North-South convergence and the allocation of CO_2 emissions

Humberto Llavador[*], John E. Roemer[†] and Joaquim Silvestre[‡]

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Abstract.

Mankind must cooperate to reduce GHG emissions to prevent a catastrophic rise in global temperature. How can the necessary costs of reducing GHG emissions be allocated across regions of the world, within the next few generations, and simultaneously address growth expectations and economic development? We postulate a two-region world and, based on sustainability and egalitarian criteria, calculate optimal paths in which a South, like China, and a North, like the United States, converge in welfare per capita to a path of sustained growth of 1.3% per year by 2080, while global CO_2 emissions are restricted to a conservative path that leads to the stabilization of concentrations at 450 ppm CO_2.

Growth expectations in the North and the South must be scaled back substantially, not only after 2080, but also in the transition period. Global negotiations to restrict emissions to an acceptably low level cannot succeed absent such an understanding. Feasible growth paths with low levels of emissions require heavy investments in education and knowledge. Northern and Southern growth must be restricted to 1.2% and 3.2% per year, respectively, over the next 75 years. Politicians who wish to solve the global-warming problem must prepare their polities to accept this reality.

Key Words: Economic models, sustainability, North-South convergence, climate negotiations, growth, GHG concentrations

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[*] Universitat Pompeu Fabra and Barcelona GSE.
[†] Yale University.
[‡] University of California, Davis.

1. Introduction. Two questions must be answered for a successful attack on the problem of global warming: (i) what is the time path of global emissions of greenhouse gases (GHG) that should be set as the target, in order to approximately stabilize the concentration of carbon in the atmosphere at an acceptably low level, and (ii) how should this timed budget of total emissions be allocated to the regions of the world. Both issues are contentious. In this paper, it is assumed the first question has been answered; the path of emissions is one that will approximately stabilize CO_2 atmospheric concentration at 450 ppm.[1]

This study addresses the second question.

Assume that all countries, developed and underdeveloped, must share in the effort to reduce GHG emissions, a view that is gaining generalized acceptance (see e.g. Aldy and Stavins, 2012). Indeed, the 17th Conference of the Parties (COP-17, Durban, November-December 2011) of the United Nations Framework Convention on Climate Change (UNFCCC) produced a non-binding agreement to reach a deal by 2015 that would bring all countries under the same legal regime by 2020.

For the sake of simplicity, our analysis is cast in a world with two regions, North and South, populated by representative households in each region and generation. (Population size is addressed below.) The North is postulated to have the level of economic development of the United States, and the South that of China. The reader may consider the model to be one of how the actual nations of the US and China should allocate emission rights between them, were they to be the only countries in the world, and that the total amount of emissions has already been decided upon, as required by the 450 ppm CO_2 target.

Indeed, it is probably the case that an agreement between the US and China concerning how to constrain their emissions is both necessary and sufficient for a global

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[1] The associated concentration of all greenhouse gases would be approximately 522 ppm CO_2e. Although this may not be ‘acceptably low,’ it is perhaps a lower bound of what concentrations are realizable given present political constraints. For instance, the most demanding emission-reduction scenario of the Interagency Working Group on the Social Cost of Carbon stabilizes concentrations at 550ppm CO_2e (425-484 ppm of CO_2 concentrations), “considered consistent with widespread action by countries to mitigate ghg emissions, or unexpected advances in low-carbon technology” (Johnson and Hope, 2012).

agreement. It is obviously necessary, since these are the two largest emitters of greenhouse gases. It may well be sufficient, since if these two giants can agree, the rest of the world will fall into line (see Wagner, 2011). In the concluding section, the generalization to a multi-region world is described.

Our analysis is normative. We adopt the two constraints:

(1) the usual resource and technology restrictions;

(2) the condition that the world emissions path stabilizes atmospheric CO_2 concentration at 450 ppm,

and look for paths of region-by-region emissions and of all economic variables that satisfy the following desiderata:

(A) Sustainability,

(B) Egalitarianism,

(C) Convergence,

(D) Efficiency.

We adopt particular formulations of these desiderata. For **(A)**, we focus on the sustainable growth of human welfare, and we explore the maximal sustainable growth rate, see Section 3 below. Egalitarianism, **(B)**, motivates, on the one hand **(C)**, the long run equality of welfare in North and South, and, on the other, a maximin-based approach to the welfare of the South during transition to the steady state. Of course, the intergenerational, inter-regional maximin criterion would require the maximization of the utility of the worst-off generation, which is Generation 1 in South. We choose to maximize, instead, the utility of Generation 2 in South because we find by experimentation that doing so yields a smoother convergent path, with relatively little sacrifice to the utility of Generation 1.[2] As for **(C)**, we require North and South's welfare per capita to converge in three generations. Some readers may feel that, say, four instead of three would be a better target: we offer some support for our choice in Section 2 below.

Granted, some of these particular choices may well be challenged, but more

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[2] Maximizing Generation 1's utility for a sustainable 1.2% annual growth rate implies a 6% increase in the utility of Generation 1 and a fall of 59% in the utility of Generation 2. Section S.6.6. in the Appendix presents the transition path for maximizing Generation 1's utility while growing at a sustainable 1.2% annual rate.

generally we provide a method to address the *critical issue of identifying the existence of feasible paths that satisfy the above mentioned desiderata*. In particular, our method helps discover how much growth is consistent with a successful resolution of the climate-change problem in line with egalitarian principles.

Normative paths are usually interpreted as what a benevolent social planner would advocate. But they can also be construed as the result of complete bargaining. Thus, desideratum **(D)** can be justified by the exhaustion of all possible mutually beneficial arrangements. Section 2 justifies our formulation of desideratum **(C)**.

2. Convergence and negotiation. As just mentioned, egalitarianism would be inconsistent with an everlasting welfare gap between North and South. Our particular choice of convergence in three generations can be motivated as follows.

Suppose than North and South engage in comprehensive bargaining on the allocation of GHG emissions and on international economic cooperation. A starting point is provided by the projected ‘business as usual’ (BAU) growth factors: BAU growth factors here denote those growth factors conforming with commonly held expectations, often enunciated as growth policy targets by governments. Such targets may well be unrealistic, but if held, they imply expectations of convergence at a certain date of standards of living across nations.

Maintaining the ‘business-as-usual’ estimated date of convergence implements a kind of neutrality that is a natural focal point. Perhaps more importantly, it is a concept that may be explicable to the electorate.

Suppose that current GDP per capita in the US (China) is y^{US} (y^{Ch}), and suppose that annual growth rates of GDP per capita were to average g^{US} and g^{Ch} over the next 75 years or so, under BAU assumptions. Then convergence would occur in the number of years T which solves:

$$\frac{\left(1+g^{Ch}\right)^{T} y^{Ch}}{\left(1+g^{US}\right)^{T} y^{US}} = 1 . \qquad [1]$$

Taking $y^{US} = \$43{,}228$ and $y^{Ch} = \$4{,}611$ (2006 figures, constant 2005 international dollars PPP) and $\left(g^{US}, g^{Ch}\right) = \left(0.02, 0.05\right)$, equation [1] solves to $T^* \approx 77$ years.[3] Now suppose a proposal were on the table for how China and the US were to share the global emissions budget that entailed convergence in 100 years. The Chinese, we claim, would not accept this proposal: their negotiators would say it was unacceptable to delay the date of convergence by 25 years because of the climate-change problem. Similarly, we claim, the US negotiators would veto a proposal that entailed convergence in 50 years. These vetoes may well be comprehensible to both sides because of audience costs – the necessity to convince their respective polities.[4] A reasonable solution to the bargaining problem will entail reductions of the BAU growth rates that preserve the estimated convergence date. Thus, we view this invariance condition not as something that sophisticated negotiators believe is necessary, but as a selling point to their polities, to garner their support.

3. Sustainability. Our guiding ethic is the sustainability of human welfare over time.[5] Consider, first, a simpler world, with only one region, inhabited by one representative household at each period (generation), indexed by $t = 1, 2, \ldots$. Consider two interpretations of sustainability as proposed in Llavador, Roemer, and Silvestre (2011) and Roemer (2011). The first, *pure sustainability,* finds the highest level of welfare that can be sustained for all generations. Denote by u_t the utility (welfare) of the household in period t. Let U be the set of utility paths $u = (u_1, u_2, \ldots)$ which can be achieved, given current endowments and technology, and constraining economic activity to stay on the path of carbon emissions which will converge to a CO_2 concentration of 450 ppm. Pure sustainability directs us to solve this program:

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[3] Per capita income data from World Development Indicators (World Bank, 2013); growth rates roughly coincide with the Asian Development Bank forecasts for the next 20 years.

[4] We thank Robert Keohane for this point.

[5] In other contexts, sustainability applies to maintaining some index of natural resources.

$$\begin{aligned} &\max \Lambda \\ &\text{s.t.} \quad u \in U \\ &\qquad u_t \geq \Lambda, \quad t \geq 1. \end{aligned} \qquad [2]$$

The ethical justification of [2] is that the period at which a person is born is morally arbitrary, and so each generation is *entitled* to as much welfare as each other generation.

Nevertheless, humans may value the possibility of rendering future generations better off than themselves, and may decide not to enforce this entitlement. Let $\rho > 0$ be a rate of welfare growth. Then *sustaining growth* directs us to solve this program:

$$\begin{aligned} &\max \Lambda \\ &\text{s.t.} \quad u \in U \\ &\qquad u_t \geq (1+\rho)^{t-1} \Lambda, \quad t \geq 1. \end{aligned} \qquad [3]$$

for some perhaps small value of ρ. Here, we will implement a version of [3] adapted to the two-region world. The *sustainabilitarian* approach to climate change contrasts with the *discounted utilitarian* approach of Nordhaus (2008) and Stern (2007), as discussed in Llavador, Roemer, and Silvestre (2011) and Roemer (2011).

The application of the sustainabilitarian approach to a world with two regions is based upon a turnpike theorem that is proved in Llavador, Roemer and Silvestre (2010). In the fleshed-out economic model of which program [3] is an abstract version, there is an economy that begins with a vector of endowments of capital, knowledge, and labor. A path of emissions is given that converges to the desired atmospheric concentration: not exceeding the emissions on this path yields one set of constraints defining the set U. Emissions are generated by the production of commodities used for consumption and investment. By the turnpike theorem, if emissions are constant at e^* per capita and population is constant, such as to maintain a constant level S^{m*} of atmospheric carbon concentration, and if ρ is sufficiently small, then there exists a ray $\Gamma(\rho, e^*, S^{m*}) \subset \Re^3_+$ such that, should the initial endowment vector lie upon the ray, then the solution to [3] exists and exhibits the property that all economic variables (investment, capital stock, consumption, education, labor expended in three sectors, etc.) grow at a fixed rate slightly larger than ρ forever.[6] The turnpike theorem further asserts that if the initial endowment vector does not lie upon this ray, then the optimal solution to the program converges to the ray, and hence eventually enjoys (approximately) balanced growth.[7]

Accordingly, we model the problem of North-South emissions-sharing as one where the Northern and Southern representative households begin with different endowments, and we study the paths of resource use under which both representative agents converge to the same point on the ray $\Gamma\left(\rho, e^*, S^{m^*}\right)$ in 75 years: the assumption is that both economies then enjoy balanced growth at rate ρ from that date on.

There are, however, many paths upon which North and South will converge to the same point on the ray $\Gamma\left(\rho, e^*, S^{m^*}\right)$ (for some fixed, small growth rate ρ) in 75 years. Among these we choose an optimal path. We describe in Section 4 exactly what we optimize.

A central result of the analysis is that feasible growth paths exist satisfying the conditions of Section 2 if and only if Northern growth is limited to approximately 1.2% per year over the next 75 years instead of the more conventional expectation of 2%. Correspondingly, the growth rate of South would be reduced from our projected average of 5% to 3.2%. Thus growth expectations in North and South must be scaled back substantially for global greenhouse-gas-emissions negotiations to succeed. Politicians who wish to solve the global-warming problem must prepare their polities to accept this reality.

4. The model and global emissions. We adapt the model for a single US household constructed in Llavador, Roemer and Silvestre (2011) to the two-region world of this study. We describe it verbally in the text; all precise specifications of optimization problems, parameter values, and description of estimation procedures are found in the Appendix. The economy possesses three production sectors: commodity production,

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[6] Since utility must grow at rate ρ, and one of the arguments of the utility function is essentially fixed (biospheric quality), the other arguments must grow at a slightly higher rate than ρ.

[7] The turnpike theorem for the zero growth case (program [2]) is proved in Llavador, Roemer, and Silvestre (2010).

education of the next generation, and knowledge production (R&D, the arts, science, etc.). The commodity is produced from inputs of knowledge, educated labor, capital, emissions, and biospheric quality, combined in a Cobb-Douglas technology exhibiting constant returns to scale in labor, knowledge, and capital. Treating emissions as an input into commodity production is a formalization of the idea that the larger the emissions of a firm, the more output the firm can produce, holding other inputs constant. Emissions, of course, impact biospheric quality.

Education uses a linear, labor-intensive technology: the skill embodied in the young generation is proportional to the time the older generation allots to teaching, and to the older generation's own skill (i. e., education) level.

Knowledge is produced also using labor as the only input: knowledge in North in period $t+1$ equals knowledge in North in period *t*, depreciated by a certain factor, plus a term proportional to the labor employed in the knowledge sector. As long as North has more knowledge than South, there is a process of diffusion from North to South (see Eaton and Kortum, 1999, and Keller, 2004). The law of motion of knowledge in South is modeled as follows: in period $t+1$, Southern knowledge equals depreciated Southern knowledge from period t, plus new knowledge produced by knowledge workers in South, plus knowledge which diffuses from North, which is proportional to the knowledge gap between North and South and to the level of employment of knowledge workers in South.

Consequently, labor in each period is partitioned into four uses in each region: its employment in the three sectors, plus leisure. Capital in period $t+1$ equals depreciated capital from period t plus investment. The output of the commodity sector is partitioned into consumption and investment. Note that the only sector that emits CO_2 is commodity production. Thus, beginning with endowments of trained labor, capital, knowledge and biospheric quality inherited from period *t*, there will be, as a result of production in period $t+1$, new endowments of trained labor, capital, knowledge, and biospheric quality to pass on to Generation $t+2$. The endowment vector at each date lies in $\Re_+^4$.

Human welfare, or utility, is a Cobb-Douglas function of four arguments: commodity consumption, educated leisure, the stock of human knowledge, and biospheric quality.[8] Putting *educated* leisure rather than raw leisure time in the utility function models the view that education increases the possible uses of leisure time, and therefore, ceteris paribus, increases utility. Making the stock of human knowledge an argument models the idea that people are curious, take pleasure from the arts, and have a quest to understand the world and universe they inhabit. Knowledge is a public good –it is not associated with an individual's level of education. (We value our collective possession of knowledge, even if we cannot access all of it personally.) Biospheric quality is measured as the non-carbon-polluted biosphere. It is salient that biospheric quality, knowledge, and education enter both the commodity production function and the utility function.

