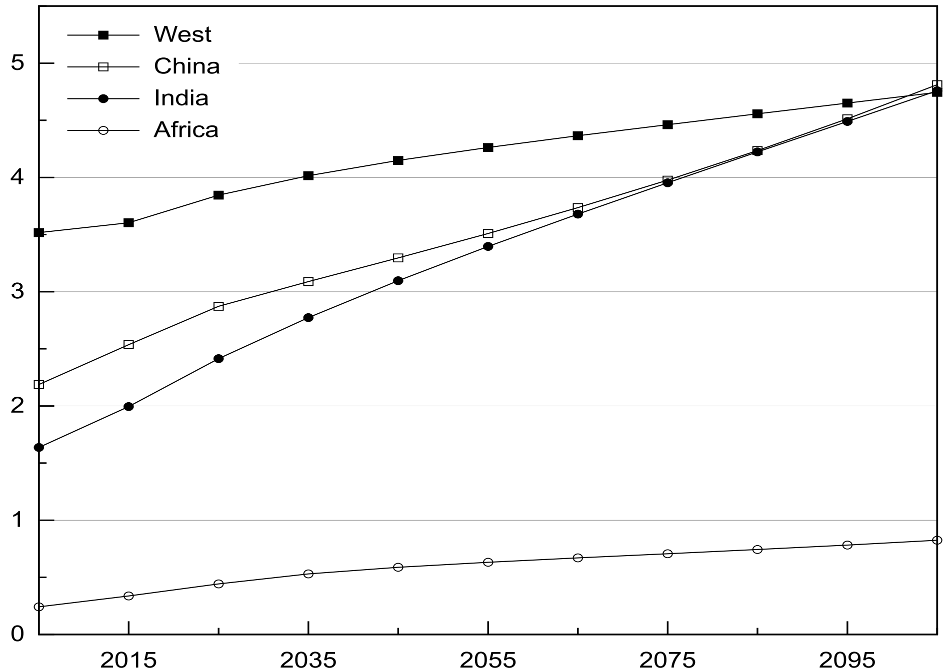

Figure 7: Carbon emission, 2005–2105

Although the equilibrium path is the optimal choice based on each region's own welfare maximization, our results might provoke a concern about equity among regions. The burden of climate change is unequally distributed, because rising temperature is more harmful in already warm regions, but also because people living in warm regions will have to live with low air quality. The indirect burden of global warming (through asthma) is especially large in Africa despite the fact that this region is least responsible for generating greenhouse gasses.

5 Parameter uncertainty

To examine the robustness of our results and further clarify their implications, we conducted extensive sensitivity analyses concerning the effects of choosing incorrect parameter values. For the parameters which represent a ratio we increased their values by 0.05 compared to the benchmark value; for the other parameters we increased their values by up to 50% compared to the benchmark value. The overall conclusion of the sensitivity analysis is that our benchmark results are fairly robust. The equilibrium path does not change much when we use different values for the exogenous parameters. Hence, in general, the inherent uncertainty surrounding parametrization does not entail serious problems in our model. Yet, some of the parameters play more important roles than others, and below we restrict our attention to these parameters.

	Λ^{μ^c}	Λ^{μ^a}	Λ^{μ^c}	Λ^{μ^a}	Λ^{μ^c}	Λ^{μ^a}	Λ^{μ^c}	Λ^{μ^a}
	$p_j^{(1)}$ [+50%]		$p_j^{(2)}$ [+50%]		$q_j^{(1)}$ [+50%]		$q_j^{(2)}$ [+50%]	
West	$-\epsilon$	$+\epsilon$	0.004	0.007	$-\epsilon$	$+\epsilon$	0.002	0.004
China	$-\epsilon$	$+\epsilon$	0.019	0.027	$-\epsilon$	$+\epsilon$	0.012	0.017
India	0.002	−0.002	0.011	0.029	0.002	−0.002	0.007	0.018
Africa	−0.002	−0.062	0.025	0.071	−0.003	−0.010	0.016	0.045
	$u_j^{(1)}$ [+0.05]		$u_j^{(2)}$ [+0.05]		$\beta_j^{(1)}$ [+0.05]		$\beta_j^{(2)}$ [+0.05]	
West	$+\epsilon$	$-\epsilon$	−0.021	−0.039	$-\epsilon$	$+\epsilon$	0.018	0.033
China	$+\epsilon$	$-\epsilon$	−0.025	−0.035	$-\epsilon$	$+\epsilon$	0.022	0.031
India	−0.012	0.011	−0.016	−0.042	0.016	−0.010	0.014	0.037
Africa	0.004	0.092	−0.030	−0.093	−0.003	−0.065	0.026	0.073
	m_j^c [+50%]		m_j^a [+50%]		ρ_j [+0.05]		χ_j^{ac} [+50%]	
West	−0.203	$-\epsilon$	−0.009	−0.209	−0.054	−0.007	0.139	−0.002
China	−0.202	$-\epsilon$	−0.002	−0.203	−0.032	−0.005	0.186	−0.002
India	−0.203	−0.002	−0.004	−0.202	−0.066	0.006	0.106	$+\epsilon$
Africa	−0.206	0.005	0.001	−0.201	−0.045	0.050	0.100	−0.002

Table 3: Effects of parametric uncertainty on μ^c and μ^a in 2055

In Table 3 we present the effects of changes in various parameters on the abatement rates μ^c and μ^a in the year 2055, compared to the benchmark results. Here, Λ^{μ^c} and Λ^{μ^a} denote the relative deviation of $\mu^c_{j,2055}$ and $\mu^a_{j,2055}$ from the benchmarks, respectively. For example, an increase of 50% in $p_j^{(1)}$ will cause μ^a in Africa to decrease by 6.2% The parameter changes listed in the table do not much affect the optimal paths of the abatement rates with three exceptions: the effect of m^c on μ^c, the effect of m^a on μ^a, and (to a lesser extent) the effect of χ^{ac} on μ^c. The parameters m^c and m^a determine the overall level of abatement efforts, because they directly change the marginal abatement cost; see Appendix A.1. Although the effects are in the order of 20%, the qualitative characteristics of the equilibrium path of our benchmark model are not affected.

The aerosol abatement rate in Africa is more sensitive than those in the other regions. This is probably because the optimal level of aerosol emission in Africa depends on a complex set of determinants, some of which contradict each other. In warm regions, aerosol emission plays an important role both in controlling regional air quality and in counteracting global temperature rise. While this is more or less true for every region, the situation in Africa is unique. The endogenous local dimming effect is the primary channel of temperature control in Africa while it is much less important in the other regions. As discussed in the preceding section, carbon abatement in Africa is not an efficient way of combating rising temperature. The temperature rise is almost entirely caused by carbon emission in the other regions. Africa is thus required to use aerosol emission to alleviate the adverse impact of climate change. In fact, $\mu^a_{j,2055}$ is sensitive not only to malaria-related parameters, but also to asthma-related parameters. This shows that Africa chooses $\mu^a_{j,t}$ so as to reach a balance between two goals: slowing down the rise in regional temperature and improving air quality. Since these two goals work against each other, the optimal level of aerosol abatement is likely to be unstable.

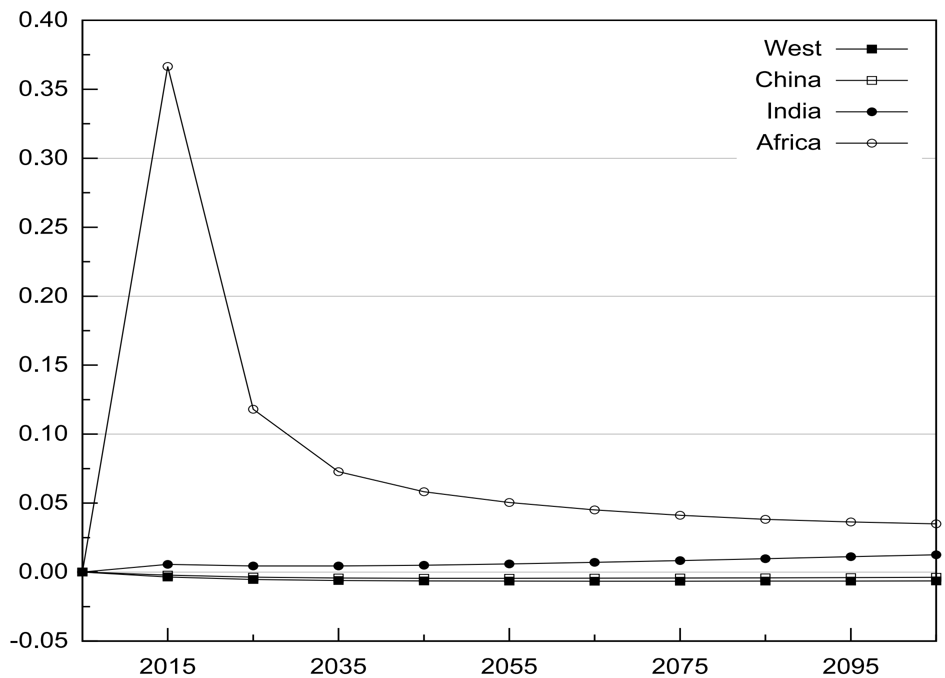

Figure 8: Relative deviation of μ^a from benchmark when ρ is increased by 0.05, 2005–2105