Modeling utility as a function of these four arguments is unusual in climate-change economics, whose practitioners frequently take utility to be a function of consumption only (Nordhaus, 2008, and Stern, 2007). We believe this practice is too narrow in not appreciating the *direct* value to humans of education, knowledge and biospheric quality (see Llavador, Roemer and Silvestre, 2013). These arguments are *not solely* important because of their usefulness in commodity production.[9]

Date 0 is taken as 2005, and a generation is understood to live for 25 years. The initial values of global CO_2 emissions (e_0^W) and concentration (S_0^m) are $\left(e_0^W, S_0^m\right) = \left(7.07\text{GtC}, 379\text{ppm}\right)$.[10] The path of annual global emissions adopted here, and the associated atmospheric concentrations of CO_2, are:

$\left(e_1^W, S_1^m\right) = \left(7.56\text{GtC}, 422\text{ppm}\right)$ for Generation 1,

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[8] Precisely: utility in period t is $c_t^{\alpha_c}\left(x_t^l\right)^{\alpha_l}\left(S_t^n\right)^{\alpha_n}\left(\hat{S}^m - S_t^m\right)^{\alpha_m}$, where $\left(c_t, x_t^l, S_t^n, \hat{S}^m - S_t^m\right)$ are consumption, leisure in units of skill, the stock of knowledge, and the clean biosphere, respectively, in period t. The four α_j exponents are positive and sum to one.

[9] Llavador, Roemer and Silvestre (2013) performs the exercise of identifying utility with consumption only, instead of the four-argument utility function, in a one-region world. The feasibility of sustaining annual growth rates around 1% is robust to this modification but, of course, the paths for the economic variables are quite different.

[10] World Resources Institute (2010). As is well known, a ton of carbon corresponds to 3.67 tons of CO_2.

$\left(e_2^W, S_2^m\right) = \left(5.61\text{GtC}, 443\text{ppm}\right)$ for Generation 2, and

$\left(e_t^{W*}, S_t^{m*}\right) = \left(3.50\text{GtC}, 450\text{ppm}\right)$ for Generation t, $t \geq 3$.

The path is based on the MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change, http://www.cgd.ucar.edu/wigley-magicc) for the Emission Scenario WRE 450 and with the default ("best estimate") set of parameters. See Section S.3.2.5 in the Appendix.

Note that this path allows for a moderate increase of emissions by the first generation, followed by substantial reductions by the second generation and beyond. Some advocate more restrictive paths for the later periods. On the other hand, some others (Nordhaus, 2008) advocate the onset of the reductions much later. The feasibility of early, substantial reductions is supported by UNEP (2011, page 7):

> "There is abundant evidence that emission reductions of between 14 to 20Gt of CO_2 equivalent are possible by 2020 and without any significant technical or financial breakthroughs needed."

The projected populations of the global North and South in 2030 and 2055 are taken from United Nations (2008). Population is assumed to be unchanging after 2055.

The parameters in the three production functions and the utility function are calibrated using US historical data. These *functions* are taken to be identical in the two regions. What differ between the regions are the initial endowments in 2005, estimated from standard sources.

The optimization program is specified as follows. Given the initial (2005) endowment vectors in both regions, the production functions, the utility function, the laws of motion of capital, knowledge, and biospheric quality, and the global emissions path which converges to a CO_2 concentration of 450 ppm, the feasible paths of all economic variables for North and South can be specified.

As mentioned earlier, knowledge diffuses automatically from North to South. In addition, the sum of consumption and investment in either region is not constrained by production in that region; rather, global consumption plus global investment must equal global commodity production. If consumption plus investment in North, for example, were to exceed commodity production in North, then commodities are exported from South to North. Thus, endogenous to the program's solution will be values of inter-regional output flows at each date. In actuality, there are currently net commodity exports from China to the United States, which are balanced by Chinese claims on US assets. However, the model here recognizes only real (as opposed to financial) variables, and so the change in property rights corresponding to the Chinese possession of US treasury bills in exchange for commodities exported from China to the US is not made explicit.

The optimization program we solve adopts a long-term growth rate ρ of utility and chooses the feasible path which maximizes the utility of Generation 2 of South, subject to the constraint that both regions' utilities grow at a rate of at least ρ in the first two generations, and that per capita endowments of both regions be identical and lie on the ρ-balanced-growth ray $\Gamma\left(\rho, e^*, S^{m^*}\right)$ at the end of period 2. It will follow that from period 3 on (i. e., from 2080), utilities will be equal in the two regions, and each region will grow at the rate ρ henceforth.

5. Results. The optimal path is computed using the 'NMaximize' routine in *Mathematica* 8. Recall that among the variables which are endogenous to the solution of the program are the allocations of global emissions to the two regions in each period. After convergence occurs, in Generation 3, emissions *per capita* in the two regions will be equal forever. In addition, investments in knowledge are endogenous, and it is the level of knowledge that determines technological improvements in commodity production. That is to say, both the allocation of emissions to the two regions and technological change are *endogenous* in the program.

Main result. *It is possible to sustain a rate of utility growth of* 1.2% *per year*, *starting from the* $t = 0$ (*year* 2005) *reference level*, *with North and South converging in* 75 *years* ($t = 3$), *while keeping global* CO_2 *emissions at the levels given in Section* 4 *above. At convergence, North and South reach a common steady state where all economic variables grow at a constant rate. In particular, the stock of knowledge, investment in knowledge and emissions are equalized in per capita terms across regions at the steady* *state. During the transition, Northern utility grows at* 1.2% *per year and after convergence, both regions grow at that rate forever.*[11]

However, there are no feasible solutions to the program at which both North and South grow at sustainable rates equal to or higher than 1.4% *per year.*

Table 1 below lists the utility values, also illustrated in Figure 1. The data for $t = 0$ are for the 2005 reference level, $t = 1,2$ are the transition generations, and the steady state is reached at $t = 3$ and continues forever at the constant growth rate.

[Table 1 and Figure 1 here]

To establish the last sentence in the above-stated result, we have run a program that maximizes the growth rate subject to the previous constraints on convergence and sustainability. The highest growth rate than can be sustained for all generations in all regions is 1.337% per year.[12] Higher steady-state growth rates could in principle be reached if we allowed for lower growth rates in North during the transition. Our computations lead to the conclusion that *reaching a convergent steady state with growth rates distinctly higher than* 1.3% *per year is not possible unless a transition generation in North or South grows at less than the target rate.*

As noted, the time paths that we propose have two distinct stages: the *transition* ($t = 1, 2$) and the *steady state* ($t \geq 3$). *The steady state requires North and South to have the same emissions-to-output ratio and the same emissions per capita, whereas initially* ($t = 0$*, year* 2005), *North has a lower emissions-to-output ratio, and higher emissions per capita than South.*

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[11] Not surprisingly, in order to catch up with North, South's consumption of output has to grow quite fast during the transition, see Section S.4 in the Appendix.

[12] The transition path for an annual 1.337% sustainable growth rate entails huge exports of the commodity from South to North: on the order of 166% of domestic output in North or 21% of domestic output in South for Generation 2 (see section S.6.7 in the Appendix). We believe these output flows are not politically feasible (asset transfers from North to South to balance these commodity exports would be rejected by Northern polities) and opt for reporting a path for a lower 1.2% per annum.

[Table 2 and Figure 2 here]

The optimal values for the allocation of emissions are presented in Table 2 and Figure 2. Recall that the postulated path of global emissions decreases to a low value in the steady state, and, accordingly, both emissions per capita and the emissions-to-output ratio ("GHG intensity," in IPCC parlance) must eventually decrease. The initial values show that emissions per capita in North are five times as large as those in South, whereas the emissions-to-output ratio in South doubles that of North. All per capita values are equalized in the steady state, including emissions per capita and emissions-to-output ratios. Of course, these steady-state values are substantially lower than the initial values, because we require world steady-state total emissions to halve the initial values.

[Table 3 here]

The steady-state values display the following properties (see Table 3).

* *Both North and South devote to investment in physical capital* 6.7% *of their labor-leisure resource, a figure* 29% *higher than the reference value of* 5.2% *in North, but substantially lower than the reference* 15.1% *in South*.

* *Both North and South substantially increase the creation of knowledge, and moreover South invests heavily in education. More specifically, in North (resp., South), the fraction of the labor-leisure resource devoted to knowledge in the steady state is more than twice (resp., close to five times) that of the reference year. And in the steady state South devotes to education a fraction of the labor-leisure resource* 65% *higher than the reference level.*

* *The fractions of the labor-leisure resource devoted to leisure in either region, and that of consumption in North, do not substantially differ from the reference values. But South must devote to consumption a fraction of its labor-leisure resource* 25% *higher than the reference value.*

The optimal path entails output exports from South to North at $t=1$ on the order of 9.2% of domestic output in North or 5.7% of domestic output in South, and, at $t=2$, of about 7.9% of domestic output in South and 73.3% of domestic output in North, i. e., the amount imported by North is close to North's own domestic output. As noted earlier, implementing these output flows would be accomplished with a transfer of property rights on regional assets, which do not appear in the model.[13]

Because interregional output flows are allowed, emissions are allocated efficiently between the regions, which implies that the marginal product of emissions, and hence the emissions-to-output ratios, must be equalized across the two regions not only in the steady state but also during the transition (see Table 2).[14] This requires a relatively small allocation of emissions to North at $t = 2$. The sacrifice by North is counterbalanced by South-to-North exports in order to satisfy the constraint that North's utility grow at an annual rate of at least 1.2% starting from the reference level. The point is that, because output flows are allowed, the problem becomes a completely cooperative one: who produces what goods and how emissions are allocated is decided entirely by optimization, with emissions and the production of output efficiently allocated, thus implementing Desideratum **D** of Section 1.

The marginal product of emissions in terms of output implies a shadow price of carbon. For Generation 1, the marginal product of emissions in output is \$2,412 per metric ton of carbon or \$641 per metric ton of CO_2. This is substantially higher than other policy proposals for the US (see e. g., Table 5-4 in Nordhaus, 2008).

Not surprisingly, for South to catch up to North, its consumption must rapidly increase in the first three generations. Table 3 presents the optimal allocation of labor into its four uses in South and North, at each generation. (Notation: $x^{eJ}, x^{nJ}, x^{cJ}, x^{lJ}$ denote the efficiency units of labor allocated to the education, knowledge, commodity, and leisure sectors in region J at period t, and $x_t^J = x^{eJ} + x^{nJ} + x^{cJ} + x^{lJ}$. Thus, for example, $\frac{x_t^{cJ}}{x_t^J} \cdot \frac{i_t^J}{\text{output}}$ is the fraction of labor in the commodity sector devoted to producing investment goods (i_t^J).)

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[13] Section S.6.5 in the Appendix displays the optimal paths under the additional constraint of zero interregional commodity flows. The exercise shows the robustness of main results with respect to the inclusion of this constraint.

[14] The marginal product of emissions is the rate at which output increases instantaneously as emissions are increased, holding other inputs constant. For the Cobb-Douglas production function, this rate is proportional to the output-emissions ratio.

Note from Table 3 that the fraction of Southern labor devoted to investment falls sharply from the 2005 level (from 15% to below 7% in the steady state), and labor devoted to producing consumption goods rises correspondingly. This is consistent with the observation, often made, that China is investing too much and consuming too little. The labor devoted to investment in North, however, increases about 29% in the steady state compared to 2005. Most dramatically, South increases by about 65% its labor devoted to education, and its labor devoted to the production of knowledge increases almost five fold. The fraction of labor devoted to knowledge production in North more than doubles.

6. Conclusion. The present analysis justifies the following policy recommendations.

R1. There is no politically feasible solution to the climate-change problem unless both North and South honestly recognize the connection between restricting emissions and curbing growth, and the necessity of doing both in a fair manner. International negotiators should acknowledge the intimate relationship between emissions control and economic growth, and simultaneously address both issues in bargaining venues.

R2. Accordingly, Northern politicians should prepare their citizens for the necessity of curbing growth to 1.2% per year. Similarly, Southern politicians should prepare their citizenries to accept growth rates substantially lower than are currently expressed as targets. This recommendation is in line with those recently put forth by several other authors (Skidelsky and Skidelsky, 2012, Gordon, 2012, Rogoff, 2012), who call for limiting growth, although they have arrived at the conclusion via different considerations.

R3. Both North and South should heavily invest in education and knowledge beyond the current levels, both in the transition and in the more distant future.

R4. The price of carbon should be substantially higher than what has been observed in recent permit markets.

These recommendations follow from optimizing a program, concerned with inter-generational and inter-regional equity, with a number of special features. These are:

F1. The motivation of the optimization program by the concept of sustaining growth of human welfare, rather than maximizing a sum of discounted utilities over generations (as in Stern, 2007, and Nordhaus, 2008).

F2. The specification of a global emissions path that implies convergence of CO_2 concentration to 450 ppm in 75 years. We emphasize that the regional allocation of emissions is given as part of the optimal solution, rather than being decided *a priori* through the distribution of permits to emit to countries, based on historical considerations. That is to say, we close the model by appending the constraint of convergence in three generations, and derive regional emissions as a corollary.

F3. The inclusion of education and knowledge in the utility function, as well as in the production function. Not only is this psychologically realistic, but it enables conservation on emissions by shifting to some degree resources from commodity consumption to education and knowledge.

F4. The important role of preserving the convergence date of North and South in reaching a negotiated agreement. This embodies a concept of fairness quite different from the ones where the allocation of emissions is separated from growth considerations (see Aldy and Stavins, 2012, Rose et al., 1998, Vaillancourt et al., 2008, and Page, 2006, 2011).

F5. The endogeneity of technical progress, as determined by the investment in knowledge. This contrasts, for example, with Nordhaus (2008), in which exogenous, costless technical progress is postulated.

Although this paper models a two-region world, its logic clearly extends to one with more major players. Even if very poor countries should be excused from reducing GHG emissions, all countries with sufficiently high levels of economic development could be parties to international negotiations guided by the principle of maintaining relative growth factors among them.

Any analysis attempting to capture the complex problem of climate change must ignore some features of reality. The present model does not consider uncertainty or natural-resource constraints other than GHG emissions, which are no doubt important as argued by Arrow et al. (2004), Barnosky et al. (2012), and Vitousek et al. (1997). The choice of a Cobb-Douglas production function, even though commonly used, implies a degree of substitutability between environmental and economic variables which can be challenged.