Apart from μ^c and μ^a, another parameter of interest is the rate of time preference, ρ_j. As people become more impatient, cold regions and warm regions adjust their aerosol abatement levels in opposite directions: the cold regions (West and China) abate less while the warm regions (India and Africa) abate more. An increase of impatience makes people more willing to consume and less willing to invest, which in turn decreases output in the subsequent periods relative to the benchmark level. As a result, the amount of aerosol generated through the production process declines, and this induces lower aerosol abatement rates. Also, lower aerosol emission due to lower production causes local brightening (less dimming) and thus increases regional temperature. This lessens the incentive to abate aerosol emission because this would further increase temperature. Although this reasoning applies to all regions, Africa is much more willing to abate aerosol emissions when ρ_j is increased than the other regions (Figure 8), possibly because a higher discount rate makes it easier for Africa to control local air quality.

This observation is relevant in evaluating climate policies. It is now widely recognized that the rate of social time preference plays an important, possibly decisive, role in policy evaluations for long-term environmental problems such as climate change. Stern (2007) chooses a small value for the rate of social time preference in consideration of inter-generational equity. Nordhaus (2008), on the other hand, chooses a relatively high value for the same parameter to ensure consistency between the model and real-world economic data. These different values have different policy implications. The discussion what the correct value of ρ is takes place mostly in the context of inter-generational equity. Our results indicate, however, that assumptions about the social time preference rate do not only affect the inter-generational, but also the intra-generational welfare distribution. A low discount rate shifts the cost of climate change from future generations to the present generation. Such a shift of burden is more demanding for warm regions in the sense that the present generation living in a warm region would be likely to have more difficulty in controlling local air pollution. In other words, while a lower rate of time preference implies inter-generationally more equitable climate policies, it implies at the same time intra-generationally less equitable burden sharing.

Finally, after discussing μ^c, μ^a, and ρ, we consider the sensitivity of χ^{ac}, the parameter representing the potential of co-benefits. The results imply that if there are more opportunities of gaining co-benefits, every region will be able to abate more carbon emission. This is as expected, because a decrease of aerosol emission accompanied by carbon abatement is just an additional marginal benefit of climate policies. Thus, once the potential co-benefits of climate policy are recognized in policy evaluations, recommendations for stronger carbon abatement would logically follow.

This conclusion might however be too optimistic. Table 3 shows that the optimal carbon abatement paths of warm regions are relatively insensitive to χ_j^{ac}. Figure 9 helps to clarify this point. The figure plots the relative deviation of μ^c when the value of χ^{ac} is raised by 50%. The air quality co-benefits

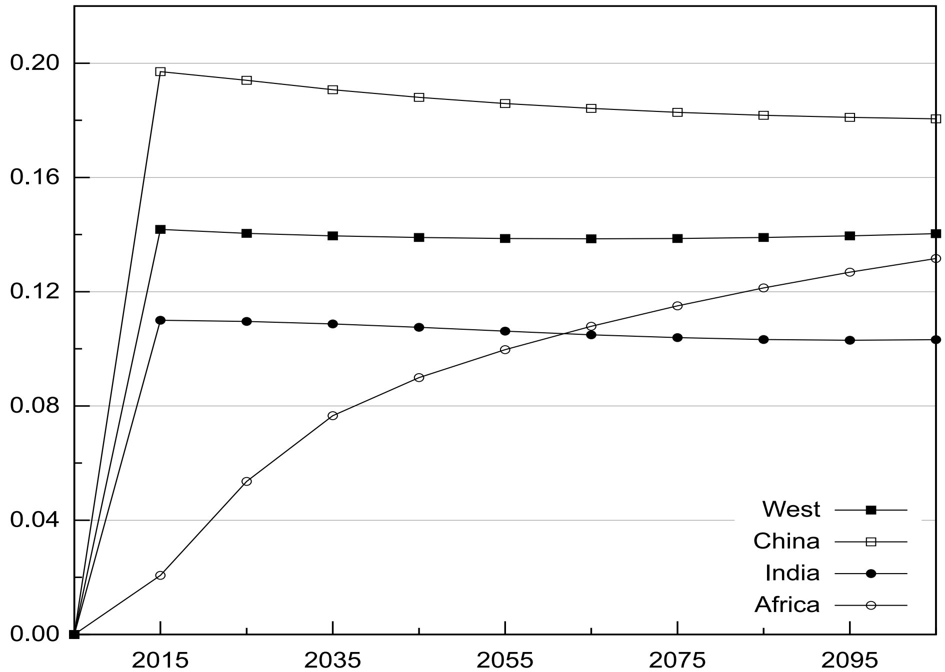

Figure 9: Relative deviation of μ^c from benchmark when χ^{ac} is increased by 50%, 2005–2105