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Tables and Figures

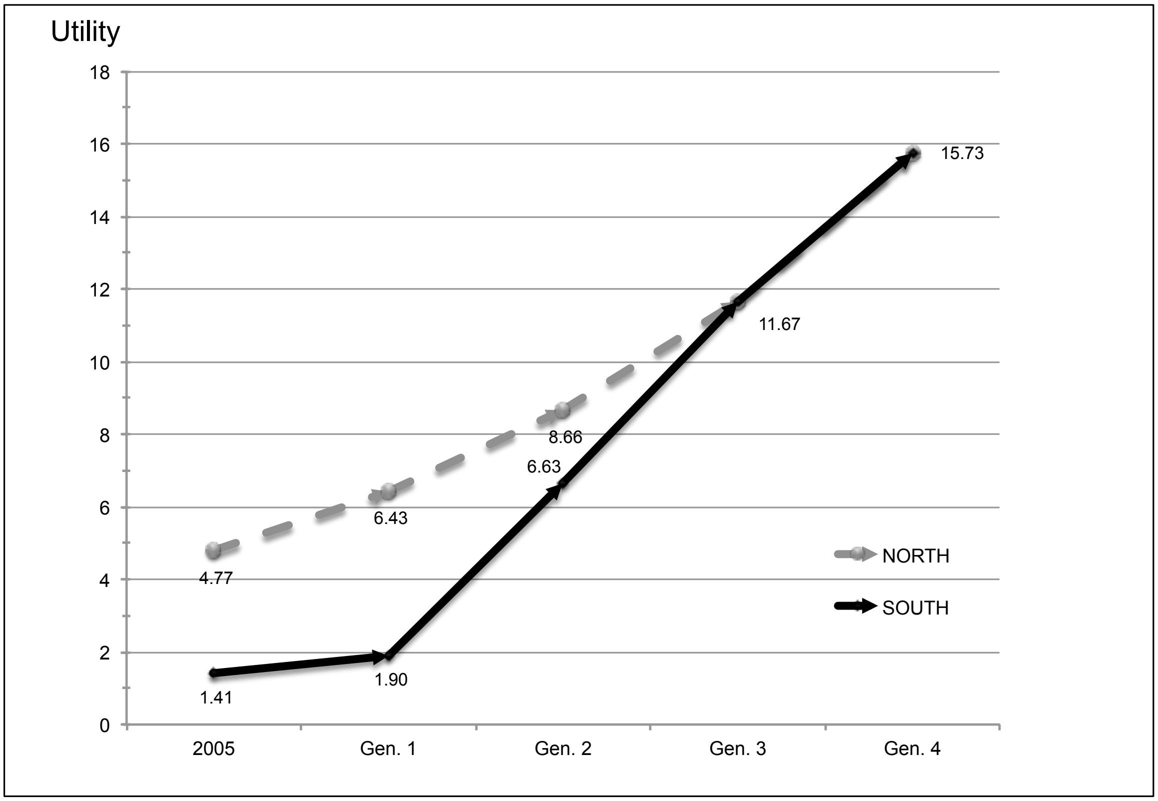


Figure 1. Utility paths for a guaranteed growth rate of 1.2% per year.

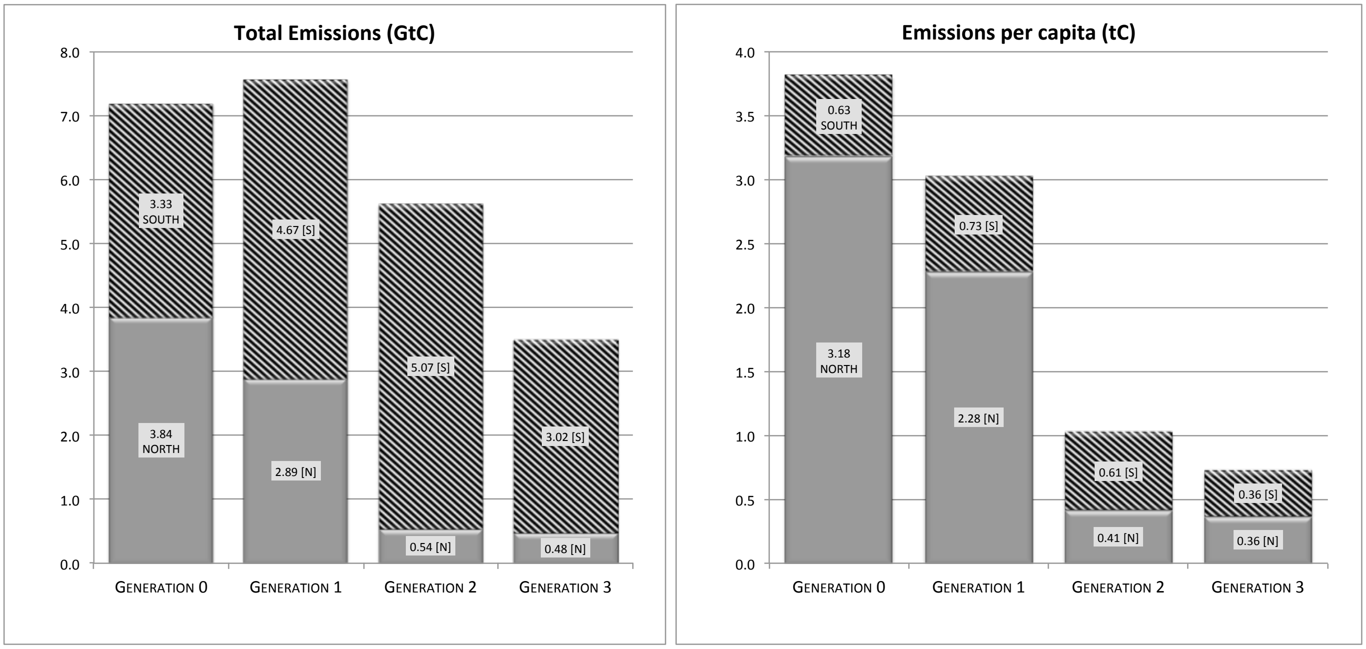
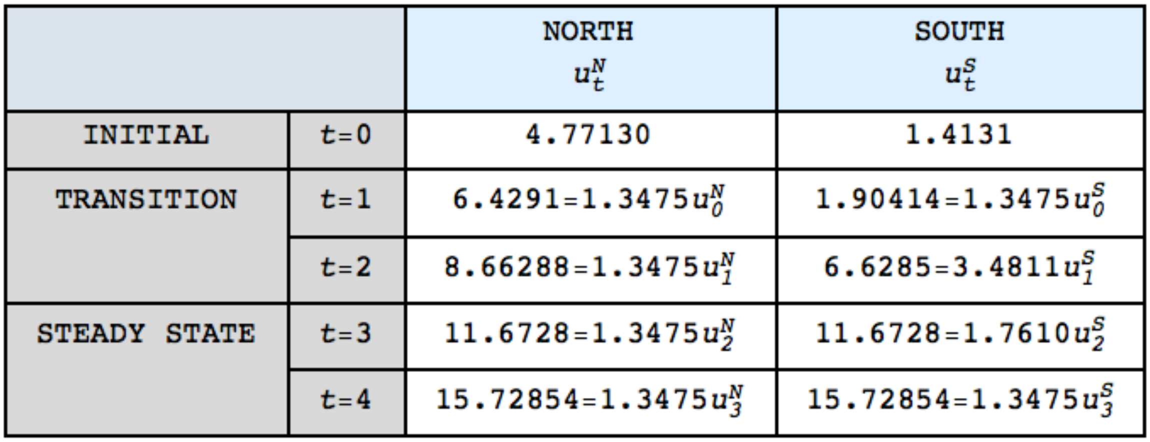
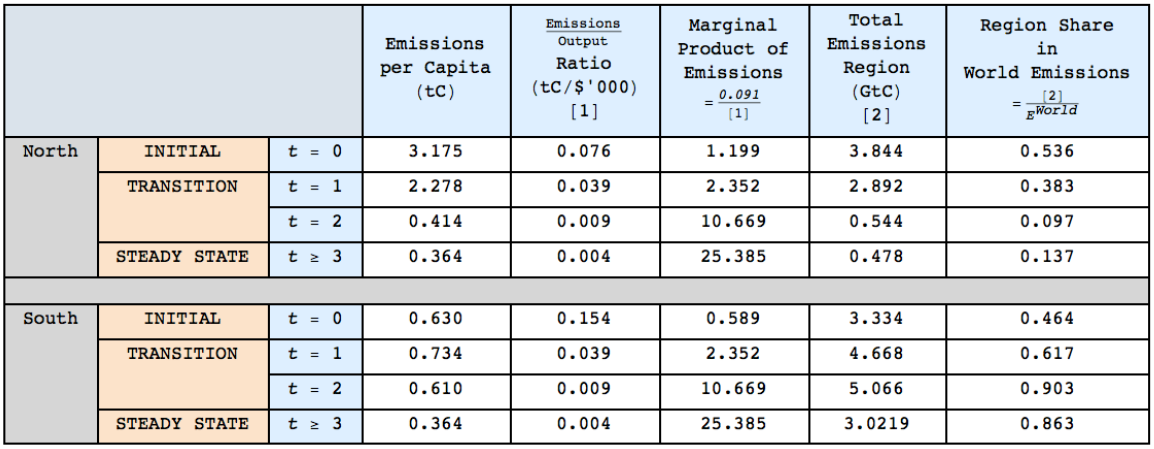


Figure 2. Total and per capita annual CO_2 emissions (North and South).



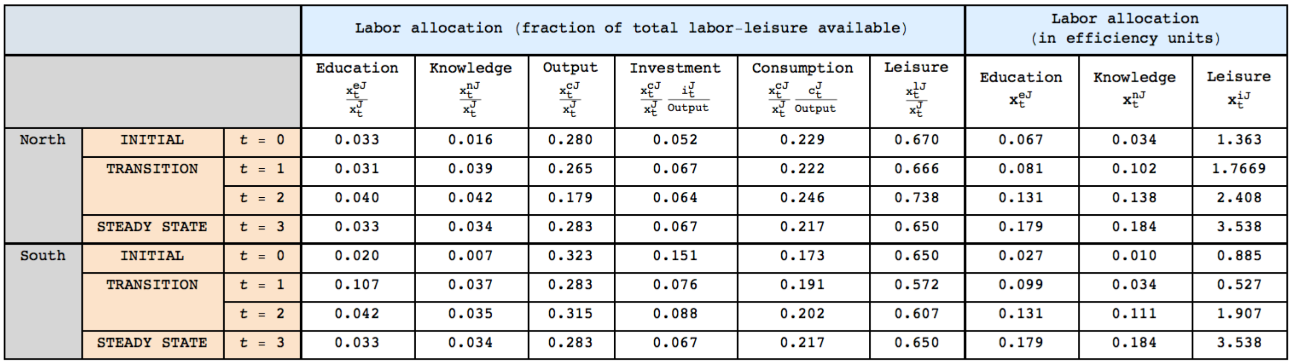
		NORTH u_t^N	SOUTH u_t^S
INITIAL	t=0	4.77130	1.4131
TRANSITION	t=1	$6.4291=1.3475u_0^N$	$1.90414=1.3475u_0^S$
	t=2	$8.66288=1.3475u_1^N$	$6.6285=3.4811u_1^S$
STEADY STATE	t=3	$11.6728=1.3475u_2^N$	$11.6728=1.7610u_2^S$
	t=4	$15.72854=1.3475u_3^N$	$15.72854=1.3475u_3^S$

Table 1. Utility paths for guaranteed per year growth rates of 1.2% (34.75% per generation).



			Emissions per Capita (tC)	$\frac{\text{Emissions}}{\text{Output}}$ Ratio (tC/$'000) [1]	Marginal Product of Emissions $=\frac{0.091}{[1]}$	Total Emissions Region (GtC) [2]	Region Share in World Emissions $=\frac{[2]}{E^{World}}$
North	INITIAL	t = 0	3.175	0.076	1.199	3.844	0.536
	TRANSITION	t = 1	2.278	0.039	2.352	2.892	0.383
		t = 2	0.414	0.009	10.669	0.544	0.097
	STEADY STATE	t ≥ 3	0.364	0.004	25.385	0.478	0.137
South	INITIAL	t = 0	0.630	0.154	0.589	3.334	0.464
	TRANSITION	t = 1	0.734	0.039	2.352	4.668	0.617
		t = 2	0.610	0.009	10.669	5.066	0.903
	STEADY STATE	t ≥ 3	0.364	0.004	25.385	3.0219	0.863

Table 2. The allocation of CO_2 emissions. The last column is obtained by dividing Total Emissions Region [2] by world emissions (Total Emissions North plus South).



			Labor allocation (fraction of total labor-leisure available)						Labor allocation (in efficiency units)		
			Education $\frac{x_t^{eJ}}{x_t^J}$	Knowledge $\frac{x_t^{nJ}}{x_t^J}$	Output $\frac{x_t^{cJ}}{x_t^J}$	Investment $\frac{x_t^{cJ}}{x_t^J}\frac{i_t^J}{\text{Output}}$	Consumption $\frac{x_t^{cJ}}{x_t^J}\frac{c_t^J}{\text{Output}}$	Leisure $\frac{x_t^{lJ}}{x_t^J}$	Education x_t^{eJ}	Knowledge x_t^{nJ}	Leisure x_t^{iJ}
North	INITIAL	t = 0	0.033	0.016	0.280	0.052	0.229	0.670	0.067	0.034	1.363
	TRANSITION	t = 1	0.031	0.039	0.265	0.067	0.222	0.666	0.081	0.102	1.7669
		t = 2	0.040	0.042	0.179	0.064	0.246	0.738	0.131	0.138	2.408
	STEADY STATE	t = 3	0.033	0.034	0.283	0.067	0.217	0.650	0.179	0.184	3.538
South	INITIAL	t = 0	0.020	0.007	0.323	0.151	0.173	0.650	0.027	0.010	0.885
	TRANSITION	t = 1	0.107	0.037	0.283	0.076	0.191	0.572	0.099	0.034	0.527
		t = 2	0.042	0.035	0.315	0.088	0.202	0.607	0.131	0.111	1.907
	STEADY STATE	t = 3	0.033	0.034	0.283	0.067	0.217	0.650	0.179	0.184	3.538

Table 3. The allocation of labor-leisure resources.
(Note: Output = Consumption + Investment + Net Exports)

APPENDIX TO “NORTH-SOUTH CONVERGENCE AND THE ALLOCATION OF CO_2 EMISSIONS”

Humberto Llavador, John E. Roemer and Joaquim Silvestre

APRIL 20, 2013

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S.7. Transition Path for the Maximum Sustainable Growth Rate.

S.1 The Model

We consider a world comprising two regions, namely North (N) and South (S). Generations are indexed by $t \geq 1$, and understood to live for 25 years. The population of Generation t in Region $J = N, S$, denoted by N_t^J, is exogenously given in accordance with United Nations projections. (See Table s.6 in Section S.3.2.4 below.) A zero subscript indicates year-2005 reference values.

S.1.1 Utility

The utility functions in North and South are identical and have consumption, educated leisure, the stock of human knowledge, and the quality of the biosphere as their arguments. The first two arguments are private goods, and the last two are public goods. We postulate a representative household in Generation t ($t \geq 1$) and region J ($J = N, S$) with utility function

$$\left(c_t^J\right)^{\alpha_c}\left(x_t^{lJ}\right)^{\alpha_l}\left(S_t^{nJ}\right)^{\alpha_n}\left(\hat{S}^m - S_t^m\right)^{\alpha_m}, \tag{s.4}$$

where the exponents are positive and normalized such that $\alpha_c + \alpha_l + \alpha_n + \alpha_m = 1$ and where:

- c_t^J = average annual consumption per capita by Generation t in region J ;
- x_t^{lJ} = average annual leisure per capita, in efficiency units, by Generation t in region J;
- S_t^{nJ} = stock of knowledge per capita in region J, which enters Generation t's utility function and production function, understood as placed in the last year of life of Generation t;
- S_t^m = CO$_2$ concentration in the atmosphere, in ppm, which is understood as placed in the last year of life of Generation t; and
- $\hat{S}^m$ = "catastrophic" concentration of CO$_2$ in the atmosphere.