do provide an additional incentive to abate carbon emission, but such an incentive is significantly suppressed in warm regions. This means that the logic of co-benefits may not work well for warm regions, where the potential of co-benefits is much needed to achieve low-carbon development. Two factors may be working together to generate this rather alarming result. First, the co-benefit is not completely a 'benefit' in our model. Carbon mitigation efforts can improve local air quality, but such improvements might offset the effectiveness of the climate policy through the endogenous local dimming effect. This dilemma makes all regions reluctant to enjoy the air quality co-benefits. The difference observed in the responses of cold and warm regions is explained by the second factor: warm regions are more vulnerable to temperature increase. In addition to the general productivity loss incurred from climate change, warm regions are likely to suffer from intensification and expansion of temperature-induced diseases. Hence, the secondary benefit of improved air quality is largely canceled out by the endogenous dimming effect. In fact, this effect seems so strong in Africa that the co-benefit almost completely disappears in the near term. This implies that, while the argument for the existence of co-benefits could be a good reason to promote more ambitious reduction targets for cold regions, this may not necessarily be the case for warm regions. Without appropriate consideration of local dimming, policy recommendations can possibly impose unfairly large burdens on warm regions.

6 Conclusions

While climate change is a global problem, the adverse impacts of an increase in temperature will not be equally distributed across regions. The same degree of temperature change can cause different damages in different regions, reflecting the diversity of geographical and economic situations around the world. The health impact is a prime example where different regions respond differently to climate change, thus emphasizing the importance of explicitly considering both global and local damages in the economic analysis of climate change. Another important channel through which climate change interacts with local issues is aerosols. Aerosol particulates counteract global warming by preventing sunlight to fall on the Earth, and they act primarily locally, in contrast to CO2 emissions which act primarily globally. While this local dimming effect could help each region reduce the adverse impact of climate change, the aerosols cause local air pollution and thus increase the risk of respiratory diseases.

With this background in mind, we looked at the interplay between climate, health, and the economy based on a simple integrated assessment model. We presented a stylized world with four heterogeneous regions, designed to capture the links between local and global aspects of climate change. If health and dimming are both taken into account, then the equilibrium paths provide some novel insights.

First, warm regions will continue to increase their aerosol emissions while cold regions will manage to improve the local air quality. As a result, people living in relatively warm regions will have to suffer more from asthma. The aerosol-induced health cost will constrain consumption for the coming decades, especially in Africa. Considering the fact that those warm regions are already suffering from increasing temperature, this is a serious and alarming issue.

Second, the existence of air quality co-benefits does not always support more stringent CO2 emission reduction targets. Our results illustrate that the value of air quality co-benefits is large in cold regions. In warm regions, however, the benefit from air quality improvement is largely offset by local brightening (less dimming). This provides yet another concern about the vulnerability of warm regions, Africa in particular.

Third, in the context of climate change, discounting can be an issue of intra-generational equity as well as inter-generational equity. Our sensitivity analysis indicates that the choice of social time preference rate affects the optimal abatement paths of different regions in different ways. Hence, careful attention to local implications of climate change is essential in the discussion of discounting.

Many questions remain. One may ask, for example, whether there are potential benefits of cooperation, and, if so, what they are. Our results suggest that cooperation between heterogeneous regions would better address the highly disproportional burden of climate change. Theoretically, this could be done by introducing cooperative game-theoretic concepts. Analyzing the possibility of such inter-regional cooperation should enable us to derive implications both from an environmental and from a socio-economic point of view.

Appendices

A Specification of the exogenous variables and choice of parameter values

A.1 Exogenous trends

The exogenous trends for population, total factor productivity, carbon intensity, and sulfur intensity are all specified in the same way:

$$\begin{aligned} N_{j,t+1} &= (1+g^n_{j,t})N_{j,t}, & g^n_{j,t+1} &= (1-\delta^n_j)g^n_{j,t}, \\ \psi_{j,t+1} &= (1+g^{\psi}_{j,t})\psi_{j,t}, & g^{\psi}_{j,t+1} &= (1-\delta^{\psi})g^{\psi}_{j,t}, \\ \sigma^{cc}_{j,t+1} &= (1-g^{\sigma_c}_{j,t})\sigma^{cc}_{j,t}, & g^{\sigma_c}_{j,t+1} &= (1-\delta^{\sigma_c})g^{\sigma_c}_{j,t}, \\ \sigma^{aa}_{j,t+1} &= (1-g^{\sigma_a}_{j,t})\sigma^{aa}_{j,t}, & g^{\sigma_a}_{j,t+1} &= (1-\delta^{\sigma_a})g^{\sigma_a}_{j,t}. \end{aligned}$$

The population trend is based on UNPD (2008). We directly input the projected population for the first three periods and then chose $g^n_{j,2025}$ and δ^n_j such that the model matches the future prediction thereafter. The parameters governing productivity and carbon intensity are basically the same as in Nordhaus (2008). The last of these four equations was calibrated based on IPCC (2000). In particular, we used the MESSAGE-B2 scenario to determine the trajectory of $\sigma^{aa}_{j,t}$.