Remark 1. The presence of the concentration of CO$_2$ in the utility function captures our view that environmental deterioration is a public bad in consumption (as well as in production). Similarly, the state of social knowledge is an argument in utility as well as in production. We understand the stock of knowledge as an aggregate index of the quantity of technical blueprints, scientific papers, works of literature, software, etc., available in the region. See Llavador et al. (2013) for further discussion.

S.1.2 Production Function

We postulate that North and South have the same technology, but different initial education levels and stocks of knowledge and physical capital. The production function is

$$f\left(x_t^{cJ}, S_t^{kJ}, S_t^{nJ}, e_t^J, S_t^m\right) \equiv k_1\left(x_t^{cJ}\right)^{\theta_c}\left(S_t^{kJ}\right)^{\theta_k}\left(S_t^{nJ}\right)^{\theta_n}\left(e_t^J\right)^{\theta_e}\left(S_t^m\right)^{\theta_m}, \quad t \geq 1, \tag{s.5}$$

where $k_1 > 0$, $\theta_c > 0$, $\theta_k > 0$, $\theta_n > 0$, $\theta_e > 0$, $\theta_c + \theta_k + \theta_n = 1$, $\theta_m < 0$, where S_t^m and S_t^{nJ} have been defined above, and where:

- x_t^{cJ} = average annual efficiency units of labor per capita devoted to the production of output by Generation t in region J;
- S_t^{kJ} = capital stock per capita available to Generation t in Region J, understood as located in the last year of the life of Generation t;
- e_t^J = average annual per capita emissions of CO$_2$ in tC by Generation t in Region J.

We call emissions e_t^J and concentrations S_t^m *environmental variables*, whereas all other variables are called *economic*.

Remark 2. The labor input in production, x_t^{cJ}, is measured in efficiency units of labor, which may be viewed as the number of labor-time units ("hours") multiplied by the amount of human capital embodied in one time unit.

Remark 3. The assumption of constant returns relative to the inputs labor, capital and knowledge reflects the notion that an increase in the knowledge input reduces the emissions-to-output ratio.

S.1.3 Law of Motion of Physical Capital

The *law of motion of physical capital* in each region is standard, namely

$$(1-d^k)S_{t-1}^{kJ}\frac{N_{t-1}^J}{N_t^J} + k_2 i_t^J \geq S_t^{kJ}, t \geq 1, J = N, S, \tag{s.6}$$

where $k_2 > 0$, $d^k \in (0,1)$, and $i_t^J \geq 0$ is the average annual investment in physical capital (units of output per capita) by Generation t in Region J.

S.1.4 Law of Motion of Knowledge and Technological Diffusion

We assume that the creation of new knowledge requires only efficiency labor (dedicated to R&D, or to "learning by not doing"), but that knowledge depreciates at a positive rate. In addition, as long as there is a technological gap between the two countries, North's knowledge spills over to South.

The generational law of motion of the stock of knowledge in North is

$$(1-d^n)\frac{N_{t-1}^N}{N_t^N}S_{t-1}^{nN} + k_3 x_t^{nN} \geq S_t^{nN}, \quad t \geq 1, \tag{s.7}$$

where $k_3 > 0$, $d^n \in (0,1)$, and $x_t^{nN} \geq 0$ is the average annual number of efficiency units of labor per capita devoted to the creation of knowledge by Generation t in North. In words, a fraction d^n of the $(t-1)$-period per capita stock of knowledge becomes obsolete by period t, but it can be increased by investing labor resources. Section S.5 below derives (s.7) from a year-to-year law of motion.

As long as North's stock of knowledge per capita is larger than that of South's, we postulate that North's knowledge spills over to South, which in addition can devote a fraction of its own efficiency labor to the creation of knowledge. Hence, the law of motion of the stock of knowledge in South captures the presence of international technological diffusion (Eaton and Kortum, 1999, Keller, 2004). Moreover, we assume that technological diffusion depends upon the gap between the stock of knowledge in both regions, and that human capital speeds the process of diffusion, the so called Nelson-Phelps technological catch-up hypothesis (Nelson and Phelps 1966; Benhabib and Spiegel, 2005).[15] Our formulation starts from a year-to-year equation for knowledge diffusion which after some manipulation (see Section S.5 below) yields the generational *law of motion of the stock of knowledge in South*

$$S_t^{nS} = (1-d^n)\frac{N_{t-1}^S}{N_t^S} S_{t-1}^{nS} + k_3 x_t^{nS} \qquad \text{if} \quad S_{t-1}^{nN} - S_{t-1}^{nS} \le 0, \tag{s.8}$$

$$S_t^{nS} = (1-d^n)\frac{N_{t-1}^S}{N_t^S} S_{t-1}^{nS} + k_3 x_t^{nS} + k_{3d}(S_{t-1}^{nN} - S_{t-1}^{nS}) x_t^{nS} \qquad \text{if} \quad S_{t-1}^{nN} - S_{t-1}^{nS} > 0, \tag{s.9}$$

where $k_3 > k_{3d} > 0$, and x_t^{nS} is the average annual efficiency units of labor per capita devoted to the production of knowledge by Generation t in South.[16]

S.1.5 Education Production Function

The education production function transforms labor-leisure time in efficiency units of labor and leisure.[17] It states that the education of a young generation requires only efficiency labor of the previous generation. Formally, the *education production function* is given by

$$x_t^J \le \xi x_{t-1}^{eJ} \frac{N_{t-1}^J}{N_t^J}, \quad t \ge 1, \quad J = N, S, \tag{s.10}$$

where $\xi > 0$, and $x_t^{eJ} \ge 0$ (resp. $x_t^J \ge 0$) is the annual average number of efficiency units of labor per capita devoted to education by Generation *t* (resp., per capita efficiency units of labor-leisure available to Generation t) in Region J. If we normalize to unity the total labor-leisure time available to Generation t, then x_t^J can be interpreted as the amount of human capital per unit time in Generation t.

S.2 Optimization Program

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[15] The catch-up hypothesis was originally proposed by Gerschenkron (1962). Benhabib and Spiegel (1994), Engelbrecht (2002), and Xu and Chiang (2005), among others, provide empirical evidence in favor of the Nelson-Phelps technological catch-up hypothesis.

[16] Of course, the law of motion (s.9) of the stock of knowledge in South when $S_{t-1}^{nN} = S_{t-1}^{nS}$ coincides with (s.8) and parallels (s.7).

[17] We justify this education production function in Llavador et al. (2011, 2013).

Given $\left(\rho, e^{*}, S^{m*}\right)$, choose $S_1^{kN}, S_1^{kS}, S_2^{k}, S_1^{nN}, S_1^{nS}, S_2^{n}$, $i_1^{N}, i_1^{S}, i_2^{N}, i_2^{S}, c_1^{N}, c_1^{S}, c_2^{N}, c_2^{S}$, $e_1^{N}, e_1^{S}, e_2^{N}, e_2^{S}$, $x_1^{lN}, x_1^{cN}, x_1^{eN}, x_1^{nN}, x_2^{lN}, x_2^{cN}, x_2^{nN}, x_2^{e}$, $x_1^{lS}, x_1^{cS}, x_1^{eS}, x_1^{nS}, x_2^{lS}, x_2^{cS}, x_2^{nS}$, T_1, T_2, c_3, x_3^{l} and S_3^{n}

in order to maximize Λ_2^{S} subject to:

$$\left(c_2^{S}\right)^{\alpha_c}\left(x_2^{lS}\right)^{\alpha_l}\left(S_2^{n}\right)^{\alpha_n}\left(\hat{S}^{m}-S_2^{m*}\right)^{\alpha_m}-\Lambda_2^{S}\geq 0,$$

$$\left.\begin{array}{l}
\left(c_1^{S}\right)^{\alpha_c}\left(x_1^{lS}\right)^{\alpha_l}\left(S_1^{nS}\right)^{\alpha_n}\left(\hat{S}^{m}-S_1^{m*}\right)^{\alpha_m}-\left(1+\rho\right)\Lambda_0^{S}\geq 0,\\
\left(c_1^{N}\right)^{\alpha_c}\left(x_1^{lN}\right)^{\alpha_l}\left(S_1^{nN}\right)^{\alpha_n}\left(\hat{S}^{m}-S_1^{m*}\right)^{\alpha_m}-\left(1+\rho\right)\Lambda_0^{N}\geq 0,\\
\left(c_2^{N}\right)^{\alpha_c}\left(x_2^{lN}\right)^{\alpha_l}\left(S_2^{n}\right)^{\alpha_n}\left(\hat{S}^{m}-S_2^{m*}\right)^{\alpha_m}-\left(1+\rho\right)^{2}\Lambda_0^{N}\geq 0,\\
\left(c_3\right)^{\alpha_c}\left(x_3^{l}\right)^{\alpha_l}\left(S_3^{n}\right)^{\alpha_n}\left(\hat{S}^{m}-S^{m*}\right)^{\alpha_m}-\left(1+\rho\right)^{3}\Lambda_0^{N}\geq 0,
\end{array}\right\}\text{utility growth,}$$

$$\left.\begin{array}{l}
\left(1-d^{k}\right)S_0^{kN}\dfrac{N_0^{N}}{N_1^{N}}+k_2\,i_1^{N}-S_1^{kN}\geq 0,\\
\left(1-d^{k}\right)S_1^{kN}\dfrac{N_1^{N}}{N_2^{N}}+k_2\,i_2^{N}-S_2^{k}\geq 0,\\
\left(1-d^{k}\right)S_0^{kS}\dfrac{N_0^{S}}{N_1^{S}}+k_2\,i_1^{S}-S_1^{kS}\geq 0,\\
\left(1-d^{k}\right)S_1^{kS}\dfrac{N_1^{S}}{N_2^{S}}+k_2\,i_2^{S}-S_2^{k}\geq 0,
\end{array}\right\}\text{physical capital accumulation,}$$

$$\left.\begin{array}{l}
\left(1-d^{n}\right)S_0^{nS}\dfrac{N_0^{S}}{N_1^{S}}+k_3x_1^{nS}+k_{3d}\left(S_0^{nN}-S_0^{nS}\right)x_1^{nS}-S_1^{nS}\geq 0,\\
\left(1-d^{n}\right)S_1^{nS}\dfrac{N_1^{S}}{N_2^{S}}+k_3x_2^{nS}+k_{3d}\left(S_1^{nN}-S_1^{nS}\right)x_2^{nS}-S_2^{nS}\geq 0,\\
\left(1-d^{n}\right)S_0^{nN}\dfrac{N_0^{N}}{N_1^{N}}+k_3\,x_1^{nN}-S_1^{nN}\geq 0,\\
\left(1-d^{n}\right)S_1^{nN}\dfrac{N_1^{N}}{N_2^{N}}+k_3\,x_2^{nN}-S_2^{n}\geq 0,
\end{array}\right\}\text{knowledge accumulation \& diffusion,}$$

$$\left.\begin{aligned}
&\xi x_0^{eN}\frac{N_0^N}{N_1^N}-x_1^{lN}-x_1^{cN}-x_1^{eN}-x_1^{nN}\geq 0,\\
&\xi x_1^{eN}\frac{N_1^N}{N_2^N}-x_2^{lN}-x_2^{cN}-x_2^{e}-x_2^{nN}\geq 0,\\
&\xi x_0^{eS}\frac{N_0^S}{N_1^S}-x_1^{lS}-x_1^{cS}-x_1^{eS}-x_1^{nS}\geq 0,\\
&\xi x_1^{eS}\frac{N_1^S}{N_2^S}-x_2^{lS}-x_2^{cS}-x_2^{e}-x_2^{nS}\geq 0,
\end{aligned}\right\}\text{human capital accumulation,}$$

$$\left.\begin{aligned}
&e_1^*-\frac{N_1^N}{N_1^N+N_1^S}e_1^N-\frac{N_1^S}{N_1^N+N_1^S}e_1^S\geq 0,\\
&e_2^*-\frac{N_2^N}{N_2^N+N_2^S}e_2^N-\frac{N_2^S}{N_2^N+N_2^S}e_2^S\geq 0,
\end{aligned}\right\}\text{emissions}\,,^{18}$$

$$\left.\begin{aligned}
&-T_1+k_1\left(x_1^{cN}\right)^{\theta_c}\left(S_1^{kN}\right)^{\theta_k}\left(S_1^{nN}\right)^{\theta_n}\left(S_1^{m*}\right)^{\theta_m}\left(e_1^{N}\right)^{\theta_e}-c_1^N-i_1^N\geq 0,\\
&-T_2+k_1\left(x_2^{cN}\right)^{\theta_c}\left(S_2^{k}\right)^{\theta_k}\left(S_2^{n}\right)^{\theta_n}\left(S_2^{m*}\right)^{\theta_m}\left(e_2^{N}\right)^{\theta_e}-c_2^N-i_2^N\geq 0,\\
&T_1\frac{N_1^N}{N_1^S}+k_1\left(x_1^{cS}\right)^{\theta_c}\left(S_1^{kS}\right)^{\theta_k}\left(S_1^{nS}\right)^{\theta_n}\left(S_1^{m*}\right)^{\theta_m}\left(e_1^{S}\right)^{\theta_e}-c_1^S-i_1^S\geq 0,\\
&T_2\frac{N_2^N}{N_2^S}+k_1\left(x_2^{cS}\right)^{\theta_c}\left(S_2^{k}\right)^{\theta_k}\left(S_2^{n}\right)^{\theta_n}\left(S_2^{m*}\right)^{\theta_m}\left(e_2^{S}\right)^{\theta_e}-c_2^S-i_2^S\geq 0,
\end{aligned}\right\}\text{output production,}$$

$$\left.\begin{aligned}
&\left(x_2^e,S_2^k,S_2^n\right)\in\Gamma\left(\rho,e^*,S^{m*}\right),\\
&S_3^n-(1+g)S_2^n\geq 0,\\
&c_3-\gamma_1\left(\rho,e^*,S^{m*}\right)\geq 0,\\
&x_3^l-\gamma_2\left(\rho,e^*,S^{m*}\right)\geq 0,
\end{aligned}\right\}\text{steady state}\,,^{19}$$

with initial conditions $\left(x_0^{eN},S_0^{kN},S_0^{nN}\right)$, $\left(x_0^{eS},S_0^{kS},S_0^{nS}\right)$, Λ_0^N and Λ_0^S.

Because of the convergence of the economic stocks of North and South at $t=2$ and of flows at $t=3$, we use the notation $S_2^j\equiv S_2^{jN}=S_2^{jS}$, $j=k,n$, $S_3^n\equiv S_3^{nN}=S_3^{nS}$, $x_2^e\equiv x_2^{eN}=x_2^{eS}$, $c_3\equiv c_3^N=c_3^S$, and $x_3^l\equiv x_3^{lN}=x_3^{lS}$.

---

[18] For t=1, 2, e_t^* denotes the average annual world emissions per capita of CO2.

[19] The rate g is the generational rate of growth of economic variables, satisfying $1+\rho=\left(1+g\right)^{1-\alpha_m}$.

The last three inequalities, involving S_3^n, c_3 and x_3^l, require both regions to be in the steady state defined by the ray $\Gamma\left(\rho, e^*, S^{m*}\right)$ at the beginning of period 3. Functions γ_1 and γ_2 are easily derived from Theorem 1 in Llavador et al. (2011) and its web supplement.

For $t = 1,2$, we denote by T_t the number of units of output per capita in North that North exports to South. A negative T_t indicates a flow from South to North. We write the optimization program with T_1 and T_2 explicit, which are unconstrained in the exports-allowed regime. But if output flows are ruled out, then the constraints $T_1 = T_2 = 0$ are imposed (see Section S.6.5)

S.3 Calibration

S.3.1 Calibrated Values

Section S.3.2 below details our calibration, which yields the values for the parameters in Table s.1 and uses the initial values of the stocks and flows for the reference year (2005) in tables s.2-s.5.

Parameter	Value	Parameter	Value
α_c	0.319	d^k	0.787
α_l	0.637	d^n	0.787
α_n	0.016	$\hat{S}^m$	1249.09
α_m	0.028	θ_c	0.667
k_1	15.363	θ_k	0.278
k_2	13.118	θ_n	0.056
k_3	567.098	θ_e	0.091
k_{3d}	5.671	θ_m	-0.036
ξ	41.434		

Table s.1. **Calibrated parameter values.**

Stocks	Value	Units
S_0^{kN}	95.281	thousands of 2005-international $ per capita
S_0^{kS}	14.739	thousands of 2005-international $ per capita
S_0^{nN}	22.100	thousands of 2005-international $ per capita
S_0^{nS}	0.370	thousands of 2005-international $ per capita
S_0^{m}	379	ppm
x_0^{eN}	0.067	USA-1950-efficiency units per capita
x_0^{eS}	0.027	USA-1950-efficiency units per capita

Table s.2. **Initial values of the stocks in the reference year (2005).**

Flows	Value	Units
y_0^N	41.83	thousands of 2005 international dollars per capita
y_0^S	4.076	thousands of 2005 international dollars per capita
c_0^N	34.09	thousands of 2005 international dollars per capita
c_0^S	2.18	thousands of 2005 international dollars per capita
i_0^N	7.74	thousands of 2005 international dollars per capita
i_0^S	1.90	thousands of 2005 international dollars per capita
e_0^N	3.2	tC per capita
e_0^S	0.6	tC per capita

***Table s.3.* Initial values of the flows in the reference year (2005).**

Variable	Value	Units
x_0^N	2.035	1950-US efficiency units per capita
x_0^S	1.362	1950-US efficiency units per capita
x_0^{lN}	1.363	1950-US efficiency units per capita
x_0^{lS}	0.885	1950-US efficiency units per capita
x_0^{cN}	0.571	1950-US efficiency units per capita
x_0^{cS}	0.440	1950-US efficiency units per capita
x_0^{eN}	0.067	1950-US efficiency units per capita
x_0^{eS}	0.027	1950-US efficiency units per capita
x_0^{nN}	0.034	1950-US efficiency units per capita
x_0^{nS}	0.010	1950-US efficiency units per capita

***Table s.4.* Labor allocation in the reference year (2005).**

Variable	Value	Units
N_0^{USA}	296,820	thousands
N_0^{China}	1,307,593	thousands
e_0^{USA}	5.4	tC per capita
e_0^{China}	1.1	tC per capita

***Table s.5.* USA’s and China’s population and emissions in the reference year (2005).**

S.3.2 Calibrations

We interpret that generations live for 25 years. For the calibration, flow variables are typically defined as per year averages, and it is understood that stocks are located in the last year of life of a generation. Our partition of the world into two regions, North and South, follows the United Nations classification of "more developed regions" (Europe, Northern America, Australia/New Zealand, and Japan) and "less developed regions" (Africa, Asia (excluding Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia).

S.3.2.1 Variables

S_t^{kJ} = capital stock available to Generation t in region J (in thousands of int. dollars per capita).

S_t^{nJ} = stock of knowledge available to Generation t in region J (in thousands of int. dollars per capita).

S_t^{m} = CO_2 concentration in the atmosphere at the end of Generation t's life (in ppm).

x_t^{J} = average annual efficiency units of time (labor and leisure) available to Generation t in region J (in efficiency units per capita).

x_t^{eJ} = average annual labor devoted to education by Generation t in region J (in efficiency units per capita).

x_t^{cJ} = average annual labor devoted to the production of output by Generation t in region J (in efficiency units per capita).

x_t^{lJ} = annual average leisure by Generation t in region J (in efficiency units per capita).

x_t^{nJ} = average annual labor devoted to the production of knowledge by Generation t in region J (in efficiency units per capita).

c_t^{J} = annual average consumption by Generation t in region J (in thousands of int. dollars per capita).

i_t^{J} = average annual investment by Generation t in region J (in thousands of int. dollars per capita).

e_t^{J} = average annual emissions per capita of CO_2 from fuel and cement by Generation t in region J (in tC per capita).

S.3.2.2 Parameters

α_j = exponents of the utility function for $j \in \{c$ (consumption), l (leisure), n (stock of knowledge), and m (CO_2 concentration)$\}$.

k_1 = parameter of the production function f.

k_2 = parameter of the law of motion of capital.

k_3 = parameter of the law of motion of the stock of knowledge.

k_{3d} = parameter of the law of motion of the stock of knowledge with technological diffusion from North to South.

ξ = parameter of the education production function.

$\hat{\lambda}$ = annual rate of technological transfer from North to South.

θ_j = exponents of the inputs in the production function f for $j \in \{ c$ (labor), k (stock of capital), n (stock of knowledge), e (emissions of CO_2), m (atmospheric carbon concentration)$\}$.

d^k = depreciation rate of the stock of capital (per generation).

d^n = depreciation rate of the stock of knowledge (per generation).

e_t^* = average annual world emissions per capita of CO_2 from fuel and cement by Generation t (in tC per capita).

S_t^m = carbon concentration in the atmosphere at the end of Generation t (in ppm).

$\hat{S}^m$ = catastrophic level of carbon concentration in the atmosphere (in ppm).

$\hat{\rho}$ = annual rate of growth of utility.

ρ = generational rate of growth of utility ($\rho = \left(1+\hat{\rho}\right)^{25}$).

S.3.2.3 Functions

Utility function: $(c_t^J)^{\alpha_c}(x_t^{lJ})^{\alpha_l}(S_t^{nJ})^{\alpha_n}(\hat{S}^m - S_t^m)^{\alpha_m}$.

Production function: $f(x_t^{cJ}, S_t^{kJ}, S_t^{nJ}, e_t^J, S_t^m) \equiv k_1(x_t^{cJ})^{\theta_c}(S_t^{kJ})^{\theta_k}(S_t^{nJ})^{\theta_n}(e_t^J)^{\theta_e}(S_t^m)^{\theta_m}$,

$\theta_c + \theta_c + \theta_n = 1$.

Law of motion of physical capital: $S_t^{kJ} \le (1-d^k)\frac{N_{t-1}^J}{N_t^J}S_{t-1}^{kJ} + k_2\, i_t^J$.

Law of motion of the stock of knowledge without technological diffusion:

$S_t^{nJ} \le (1-d^n)S_{t-1}^{nJ} + k_3\, x_t^{nJ}$.

Law of motion of the stock of knowledge with technological diffusion from North to South: $S_t^{nS} = \left(1-d^n\right)S_{t-1}^{nS}\frac{N_{t-1}^S}{N_t^S} + k_3 x_t^{nS} + k_{3d}\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)x_t^{nS}$.

Education production function: $x_t^J \le \xi \frac{N_{t-1}^J}{N_t^J} x_{t-1}^{eJ}$.

S.3.2.4 Population

We follow the United Nations (2010) population forecast, with data in five-year intervals. We assign the average forecasted population for 2010-2030 to Generation 1, and the average forecasted population for 2035-2100 to Generation 2. World population is 6.5 billion people in 2005, increases to 7.6 billion people for Generation 1, and stabilizes at 9.6 billion people from Generation 2 and on. Table s.6 reports the specific population paths for the world, North, South and the US.

	North	South	US	World

	Total population (thousand people)	Percentage of world pop.	Total population (thousand people)	Percentage of world pop.	Total population (thousand people)	Total population (thousand people)
Year 2005	1,210,897	18.6%	5,295,752	81.4%	296,820	6,506,649
Generation 1	1,269,668	16.6%	6,362,546	83.4%	336,562	7,632,214
Generation 2	1,314,454	13.7%	8,308,704	86.3%	430,981	9,623,158

***Table s.6.* World population paths**

S.3.2.5 Emissions and Carbon Concentration Paths

We stipulate a target of 450 ppm in long run CO_2 concentrations, and adopt a path of CO_2 emissions based on the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC, http://www.cgd.ucar.edu/wigley-magicc) for the Emission Scenario WRE 450 and with the default ("best estimate") set of parameters. For corroboration purposes, we have checked that the Bern model (Joos et al., 1996; Joos et al., 2001) yields similar concentration levels for the adopted path of emissions.
The emissions and concentration paths are presented in Table s.7.

	World Total CO_2 Emissions (GtC)	North's Total CO_2 Emissions (GtC)	South's Total CO_2 Emissions (GtC)	Concentration of CO_2 in (World) Atmosphere (ppm)	World CO_2 Emissions *per capita* (tC)
Year 2005	7.18	3.84	3.34	379	1.10
Generation 1	7.56	endogenous	endogenous	422	0.99
Generation 2	5.61	endogenous	endogenous	443	0.58
Generation *t*, $t \geq 3$	3.50	endogenous	endogenous	450	0.36

***Table s.7.* Our postulated paths for the world annual CO_2 emissions and end-of-generation concentrations. World emissions per capita are constructed from World Total emissions and the population data in Table s.6.**

S.3.2.6 The Calibration of the Utility Function

For the exponent of leisure, we choose $\alpha_l = 2\alpha_c$ in line with the conventional observation in the literature that, on average, households devote to work one third of their time endowment (see, e. g., Cooley and Hansen, 1992).

We calibrate $\alpha_n / \alpha_c = 0.05$ as the average ratio of expenditure in knowledge (R&D expenditure plus investment in computer components and software) over expenditure in consumption during the period 1960-2000.[20]

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[20] The data on R&D are derived from Research and Development in Industry, Academic Research and Development Expenditures, Federal Funds for Research and Development, and the Survey of Research and Development Funding and Performance by Nonprofit Organizations (National Science Foundation, 2003). Data on public investment in software are constructed taking the value of public investment in equipment and software (U.S. Bureau of Economic Analysis 2007) and assuming the same share of software in private and public investment.

The utility function has two parameters that concern the stock of CO_2, namely the catastrophic level $\hat{S}^m$ and the exponent α_m.

Because CO_2 concentration affects utility through temperature changes, here and in what follows we adopt the conventional functional form for the relation between temperature and GHG

$$\Delta T = \sigma \frac{\ln\left(S^e / S^m_{1850}\right)}{\ln 2}, \tag{s.11}$$

where S^e is the concentration of GHG measured in ppm of CO_2 equivalent, S^m_{1850} is the pre-industrial level of GHG in the atmosphere, ΔT is the *warming effect* defined as the average surface temperature increase in ºC since pre-industrial times, and the parameter σ is called the *climate sensitivity*.[21] Expression (s.11) can be inverted to yield $\widehat{S}^e(\Delta T) = S^m_{1850} \times 2^{\Delta T/\sigma}$. Because our variable S^m only considers the CO_2 concentration, which accounts for 84% of all GHG, we can write S^m as the function of ΔT

$$\widehat{S}^m(\Delta T) = \frac{S^m_{1850}}{1.16} 2^{\Delta T/\sigma} \tag{s.12}$$

We take $S^m_{1850} = 280$ ppm and adopt the common best-guess for the climate sensitivity of $\sigma = 3$[22]

We consider that an increase in temperature of 6º-8ºC (relative to pre-industrial level) would have catastrophic impacts.[23] From (s.12) an increase of 6ºC (resp. 8ºC) is associated with a S^m value of 965.52 ppm (resp. 1532.66). We calibrate $\hat{S}^m$ by the mean of these two values as $\hat{S}^m = 1249.09$ ppm.

We calibrate the exponent α_m by published information on nonmarket impacts, which include health and environmental degradation. In particular, we calibrate the ratio α_m / α_c by the Stern Review estimate that a 5ºC increase in the global temperature over the pre-industrial level would imply a nonmarket impact equivalent to a 6% loss of global GDP (Stern 2007, p. 186; see also p. x in the Executive Summary, Stern, 2006).[24] Again from (s.12) a 5ºC temperature increase corresponds to a S^m value of $766.33 \equiv \tilde{S}^m$.

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[21] In words, the climate sensitivity σ is the increase in global average surface temperature over that of year 1850 caused by doubling the preindustrial amount of GHG.

[22] Section S.6.4 analyzes higher values for the climate sensitivity parameter.

[23] The Stern Review consistently associates catastrophic consequences to temperature increases of 6-8ºC, like, for example, sea level rise threatening major world cities (including London, Shanghai, New York, Tokyo and Hong Kong), entire regions experiencing major declines in crop yields and high risk of abrupt, large scale shifts in the climate system (Stern 2006, Figure 2 in p. v), and catastrophic major disruptions and large-scale movements of population (Stern 2007, Table 3.1 in pp. 66-67).

[24] This is also in line with Nordhaus and Boyer (2000) who estimate a total cost (market and non-market) of between 9% and 11% of global GDP for a 6ºC warming (as quoted in Stern 2007, p. 167).

Accordingly, we consider a 6% decrease in consumption equivalent to suffering an atmospheric CO_2 concentration of $\tilde{S}^m$ compared to the pre-industrial level S^m_{1850}, that is,

$$\left(0.94c\right)^{\alpha_c}\left(x^l\right)^{\alpha_l}\left(S^n\right)^{\alpha_n}\left(\hat{S}^m-S^m_{1850}\right)^{\alpha_m}=\left(c\right)^{\alpha_c}\left(x^l\right)^{\alpha_l}\left(S^n\right)^{\alpha_n}\left(\hat{S}^m-\tilde{S}^m\right)^{\alpha_m},$$

which yields

$$\left(0.94\right)^{\alpha_c}\left(\hat{S}^m-S^m_{1850}\right)^{\alpha_m}=\left(\hat{S}^m-\tilde{S}^m\right)^{\alpha_m},$$

or

$$\alpha_c\ln 0.94=\alpha_m\left[\ln\left(\hat{S}^m-\tilde{S}^m\right)-\ln\left(\hat{S}^m-S^m_{1850}\right)\right].$$

It follows that $\frac{\alpha_m}{\alpha_c}=\frac{\ln 0.94}{\ln\left(\hat{S}^m-\tilde{S}^m\right)-\ln\left(\hat{S}^m-S^m_{1850}\right)}$. That is,

$$\frac{\alpha_m}{\alpha_c}=\frac{\ln 0.94}{\ln\left(1249.09-766.33\right)-\ln\left(1249.09-280\right)}=0.0888.$$

Finally, we normalize $\alpha_c+\alpha_l+\alpha_m+\alpha_n=1$ to yield the values reported in Section S.3.1.