The marginal abatement costs are assumed to decline over time. We follow Nordhaus (2008) and specify $\alpha^c_{j,t}$ and $\alpha^a_{j,t}$ as

$$\alpha^c_{j,t} = \frac{\sigma^{cc}_{j,t}}{\xi^c_j} m^c_j \left[\upsilon^c + (1 - g^{m^c})^t (1 - \upsilon^c)\right] \qquad (0 < \upsilon^c < 1),$$
$$\alpha^a_{j,t} = \frac{\sigma^{aa}_{j,t}}{\xi^a_j} m^a_j \left[\upsilon^a + (1 - g^{m^a})^t (1 - \upsilon^a)\right] \qquad (0 < \upsilon^a < 1).$$

The values of m^c_j and m^a_j are chosen so that the abatement costs are differentiated across regions in a way which is consistent with the descriptive characteristics listed in Table 1.

A.2 Temperature

Our temperature equation extends the corresponding equation in Nordhaus (2008). We begin with the following simplified version of temperature dynamics in Nordhaus' DICE model:

$$Z_{t+1} = Z_t + \varsigma \left(F_t - \frac{F_{\times 2}}{Z_{\times 2} - Z^*} (Z_t - Z^*) \right),$$

where F_t is the radiative forcing at period t, $F_{\times 2}$ is the estimated radiative forcing when carbon concentration is doubled relative to the year 1750, and $Z_{\times 2}$ is the equilibrium temperature when radiative forcing is on the level of $F_{\times 2}$. Nordhaus (2008) defines F_t by

$$F_t = F^c(M_t) + F^a_t,$$

where $F^c(M_t)$ and F^a_t are the radiative forcings by carbon dioxide and other related gasses, respectively. In the DICE model, the latter term is exogenously given while the former is defined as

$$F^c(M_t) = \Delta^c_{\times 2} \frac{\log(M_t / M_{1750})}{\log 2}.$$

This means that if carbon concentration is doubled (that is, $M_t = 2M_{1750}$), then the radiative forcing of carbon dioxide will be $\Delta^c_{\times 2}$.

For our purpose two modifications are required: we need regional rather than global temperature, and we need the aerosol radiative forcing to be endogenous rather than exogenous. This is achieved by changing the three equations to:

$$Z_{j,t+1} = Z_{j,t} + \varsigma \left(F_{j,t} - \frac{F_{\times 2,j}}{Z_{\times 2,j} - Z^*_j} \left(Z_{j,t} - Z^*_j\right) \right),$$

$$F_{j,t} = F^c(M_t) + F_j^a(E_{j,t}^a),$$

and

$$F^c(M_t) = \Delta_{\times 2}^c \frac{\log(M_t/M_{1750})}{\log 2},$$

and assuming that the radiative forcing from aerosol emissions is endogenously determined by

$$F_j^a(E_{j,t}^a) = \Delta_{0,j}^a + \Delta_{dir}^a \frac{E_{j,t}^a}{E_{j,1990}^a} + \Delta_{ind}^a \frac{\log(1 + E_{j,t}^a/E_{j,nat}^a)}{\log(1 + E_{j,1990}^a/E_{j,nat}^a)}.$$

The latter specification is based on Harvey *et al.* (1997). Here, Δ_{dir}^a and Δ_{ind}^a are the direct and indirect radiative forcings caused by aerosols in the atmosphere when $E_{j,t}^a = E_{j,1990}^a$, and the symbol $E_{j,nat}^a$ denotes the amount of natural aerosol emission.