S.3.2.7 The Calibration of the Production Function

We calibrate the production function

$$f\left(x^c_t,S^k_t,S^n_t,e_t,S^m_t\right)\equiv k_1\left(x^c_t\right)^{\theta_c}\left(S^k_t\right)^{\theta_k}\left(S^n_t\right)^{\theta_n}\left(e_t\right)^{\theta_e}\left(S^m_t\right)^{\theta_m}$$

in the following inputs: first the more usual labor, physical capital and knowledge, to which we add the environmental emissions and stock.

We assume constant returns to scale in the first three inputs, that is, $\theta_c+\theta_k+\theta_n=1$. Following standard growth literature, we take labor income share equal to two thirds (Kaldor, 1961, Kongsamut, Rebelo and Xie, 2001, Valentinyi and Herrendorf, 2008). We construct time series for the stocks of physical capital and knowledge (see sections S.3.2.8 and S.3.2.9 below), and we compute their average shares in the total stock of capital for the period 1960-2000, corresponding to 5/6 and 1/6, respectively. Hence, $\theta_c=0.667$, $\theta_k=0.278$ and $\theta_n=0.056$, representing the income share of each input.

We calibrate $\theta_e=0.091$ as the "elasticity of output with respect to carbon services" from RICE99 in Nordhaus and Boyer (2000, p. 191).

We calibrate θ_m, the elasticity of output to the CO_2 concentration in the atmosphere, by published information on market or economic damages. The composition of the production function and (s.12) yields

$$\overset{\frown}{f}(x^c_t,S^k_t,S^n_t,e_t,\Delta T)=\left(\frac{280}{1.16}2^{\Delta T/3}\right)^{\theta_m}\overset{\frown}{a}(.),\text{ where}\equiv\overset{\frown}{a}(.)=k_1(x^c_t)^{\theta_c}(S^k_t)^{\theta_k}(S^n_t)^{\theta_n}(e_t)^{\theta_e}.$$

We assume, following Nordhaus (2010, p. 11723), that a 3.4ºC increase in temperature implies a 2.8% loss of GDP, i. e., $\left(\frac{280}{1.16}2^{3.4/3}\right)^{\theta_m}\hat{a}(.) = 0.972\left(\frac{280}{1.16}2^{0/3}\right)^{\theta_m}\hat{a}(.)$, or $2^{1.13\theta_m} = 0.972$, i.e., $\theta_m = \frac{\ln 0.972}{1.13\ln 2} = -0.036$.

Finally, we compute k_1 as the TFP of the USA economy calibrated to year 2005 values:[25]

$$k_1 = \frac{y^{USA}_{2005}}{\left(x^{c,USA}_{2005}\right)^{\theta_c}\left(S^{k,USA}_{2005}\right)^{\theta_k}\left(S^{n,USA}_{2005}\right)^{\theta_n}\left(e^{USA}_{2005}\right)^{\theta_e}\left(S^{m}_{2005}\right)^{\theta_m}} =$$

$$\frac{41.833}{0.571^{0.667}\,95.281^{0.278}\,22.1^{0.056}\,5.34^{0.091}\,379^{-0.036}} = 15.363.$$

S.3.2.8 The Stock of Physical Capital

The generational *law of motion of physical capital* in each region is standard:

$$(1-d^k)S^{kJ}_{t-1}\frac{N^J_{t-1}}{N^J_t} + k_2 i^J_t \geq S^{kJ}_t .$$

We take $\hat{d}^k = 0.06$ as the annual rate of depreciation (Cooley and Prescott 1995). In generational terms, $d^k = 1-\left(1-\hat{d}^k\right)^{25} = 0.787$.

To approximate the year-to-year discounting, we take *i* as the average investment in physical capital per year of a given generation, and compute that, at the end of the generation 's life, the accumulated investment amounts are

$$i + i\times\left(1-\hat{d}^k\right) + i\times\left(1-\hat{d}^k\right)^2 + \cdots + i\times\left(1-\hat{d}^k\right)^{24} = \frac{1-\left(1-\hat{d}^k\right)^{25}}{1-\left(1-\hat{d}^k\right)}i .$$

Thus, since $1-\hat{d}^k = 0.94$, the parameter $k_2 = \frac{1-\left(1-\hat{d}^k\right)^{25}}{1-\left(1-\hat{d}^k\right)} = 13.118$.

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[25] GDP is denoted in thousands of constant 2005 dollars per capita from the World Development Indicator (World Bank 2010). USA emissions are obtained from the World Resources Institute (2010). See sections s.3.2.8-12 below for the values of the other stocks and flows in the year 2005.

Initial stock of physical capital for North

We assign North the stock of physical capital per capita in USA. The time series of the stock of physical capital is constructed by the perpetual inventory method (PIM), using USA data for 1960-2005 (U.S. Bureau of Economic Analysis, 2007) and taking 1960 as initial value. For the initial year, $S_{1960}^{kN} = i_{1960}^{kN} \big/ \left(\hat{d}^k + g^{kN}\right) = 2.51 \big/ \left(0.06 + 0.025\right) = 29.57$ thousands of constant 2000-dollars per capita, where i^{kN} represents total (private and public) investment per capita minus expenditure in software, and g^{kN} represents the average yearly growth rate of investment between 1960-1970 (set at 2.5%). The value for the stock of physical capital in the year 2005 is $S_0^{kN} = 95.281$ thousands of 2005-international dollars per capita. (We use data from WDI to convert from 2000 to 2005 international dollars.)

Initial stock of physical capital for South

We assign South the stock of physical capital per capita in China. We use the Albala-Bertrand and Feng (2007) value, who provide a figure of 11,243.3 billion 1952-Yuan for the capital stock in 2005. Dividing by population, using CPI data from Officer and Williamson (2008), and World Bank PPP, we obtain $S_0^{kS} = 14.739$ thousands of 2005-international dollars per capita.

S.3.2.9 The Stock of Knowledge.

Law of motion of the stock of knowledge

We calibrate the law of motion of the stock of knowledge with technological diffusion from North to South

$$S_t^{nS} = \left(1 - d^n\right) S_{t-1}^{nS} \frac{N_{t-1}^S}{N_t^S} + k_3 x_t^{nS} + k_{3d} \left(S_{t-1}^{nN} - S_{t-1}^{nS}\right) x_t^{nS}, \tag{s.13}$$

where

$$k_3 = \frac{d^n}{\hat{d}^n} \bar{w}, \;\; k_{3d} = \hat{\lambda} k_3, \tag{s.14}$$

$\bar{w}$ is the average wage of an efficiency unit of labor, and $\hat{\lambda}$ is the rate of annual technological diffusion. Section S.5 below presents the derivation of these expressions from a year-to-year law of motion.

In the absence of technological diffusion, $k_{3d} = 0$ and South's law of motion becomes the same as North's. Therefore, the calibration of the laws of motion of the stock of knowledge only requires the estimation of three values: the annual depreciation rate of knowledge ($\hat{d}^n$), the average wage of an efficiency unit of labor ($\bar{w}$), and the diffusion rate of knowledge from North to South per year ($\hat{\lambda}$).

The yearly depreciation rate for knowledge commonly used is much higher than the one for capital (e. g., the Bank of Spain uses 15%, which would mean that knowledge dissipates almost entirely in one generation). We believe that the discount factor should be higher because of the intergenerational-public-good character of knowledge. A dollar invested in R&D by a firm may well generate no returns to the firm 25 years later, yet its impact to the accumulation of social knowledge capital may be substantial.[26] Thus, as an approximation we take the depreciation rate of the stock of knowledge to be the same as that of physical capital, that is, $\hat{d}^n = \hat{d}^k = 0.06$, and in generational terms, $d^n = 0.787$.

We approximate the wage of an efficiency unit of labor by $\bar{w} = i_t^n / x_t^n$, where i_t^n is the average annual expenditure per capita in knowledge, and x_t^n is the share of labor devoted to the production of knowledge. We use the average U.S. values of expenditures and labor in knowledge for the last generation (1976-2000) to obtain $i_{1976-2000}^n / x_{1976-2000}^n = 1.04/0.03 = 38.04$ thousands of 2000-dollars, or $\bar{w} = 43.23$ thousands of 2005-dollars (using CPI from WDI).

A value for $\hat{\lambda}$ is more complicated to obtain.[27] We choose a conservative value of $\hat{\lambda} = 0.01$ and repeat our computations for a range of values of $\hat{\lambda}$ above and below (see Section S.6.1).

Using the depreciation rate $\hat{d}^n = 0.06$, the annual rate of diffusion $\hat{\lambda} = 0.01$, and the estimation of $\bar{w} = 43.23$, we compute $k_3 = 567.098$, and $k_{3d} = 5.671$, in accordance with (s.14).

Initial stock of knowledge for North

The time series of the stock of knowledge in North is constructed by PIM, using USA data for 1960-2005 and taking 1960 as initial value. For the stock of knowledge in 1960 we take $S_{1960}^{nN} = i_{1960}^{nN} / \left(\hat{d}^n + g^{nN}\right) = 0.426/\left(0.06 + 0.028\right) = 4.21$ thousands of constant 2000-dollars per capita, where i^{nN} represents total expenditure per capita in R&D plus public and private investment in software, and g^{nN} represents the average yearly growth rate between 1960-1970. The value for the stock of knowledge in the year 2005 is $S_0^{nN} = 22.10$ (in thousands of 2005-international dollars per capita).

Initial stock of knowledge for South

We assign to South the per capita stock of China. The time series of the stock of knowledge in China is constructed by PIM, using the annual knowledge equation with technology diffusion represented in (s.13). We take 1/3 of the GDP per capita in 1980 (i. e., 278 international dollars per capita) as the initial value of the stock of knowledge in China.[28] The date is unusually recent for applying PIM, but it can be justified by the particular circumstances of China.[29] This year roughly coincides with the new

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[26] See, e. g., Jones and Williams (1998) for a discussion of the "standing on the shoulders of giants" effect.

[27] The recent literature on technological diffusion estimates a 25 years adoption lag (Comin and Hobijn, 2010). This implies an annual technological diffusion rate of 4%.

[28] Currency is always in constant 2000 PPP international dollars.

[29] The choice of the initial value has a moderate effect for the stock in 2005. Choosing as initial value R&D investment in 1980 would decrease the year 2005 stock in less than $10 per capita. But this figure most likely underestimates the real value (see notes in the OECD statistics). On the other hand, choosing total GDP would increase year 2005 stock

development path set by Deng Xiaoping after the failure of the "Great Leap" experiment.[30] As Song (2008, p. 236) argues, "for the first time in China's history, science and technology were viewed as driving force behind economic development." The reform also initiated the flow of many students to the West for further scientific education, which also justifies the use of a rate of diffusion starting in 1980.[31] For the time series of investment in knowledge, we take the data on R&D investment 1980-2000 from Gao and Jefferson (2007) and the China Science and Technology Statistical Data Yearbook (MOST 2000).[32] The PIM with a 6% annual depreciation rate and a diffusion rate $\hat{\lambda} = 0.01$ yields a value for the stock of knowledge in the year 2005 of $S_0^{n,S} = 0.37$ thousands of 2005-international dollars per capita (using CPI from WDI).

S.3.2.10 The Calibration of the Education Production Function

We assume that both regions have access to the same production function of education (as given in (s.10)), which we calibrate with US data. The parameter ξ, capturing the productivity of education, plays an important role in the model. By definition, $\xi = N_t^J x_t^J / N_{t-1}^J x_{t-1}^e$, where both the numerator and the denominator are measured in efficiency units. We can transform efficiency units into hours by the equality

$$\frac{N_t^J x_t^J}{N_{t-1}^J x_{t-1}^{eJ}} = \frac{(1+s)^{\bar{t}} \hat{x}_t}{(1+s)^{\bar{t}-1} \hat{x}_{t-1}^e} = (1+s) \frac{\hat{x}_t}{\hat{x}_{t-1}^e},$$

where $\bar{t}$ is given and plays no role, $(1+s)$ is the growth factor of human capital per generation, and where the "hats" represent the data in total annual hours. Hence, the calibration of ξ is based on two rates: s and the share $\hat{x}_{t-1}^e / \hat{x}_t$ of time devoted to education out of total time. Note that ξ is increasing in s and decreasing in the share $\hat{x}_{t-1}^e / \hat{x}_t$.

We take the value $\hat{s} = 1.3\%$ for the average yearly growth rate of the human capital stock, which yields the per-generation factor $(1+s) = (1+\hat{s})^{25} = 1.381$. This figure is based on the 1950-2010 average provided by Barro and Lee (2010), and supported by other recent findings (see e. g. Christian, 2010), Wei, 2008, or Gu and Wong, 2010).[33]

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in less than $10 per capita.

[30] Deng Xiaoping reforms started in 1978. We choose 1980 instead since this is the first year for which we have a PPP conversion factor.

[31] By 2006, 1.67 million Chinese students had enrolled in universities in more than 108 countries. "This confirms that the policy of free access to overseas education is and will continue to be instrumental in China's drive toward modernization." (Song 2008, p. 236).

[32] Since there is only data available from 1986, we take investment in R&D constant at 0.5% of GDP for the decade of the 80s (the value for the years where we have data).

[33] Looking at a twelve-year period in U.S. data, Christian (2010, p. 34) finds an average growth in the human capital stock of 1.1%. The Australian Bureau of Statistics finds an average growth rate of 1.3% over a twenty-year period (Wei 2008, p. 8). Gu and Wong (2010) find a growth rate of 1.7% in Canada over a 27-year period.

The rate $\hat{x}^e_{t-1}/\hat{x}_t$ is the product of the rate of education in labor and the rate of labor in total time. We infer from our time series that about 10% of total labor is devoted to education, and that labor accounts for 1/3 of total time. It follows that

$$\xi = (1.013)^{25} \frac{1}{0.0334} = 41.434\,. \tag{s.15}$$

This figure is conservative in the sense that higher growth rates of human capital, lower labor rates, and population growth would yield a larger value for ξ.