Based on these equations the temperature equation boils down to Equation (15):

$$\begin{aligned} Z_{j,t+1} = {} & \tau_{0,j} + \tau_{1,j} Z_{j,t} + \tau_2 \log(M_t) \\ & + \tau_{3,j} E_{j,t}^a + \tau_{4,j} \log(1 + \tau_{5,j} E_{j,t}^a), \end{aligned}$$

where

$$\tau_{0,j} = \varsigma \left(\Delta_{0,j}^a - \Delta_{\times 2}^c \frac{\log(M_{1750})}{\log 2} + \frac{F_{\times 2}}{Z_{\times 2,j} - Z_j^*} Z_j^* \right),$$

$$\tau_{1,j} = 1 - \frac{\varsigma F_{\times 2,j}}{Z_{\times 2,j} - Z_j^*}, \qquad \tau_2 = \frac{\varsigma \Delta_{\times 2}^c}{\log 2},$$

$$\tau_{3,j} = \frac{\varsigma \Delta_{dir}^a}{E_{j,1990}^a}, \qquad \tau_{4,j} = \frac{\varsigma \Delta_{ind}^a}{\log(1 + E_{j,1990}^a/E_{j,nat}^a)}, \qquad \tau_{5,j} = \frac{1}{E_{j,nat}^a},$$

and

$$F_{\times 2,j} = \Delta_{\times 2}^c + \Delta_{0,j}^a + \Delta_{dir}^a + \Delta_{ind}^a.$$

We chose the value of $\Delta_{0,j}^a$ such that the time-path of temperature generated by (15) mimics the historical temperature data from 1960 to 2000.

A.3 Health-related parameters

A key feature of our model is the treatment of health, and in particular the two types of disease: malaria (temperature induced) and asthma (aerosol induced). We assume that there is no malaria in cold regions, because malaria-carrying mosquitoes cannot survive when the temperature is below a certain threshold. The marginal impact on malaria at temperatures above about

23°C is larger in India than in Africa, because of the fact that Africa is already highly endemic for malaria so that the effect of a further increase in temperature is limited; see the discussion in van Lieshout *et al.* (2004). In warm countries outside Africa, on the other hand, the marginal health impact may be large. This feature is incorporated into our model by assuming that the malaria functions for Africa and India are locally concave and convex, respectively.

The slope of the asthma function of West is steeper than of the other regions. In West the population is more concentrated, and this makes the region more vulnerable to air pollution. The marginal benefit of abating aerosol emission is therefore larger in West. In the other regions, the marginal health impact of air pollution is more or less the same because the values of ν_j are not much different.

Relatively large uncertainty remains in the choice of health-related parameters. The cost of treating and preventing malaria in Africa is based on Guiguemde *et al.* (1994), Chima *et al.* (2003), and Chuma *et al.* (2006). These values are scaled up for the other regions on the basis of the level of economic development. The treatment cost of asthma in West and India is in line with the studies of Ungar *et al.* (1998), Serra-Batlles *et al.* (1998), Chew *et al.* (1999), Aït-Khaled *et al.* (2000), and Cisternas *et al.* (2003). These numbers are scaled down for the poor regions. The malaria function $r_{j,t}^{(1)}$ for Africa is calibrated based on the data of Korenromp (2005). There is some arbitrariness in the choice of parameters for the malaria function in India. The asthma function is calibrated so that the function is consistent with the data provided by Masoli *et al.* (2004). Sensitivity analysis is required to see whether the uncertainty surrounding those parameters changes our results, and this analysis is provided in Section 5.

A.4 Specification of ν_j

Aerosol emissions cause air pollution, and the air pollution increases the fraction of population at risk of asthma. The impact of air pollution is not the same across different regions. Even if the amount of emission were the same, the health impact of air pollution must be different depending on how large the region is and how the population is distributed within the region. We introduce a region-specific parameter ν_j to account for this and we assume that the number of asthma patients depends on $\nu_j E_{j,t}^a$, rather than on $E_{j,t}^a$.

We obtain the value of ν_j as follows. First, divide region j into k_j grid cells or 'provinces'. The size of each province is the same not only within one region, but also across regions. Suppose there are N_j^k people living in the k-th province ($k = 1, 2, \ldots, k_j$). Then the average number of people per province in region j is given by $\overline{N}_j = N_j/k_j$, where N_j is the total population of region j. Let k_j^* denote the number of provinces within region j where $N_j^k \geq \overline{N}_j$ (UNEP/GRID, 1997). We then assume that the fraction of population at risk of asthma depends on

$$\nu_j E_{j,t}^a = \frac{E_{j,t}^a}{\text{AREA}_j}\left(\frac{k_j}{k_j^*}\right),$$

where AREA_j is the geographical size of region j. The first component, $E_{j,t}^a/\text{AREA}_j$, represents the average level of air pollution while the second component, k_j/k_j^*, captures the population distribution in the region. Notice that the latter component scales the impact of air pollution upwards when the population is concentrated in a small part of the region. For example, if the majority of the population lives in only half of the total area, then $k_j/k_j^* = 2$, and the impact is doubled.

A.5 Other variables and parameters

The emission data of carbon dioxide were taken from USEIA (2006). We used sulfur emission as a representative index of aerosols in the atmosphere. The sulfur emission data are based on Stern (2005). The GDP data of IMF (2010) were used for the initial output of each region. The regional mean temperature was calculated on the basis of Mitchell *et al.* (2004). The data of carbon concentration come from Keeling *et al.* (2001).