S.3.2.11 Initial Values for Total Labor and Labor Allocation

We construct the USA human capital stock (in efficiency units) by normalizing year 1950 equal to 1 and taking the average yearly growth rate of human capital stock equal to 1.3% (Barro and Lee 2010). Hence, $x_t^N = 1.013^{t-1950}$ in 1950-USA efficiency units, and therefore $x_0^N = 1.013^{55} = 2.035$. We take the standard assumption of 33% of time devoted to working hours. We allocate total working hours among education, knowledge and production in North according to their average proportions in the USA, namely 10% in education, 5% in knowledge, and the remaining 85% in the production of consumption good.[34]

For the estimation of human capital in South, we use the ratio of years of education between China and USA. We obtain from Barro and Lee (2010) the average years of school of the total population aged 15 and over for USA and China: 12.201 and 8.167 years, respectively.[35] Therefore, $x_0^S = 2.035 \times \left(8.167/12.201\right) = 1.362$, in 1950-USA efficiency units. Based on the study by Li and Zax (2003), we take Chinese workers to devote 65% of their time to leisure. We use the data of the China Statistical Yearbook (National Bureau of Statistics of China 2010) for the allocation of working time: 5.6% in education, 2.1% in knowledge, and the remaining 92.3% in the production of output.[36]

S.3.2.12 Initial Values for GDP, Consumption and Investment

The values of GDP, consumption and investment in the benchmark year for North and South are presented in Table s.3. We assign to them the values in the World Development Indicators 2010 for the USA and China, respectively (World Bank 2010). For consumption and investment we use "Final consumption expenditure" and "Gross capital

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[34] U.S. Bureau of Labor Statistics (2010): From the BLS classification, we compute education as the labor in education (local and state labor in education), and 40% of the time of labor in research.

[35] More sophisticated analyses, like those of Wang and Yao (2001) and Perkins and Rawski (2008), find similar values for China.

[36] For labor in knowledge we compute employed persons in urban units in "Scientific Research, Technical Services, and Geological Prospecting," "Information Transmission, Computer Service and Software," "Management of Water Conservancy, Environment and Public Facilities," and "Culture, Sports and Entertainment." For education we compute employed persons in "Education" in urban areas plus 1.5% of employed persons in rural areas.

formation” as percentages of GDP, after adjusting for “Net Exports of Goods and Services (*X*)”. We allocate *X* into consumption and capital formation according to their contributions to GDP.

S.4 Economic Variables along the Transition and in the Steady State

The paths for the economic variables are presented in tables s.8 and s.9. Table s.8, which reproduces Table 3 in the main text, displays the fractions of each period’s labor-leisure resource allocated to the various uses, whereas Table s.9 shows the path of stocks (knowledge, physical capital, and human capital) and flows (consumption and investment). For each region, the rows for $t=0$ and $t=3$ permit the comparison between the steady state values recommended by our analysis and the initial conditions, which can be interpreted as those of the BAU *status quo*.[37]

As noted in the text,_South’s consumption of output has to grow quite fast during rhe transition. Specifically, South’s consumption at $t=1$ (resp., $t=2$) is almost six times (over seventeen times), its reference level, and thirty one times at the convergence point $t=3$). North’s consumption grows more slowly, to almost twice its reference level at the convergence point $t=3$ (see Table s.9).

			Labor allocation (fraction of total labor-leisure available)							Labor (in efficiency units)		
			Education	Knowledge	Output	Investment	Consumption	Net Exports	Leisure	Education	Knowledge	Leisure
North	INITIAL	$t=0$	**0.033**	**0.016**	**0.28**	**0.052**	**0.229**	**0**	**0.67**	**0.067**	**0.034**	**1.363**
	TRANSITION	$t=1$	**0.031**	**0.039**	**0.265**	**0.067**	**0.222**	**0**	**0.666**	**0.081**	**0.102**	**1.767**
		$t=2$	**0.04**	**0.042**	**0.179**	**0.064**	**0.246**	**0**	**0.738**	**0.131**	**0.138**	**2.408**
	STEADY STATE	$t \geq 3$	**0.033**	**0.034**	**0.283**	**0.067**	**0.217**	**0**	**0.65**	**0.179**	**0.184**	**3.538**
South	INITIAL	$t=0$	**0.02**	**0.007**	**0.323**	**0.151**	**0.173**	**0**	**0.65**	**0.027**	**0.01**	**0.885**
	TRANSITION	$t=1$	**0.107**	**0.037**	**0.283**	**0.076**	**0.191**	**0.016**	**0.572**	**0.099**	**0.034**	**0.527**
		$t=2$	**0.042**	**0.035**	**0.315**	**0.088**	**0.202**	**0.025**	**0.607**	**0.131**	**0.111**	**1.907**
	STEADY STATE	$t \geq 3$	**0.033**	**0.034**	**0.283**	**0.067**	**0.217**	**0**	**0.65**	**0.179**	**0.184**	**3.538**

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[37] It follows from the optimization program of Section S.2 above that the per capita stocks of physical capital, human capital and knowledge are equalized across the two regions at $t = 2$, whereas all stocks and flows of economic variables are equalized at $t = 3$. See Llavador et al. (2011) for the detailed turnpike analysis of the convergence to the steady state.

Table s.8. The allocation of labor-leisure resources. This table reproduces Table 3 in the main text. (Note: Output = Consumption + Investment + Net Exports)

			Stock of Physical Capital S_t^{kJ}	Stock of Knowledge S_t^{nJ}	Human Capital x_t^{eJ}	Consumption per Capita c_t^J	Consumption per Capita Growth c_t^J / c_0^J	Investment per Capita i_t^J
North	Initial	$t=0$	95.281	22.1	0.067	34.094	1	7.739
	Transition	$t=1$	215.72	62.467	0.081	49.355	1.448	14.97
		$t=2$	273.408	91.016	0.131	66.674	1.956	17.46
	Steady state	$t=3$	371.617	123.708	0.179	77.567	2.275	23.891
		$t=4$	505.101	168.144	0.243	105.429	3.092	32.473
South	Initial	$t=0$	14.739	0.37	0.027	2.177	1	1.899
	Transition	$t=1$	69.465	23.773	0.099	12.784	5.874	5.096
		$t=2$	273.408	91.016	0.131	45.875	21.077	19.979
	Steady state	$t=3$	371.617	123.708	0.179	77.567	35.637	23.891
		$t=4$	505.101	168.144	0.243	105.429	48.438	32.473

Table s.9. The evolution of stocks (physical capital, knowledge and human capital) and flows (consumption and investment).

S.5 Annual and Generational Laws of Motion of Knowledge

Our model is generational, with laws of motion for knowledge given by (s.7), for North, and (s.8)-(s.9), for South, where the investment in knowledge is written in efficiency units of labor. But our calibration uses yearly data, with investment measured in thousands of 2005-international dollars. This appendix obtains the generational laws (s.7), (s.8) and (s.9) from annual laws of motion.

Consider a given generation, Generation *t*, which, it will be recalled, lives for 25 years. A double subscript $t\tau$, $\tau = 1,\ldots,25$, denotes year τ in the life of Generation t. We adopt the following simplifying assumptions. For region J, $J = N,S$: (i) Annual per capita investment in knowledge is constant, written i_t^{nJ} if expressed in monetary units and x_t^{nJ} if expressed in efficiency units of labor; (ii) We take $i_t^{nJ} = \bar{w}x_t^{nJ}$, where $\bar{w}$ denotes the steady state wage for an efficiency unit of labor; (iii) Population remains constant within a generation: $\hat{N}_{t0}^{nJ} = N_{t-1}^{nJ}$ and, for $\tau \geq 1$, $N_{t\tau}^{nJ} = N_t^{nJ}$.

North. Our starting point is the annual law of motion

$$\hat{S}_{t\tau}^{nN} = (1-\hat{\delta}^n)\frac{N_{t,\tau-1}^{N}}{N_{t\tau}^{N}}\hat{S}_{t,\tau-1}^{nN} + \bar{w}x_t^{nN}, \tau = 1,\ldots,25, \qquad (s.16)$$

which incorporates simplifying assumptions (i)-(iii), where $\hat{S}^{nN}_{t\tau}$ denotes the per capita stock of knowledge in North in year τ, with $S^{nN}_{t-1} = \hat{S}^{nN}_{t0}$ and $S^{nN}_{t} = \hat{S}^{nN}_{t,25}$ (i. e., the generational stock is that of the last year of the generation.[38] The iteration of (s.16) gives

$$\hat{S}^{nN}_{t1} = (1-\hat{\delta}^n)\frac{N^N_{t-1}}{N^N_t}S^{nN}_{t-1} + \bar{w}x^{nN}_t,$$

$$\begin{aligned}\hat{S}^{nN}_{t2} &= (1-\hat{\delta}^n)\hat{S}^{nN}_{t1} + \bar{w}x^{nN}_t \\ &= (1-\hat{\delta}^n)^2\frac{N^N_{t-1}}{N^N_t}S^{nN}_{t-1} + (1-\hat{\delta}^n)\bar{w}x^{nN}_t + \bar{w}x^{nN}_t,\end{aligned}$$

$$\begin{aligned}\hat{S}^{nN}_{t3} &= (1-\hat{\delta}^n)\hat{S}^{nN}_{t2} + \bar{w}x^{nN}_t \\ &= (1-\hat{\delta}^n)^3\frac{N^N_{t-1}}{N^N_t}S^{nN}_{t-1} + [(1-\hat{\delta}^n)^2 + (1-\hat{\delta}^n) + 1]\bar{w}x^{nN}_t,\end{aligned}$$

...

$$\hat{S}^{nN}_{t\tau} = (1-\hat{\delta}^n)^\tau\frac{N^N_{t-1}}{N^N_t}S^{nN}_{t-1} + \frac{1-(1-\hat{\delta}^n)^\tau}{\hat{\delta}^n}\bar{w}x^{nN}_t, \tau = 1,...,25, \tag{s.17}$$

and in particular

$$S^{nN}_t \equiv \hat{S}^{nN}_{t25} = (1-\hat{d}^n)^{25}\frac{N^N_{t-1}}{N^N_t}S^{nN}_{t-1} + \frac{1-(1-\hat{d}^n)^{25}}{\hat{d}^n}\bar{w}x^{nN}_t,$$

which is (s.7) for

$$1-d^n = (1-\hat{d}^n)^{25}, \tag{s.18}$$

and

$$k_3 = \frac{1-(1-\hat{d}^n)^{25}}{\hat{d}^n}\bar{w} = \frac{d^n}{\hat{d}^n}\bar{w}. \tag{s.19}$$

South. An argument parallel to the preceding one leads to (s.8).

The generational law of motion for the stock of knowledge of South when $S^{nN}_{t-1} - S^{nS}_{t-1} > 0$ is given by (s.9), which in equality form can be written

$$S^{nS}_t = \left(1-d^n\right)S^{nS}_{t-1}\frac{N^S_{t-1}}{N^S_t} + k_3x^{nS}_t + k_{3d}\left(S^{nN}_{t-1} - S^{nS}_{t-1}\right)x^{nS}_t. \tag{s.20}$$

---

[38] Recall that we denote with a tilde variables in annual terms.

We start from an annual law of motion of knowledge for South where knowledge diffusion from North is a function of both the knowledge gap $S_{t-1}^{nN} - S_{t-1}^{nS}$ inherited from the previous generation and the investment $\overline{w}\hat{x}_t^{nS}$ in knowledge in South in that year, i. e.,

$$\hat{S}_{t\tau}^{nS} = \left(1-\hat{d}^n\right)\frac{\hat{N}_{t,\tau-1}^S}{\hat{N}_{t\tau}^S}\hat{S}_{t,\tau-1}^{nS} + \overline{w}\,x_t^{nS} + \hat{\lambda}\left(1-\hat{d}^n\right)\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)\overline{w}\,x_t^{nS},\ \tau = 1,\ldots,25, \quad \text{(s.21)}$$

where we adopt the simplifying assumptions $\hat{N}_{t0}^{nS} = N_{t-1}^{nS}$ and, for $\tau \geq 1$, $N_{t\tau}^{nS} = N_t^{nS}$, and, as before, $\hat{S}_{t0}^{nS} = S_{t-1}^{nS}$, $\hat{S}_{t,25}^{nS} = S_t^{nS}$. The iteration of (s.20) gives

$$\hat{S}_{t1}^{nS} = \left(1-\hat{d}^n\right)\frac{N_{t-1}^S}{N_t^S}S_{t-1}^{nS} + \overline{w}x_t^{nS} + \hat{\lambda}\left(1-\hat{d}^n\right)\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)\overline{w}x_t^{nS};$$

$$\begin{aligned}
\hat{S}_{t2}^{nS} &= \left(1-\hat{d}^n\right)\hat{S}_{t1}^{nS} + \overline{w}x_t^{nS} + \hat{\lambda}\left(1-\hat{d}^n\right)\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)\overline{w}x_t^{nS} \\
&= \left(1-\hat{d}^n\right)\left[\left(1-\hat{d}^n\right)\frac{N_{t-1}^S}{N_t^S}S_{t-1}^{nS} + \overline{w}x_t^{nS} + \hat{\lambda}\left(1-\hat{d}^n\right)\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)\overline{w}x_t^{nS}\right] + \overline{w}x_t^{nS} + \hat{\lambda}\left(1-\hat{d}^n\right)\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)\overline{w}x_t^{nS} \\
&= \left(1-\hat{d}^n\right)^2\frac{N_{t-1}^S}{N_t^S}S_{t-1}^{nS} + \left[\left(1-\hat{d}^n\right)+1\right]\overline{w}x_t^{nS} + \hat{\lambda}\left(1-\hat{d}^n\right)\left[\left(1-\hat{d}^n\right)+1\right]\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)\overline{w}x_t^{nS};
\end{aligned}$$

…

$$\hat{S}_{t\tau}^{nS} = \left(1-\hat{d}^n\right)^{\tau}\frac{N_{t-1}^S}{N_t^S}S_{t-1}^{nS} + \overline{w}x_t^{nS}\sum\nolimits_{\theta=0}^{\tau-1}\left(1-\hat{d}^n\right)^{\theta} + \hat{\lambda}\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)\overline{w}x_t^{nS}\sum\nolimits_{\theta=0}^{\tau-1}\left(1-\hat{d}^n\right)^{\theta}, \tau = 1,\ldots,25,$$

…

$$\begin{aligned}
S^{nS} \equiv \hat{S}_{t25}^{nS} &= \left(1-\hat{d}^n\right)^{25}\frac{N_{t-1}^S}{N_t^S}S_{t-1}^{nS} + \overline{w}x_t^{nS}\sum_{\theta=0}^{24}\left(1-\hat{d}^n\right)^{\theta} + \hat{\lambda}\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)\overline{w}\,x_t^{nS}\sum_{\theta=0}^{24}\left(1-\hat{d}^n\right)^{\theta} \\
&= \left(1-\hat{d}^n\right)^{25}\frac{N_{t-1}^S}{N_t^S}S_{t-1}^{nS} + \frac{1-\left(1-\hat{d}^n\right)^{25}}{\hat{d}^n}\overline{w}x_t^{nS} + \hat{\lambda}\frac{1-\left(1-\hat{\delta}^n\right)^{25}}{\hat{\delta}^n}\left(S_{t-1}^{nN} - S_{t-1}^{nS}\right)\overline{w}\,x_t^{nS},
\end{aligned}$$

which is (s.20) for $1-d$ as given by (s.18), k_3 as given by(s.19), and for $k_{3d} = \hat{\lambda}k_3$.