B Specification of the π coefficients

As mentioned in Section 3, to find the expressions of the π coefficients is somewhat tedious. These are presented below. From (17) we write

$$(dY_{j,t}) = \Gamma_{j,t}^c(d\mu_{j,t}^c) + \Gamma_{j,t}^a(d\mu_{j,t}^a) + \Gamma_{j,t}^k(dK_{j,t}) + \Gamma_{j,t}^\tau(dZ_{j,t}).$$

We present the coefficients in three groups. First, the coefficients with respect to capital:

$$\pi_{j,t}^{ck} = -\frac{\partial a_{j,t}}{\partial \mu_{j,t}^c}Y_{j,t} + \theta_{j,t}^{(2)}\frac{\partial r_{j,t}^{(2)}}{\partial E_{j,t}^a}N_{j,t}\sigma_{j,t}^{ac}Y_{j,t}$$
$$- \theta_{j,t}^{(2)}\frac{\partial r_{j,t}^{(2)}}{\partial E_{j,t}^a}N_{j,t}e_{j,t}^a\Gamma_{j,t}^c + (1-a_{j,t})\Gamma_{j,t}^c,$$

Symbol	Value	Description	Unit
ρ_j	0.344	Pure time preference rate per decade	—
ω_j	1	Natural labor-population ratio	—
ϵ_j	0.3	Capital's share of income	—
γ_j	0.00284	Damage coefficient	—
M_{2005}	809	Carbon concentration (2005)	GtC
δ^c	0.0524	Carbon depreciation rate per decade	—
ζ^c	0.47	Carbon retention rate per decade	—
ς	0.02	Parameter in temperature equation	—
$Z_{\times 2,j} - Z_j^*$	3	Temperature change when CO2 doubled	°C
$\Delta^c_{\times 2}$	3.8	CO2 radiative forcing when CO2 doubled	Wm^{-2}
Δ^a_{dir}	-0.3	Aerosol direct radiative forcing (1990)	Wm^{-2}
Δ^a_{ind}	-0.8	Aerosol indirect radiative forcing (1990)	Wm^{-2}
M_{1750}	596	Carbon concentration (1750)	GtC
$u_j^{(1)}$	0.5	Success rate of malaria prevention	—
$u_j^{(2)}$	0.2	Success rate of asthma prevention	—
υ^c	0.5	Ratio of initial to final abatement cost	—
υ^a	0.5	Ratio of initial to final abatement cost	—
g^{m^c}	0.05	Convergence rate of carbon abatement cost	—
g^{m^a}	0.05	Convergence rate of aerosol abatement cost	—
δ^k	0.651	Capital depreciation rate per decade	—

Table 4: Global parameter values

$$\begin{aligned}
\pi^{ak}_{j,t} = &-\frac{\partial a_{j,t}}{\partial \mu^a_{j,t}} Y_{j,t} + \theta^{(2)}_{j,t}\frac{\partial r^{(2)}_{j,t}}{\partial E^a_{j,t}} N_{j,t}\sigma^{aa}_{j,t} Y_{j,t} \\
&- \theta^{(2)}_{j,t}\frac{\partial r^{(2)}_{j,t}}{\partial E^a_{j,t}} N_{j,t} e^a_{j,t}\Gamma^a_{j,t} + (1-a_{j,t})\Gamma^a_{j,t},
\end{aligned}$$

$$\pi^{kk}_{j,t} = (1-\delta^k_j) - \theta^{(2)}_{j,t}\frac{\partial r^{(2)}_{j,t}}{\partial E^a_{j,t}} N_{j,t} e^a_{j,t}\Gamma^k_{j,t} + (1-a_{j,t})\Gamma^k_{j,t},$$

	$N_{j,2025}$	$g^n_{j,2025}$	δ^n_j	$K_{j,2005}$	$Z_{j,2005}$	Z^*_j
West	10.46	0.0166	0.3728	65.806	3.85	2.84
China	17.55	-0.0084	0.0406	5.730	0.22	-0.55
India	38.62	0.0756	0.3098	11.330	21.14	21.17
Africa	12.29	0.1305	0.6178	1.123	22.05	21.58

	$Y_{j,2005}$	$\psi_{j,2005}$	$g^\psi_{j,2005}$	δ^ψ_j	$E^a_{j,1990}$	$E^a_{j,nat}$
West	34.065	2.100	0.065	0.001	27.26	18.94
China	3.400	0.298	0.095	0.001	16.82	11.69
India	7.117	0.336	0.095	0.001	12.65	8.72
Africa	0.883	0.206	0.085	0.001	3.82	2.65

	$\Delta^a_{0,j}$	ν_j	m^c_j	m^a_j	ξ^c_j	ξ^a_j
West	1.4727	0.0214	3.00	3.00	2.8	2.8
China	1.8759	0.0120	2.00	2.00	2.8	2.8
India	0.1734	0.0102	2.00	2.00	2.8	2.8
Africa	0.7234	0.0128	1.00	1.00	2.8	2.8

	$\beta^{(1)}_j$	$\eta^{(1)}_j$	$\kappa^{(1)}_j$	$\beta^{(2)}_j$	$\eta^{(2)}_j$	$\kappa^{(2)}_j$
West	0.00	10	25.00	0.95	1.0	2.00
China	0.00	10	25.00	0.95	1.0	2.00
India	0.57	10	25.00	0.95	1.0	2.00
Africa	0.83	15	20.00	0.95	1.0	2.00

	$\sigma^{cc}_{j,2005}$	$g^{\sigma_c}_{j,2005}$	$\delta^{\sigma_c}_j$	$\sigma^{aa}_{j,2005}$	$g^{\sigma_a}_{j,2005}$	$\delta^{\sigma_a}_j$
West	0.104	0.0724	0.0296	0.428	0.1905	0.0644
China	0.644	0.0724	0.0296	3.479	0.1805	0.0644
India	0.227	0.0724	0.0296	2.180	0.1905	0.0644
Africa	0.343	0.0724	0.0296	4.714	0.1805	0.0644

	χ^{ca}_j	χ^{ac}_j	$q^{(1)}_j$	$p^{(1)}_j$	$q^{(2)}_j$	$p^{(2)}_j$
West	0.0	0.15	0.020	0.020	0.120	0.060
China	0.0	0.45	0.012	0.012	0.040	0.020
India	0.0	0.45	0.012	0.012	0.040	0.020
Africa	0.0	0.45	0.006	0.006	0.020	0.010

Table 5: Calibrated parameter values

and

$$\pi_{j,t}^{\tau k} = -\theta_{j,t}^{(1)} \frac{\partial r_{j,t}^{(1)}}{\partial Z_{j,t}} N_{j,t} - \theta_{j,t}^{(2)} \frac{\partial r_{j,t}^{(2)}}{\partial E_{j,t}^{a}} N_{j,t} e_{j,t}^{a} \Gamma_{j,t}^{\tau} + (1 - a_{j,t}) \Gamma_{j,t}^{\tau}.$$

Next the coefficients with respect to CO2 concentration:

$$\pi_{j,t}^{cm} = -\zeta^{c} \sigma_{j,t}^{cc} Y_{j,t} + \zeta^{c} e_{j,t}^{c} \Gamma_{j,t}^{c}, \qquad \pi_{j,t}^{am} = -\zeta^{c} \sigma_{j,t}^{ca} Y_{j,t} + \zeta^{c} e_{j,t}^{c} \Gamma_{j,t}^{a},$$

and

$$\pi_{j,t}^{km} = \zeta^{c} e_{j,t}^{c} \Gamma_{j,t}^{k}, \qquad \pi_{j,t}^{mm} = 1 - \delta^{c}, \qquad \pi_{j,t}^{\tau m} = \zeta^{c} e_{j,t}^{c} \Gamma_{j,t}^{\tau}.$$

And finally the coefficients with respect to temperature:

$$\pi_{j,t}^{c\tau} = -\frac{\partial Z_{j,t+1}}{\partial E_{j,t}^{a}} \sigma_{j,t}^{ac} Y_{j,t} + \frac{\partial Z_{j,t+1}}{\partial E_{j,t}^{a}} e_{j,t}^{a} \Gamma_{j,t}^{c},$$

$$\pi_{j,t}^{a\tau} = -\frac{\partial Z_{j,t+1}}{\partial E_{j,t}^{a}} \sigma_{j,t}^{aa} Y_{j,t} + \frac{\partial Z_{j,t+1}}{\partial E_{j,t}^{a}} e_{j,t}^{a} \Gamma_{j,t}^{a},$$

and

$$\pi_{j,t}^{k\tau} = \frac{\partial Z_{j,t+1}}{\partial E_{j,t}^{a}} e_{j,t}^{a} \Gamma_{j,t}^{k}, \qquad \pi_{j,t}^{m\tau} = \frac{\partial Z_{j,t+1}}{\partial M_{t}}, \qquad \pi_{j,t}^{\tau\tau} = \tau_{1,j} + \frac{\partial Z_{j,t+1}}{\partial E_{j,t}^{a}} e_{j,t}^{a} \Gamma_{j,t}^{\tau}.$$

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