S.6 Sensitivity Analysis

S.6.1 Sensitivity to the Value of Technological Diffusion ($\hat{\lambda}$).

We choose a conservative low value of $\hat{\lambda} = 0.01$ for our calibrated model. Figures s.1 and s.2 below shows that the convergent utility path as well as the magnitudes of stocks and flows along the optimal path move smoothly with changes in the value of $\hat{\lambda}$ above and below our set value ($\hat{\lambda}$ = 0, 0.005, 0.01, 0.02, 0.03).

Furthermore, Figure s.1 shows that technological diffusion is not a necessary condition for our results. Setting $\hat{\lambda} = 0$, we still obtain a feasible path to a sustained 1.2% annual growth satisfying all our conditions. As might be expected, the welfare of the second generation in South increases with $\hat{\lambda}$, while the steady state is unaffected since North and South converge there.

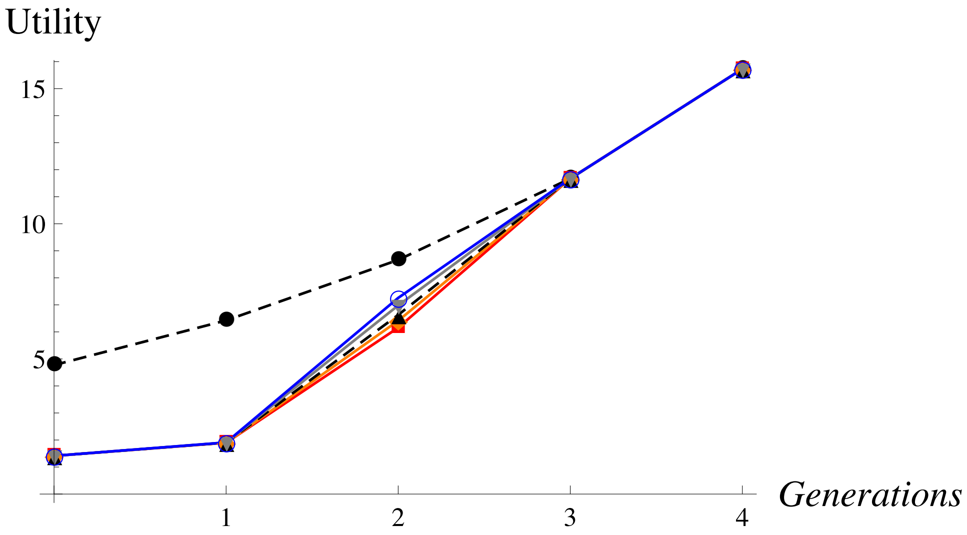


Figure s.1. Sensitivity analysis to different values of $\hat{\lambda}$. Convergent utility paths for $\hat{\lambda} = 0$, 0.005, 0.01, 0.02, 0.03. Our calibrated value is $\hat{\lambda} = 0.01$, whose path is represented by the discontinuous line.

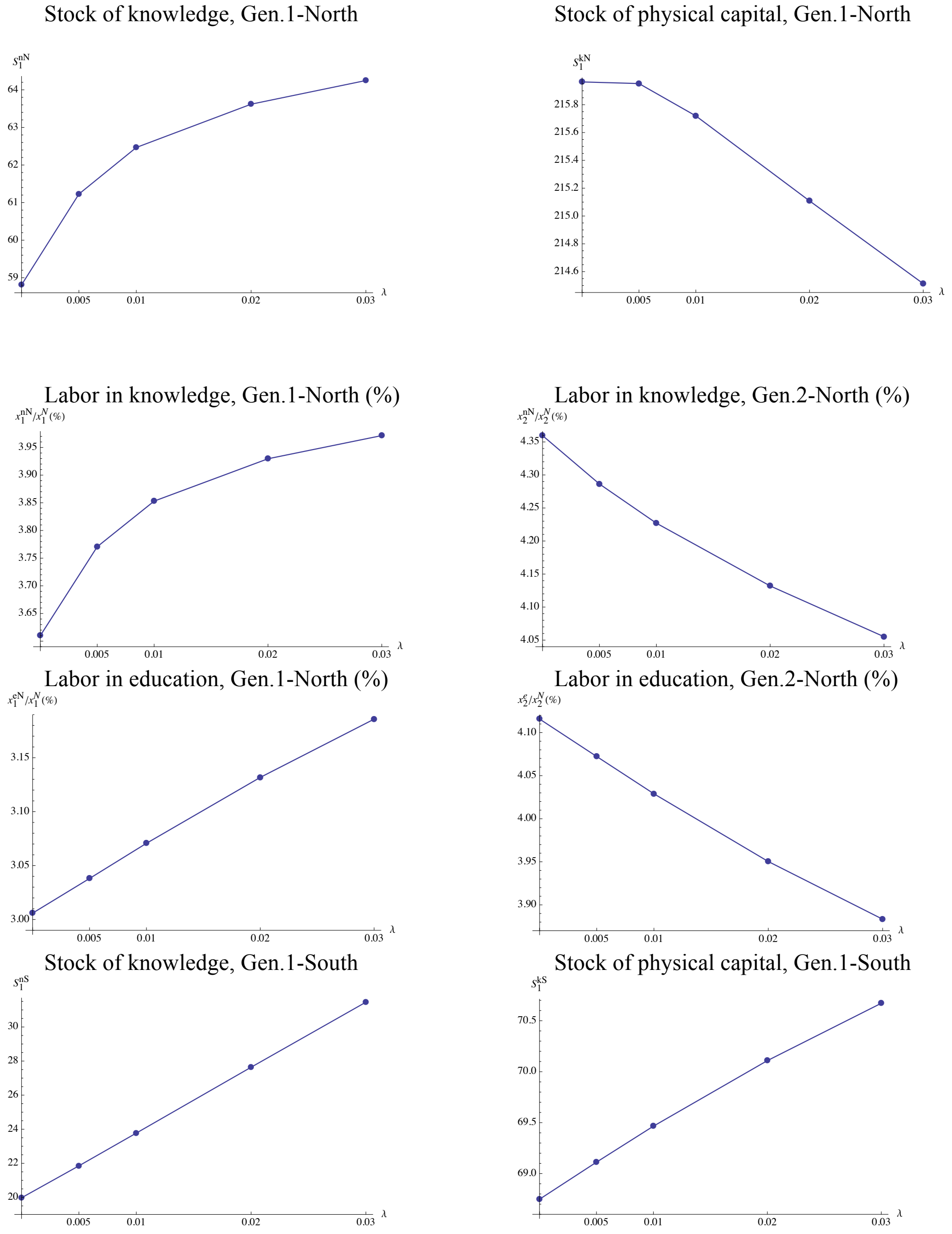


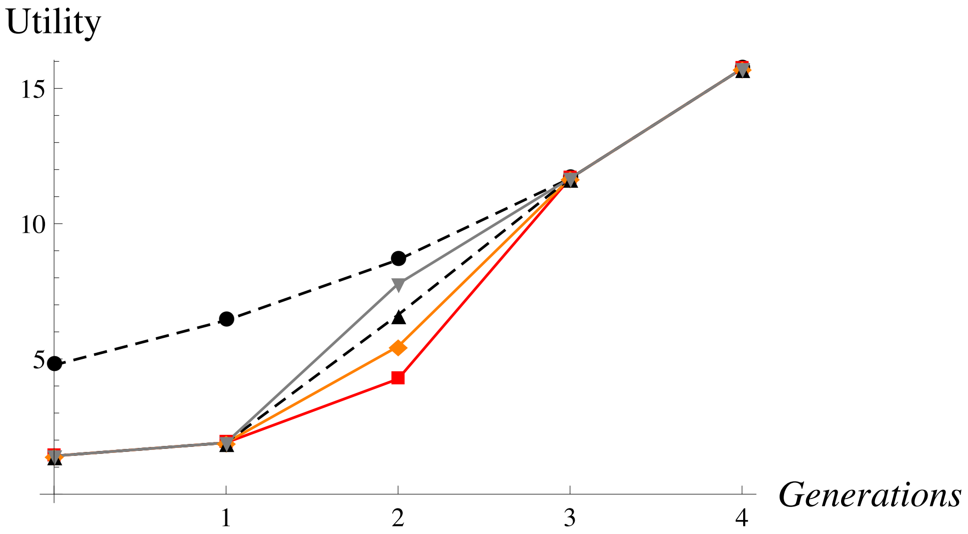
Figure s.2. Sensitivity analysis to different values of $\hat{\lambda}$. Convergent utility paths and the dependence of relevant stocks and flows of $\hat{\lambda}$ along the optimal paths.

S.6.2 Sensitivity to Human Capital Values: Initial Fraction of Labor in Education in South $\left(x_0^{eS}\right)$ and the Productivity of Education (ξ).

Human capital is the engine of our model, thus it is not surprising that the initial amount of human capital and the productivity of education play an important role for sustaining growth.

Our calibration takes the initial labor force in South to be 5.6% of the total labor force in 2005. Figure s.3 shows feasible paths that sustain an annual 1% growth rate satisfying our requirements of convergence. We vary the labor force in education in South between 5.4% and 5.7% of total labor. Sustainable growth and convergence are not feasible for values below 5.4%, while values above 5.7% could sustain much higher rates of growth.

Convergent paths for $x_0^{eS} \Big/ \left(x_0^{S} - x_0^{lS}\right)$ = 0.054, 0.055, 0.056 and 0.057.



Labor in education, Gen. 1 (efficiency units) Labor in education, Gen. 2 (% of total labor)

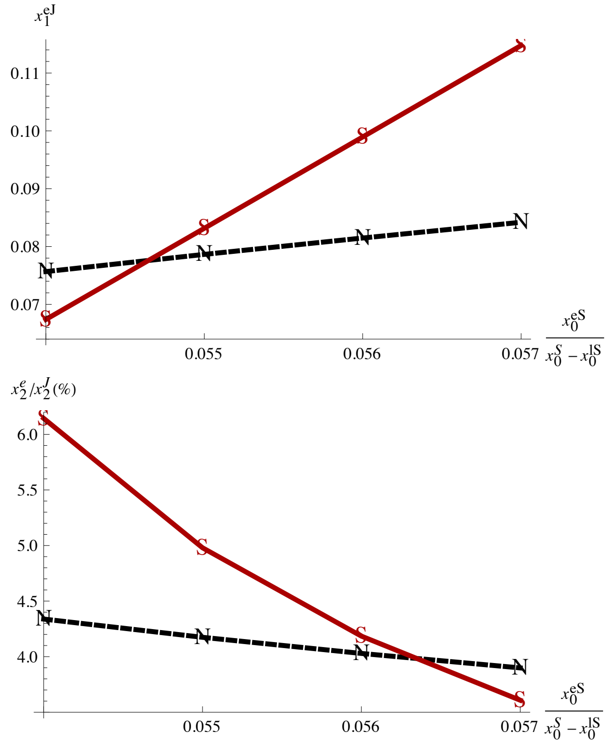
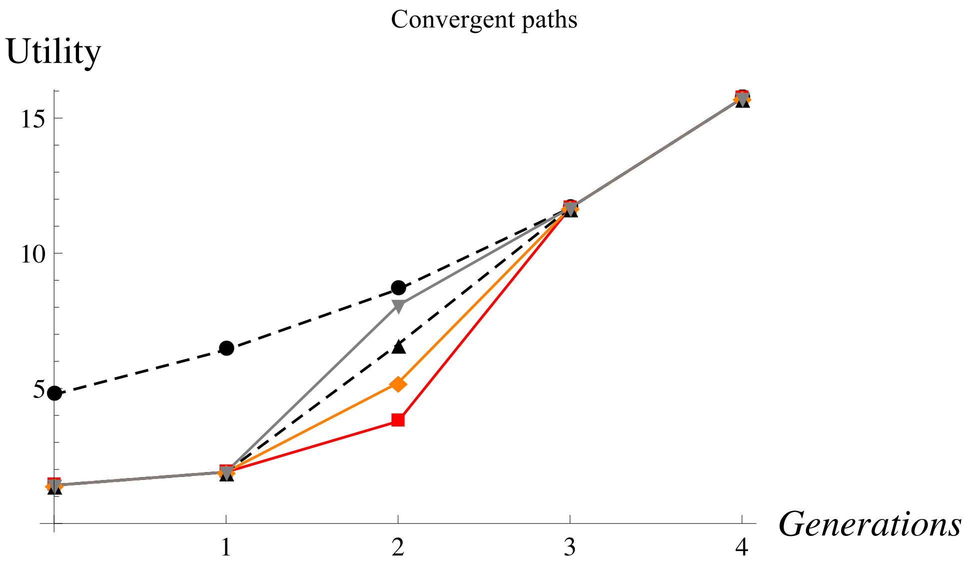
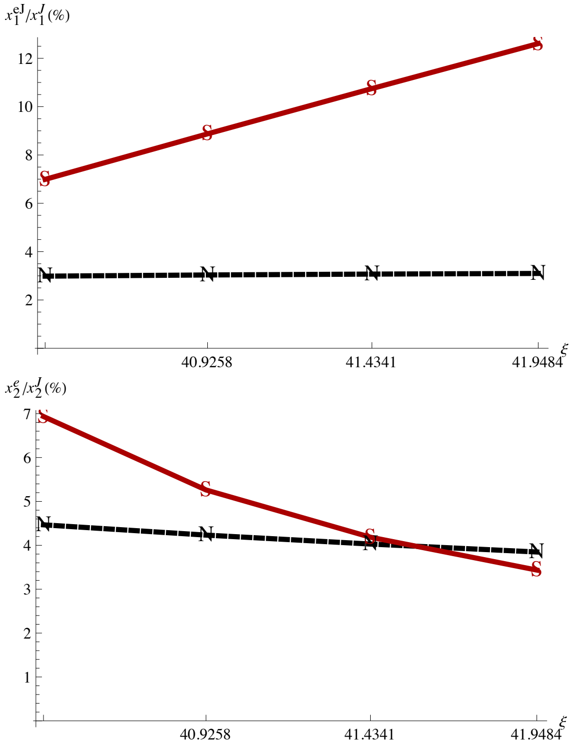


Figure s.3. Sensitivity analysis to different values of the fraction of labor force devoted to education in South for the initial period. The first graph presents the convergent utility paths (with generations in the horizontal axis). Higher values of $x_0^{eS}/\left(x_0^S - x_0^{lS}\right)$ correspond to higher levels of the utility of Generation 2 in South. The bottom graphs show the effect on the amount of labor in education (in efficiency units) and in knowledge (as percentage of the total labor force). Our calibration uses the value $x_0^{eS}/\left(x_0^S - x_0^{lS}\right) = 0.056$.


Convergent paths

Labor in education, Gen. 1 (% of total labor) Labor in education, Gen. 2 (% of total labor)



Labor in knowledge, Gen. 1 (% of total labor) Labor in knowledge, Gen. 2 (% of total labor)

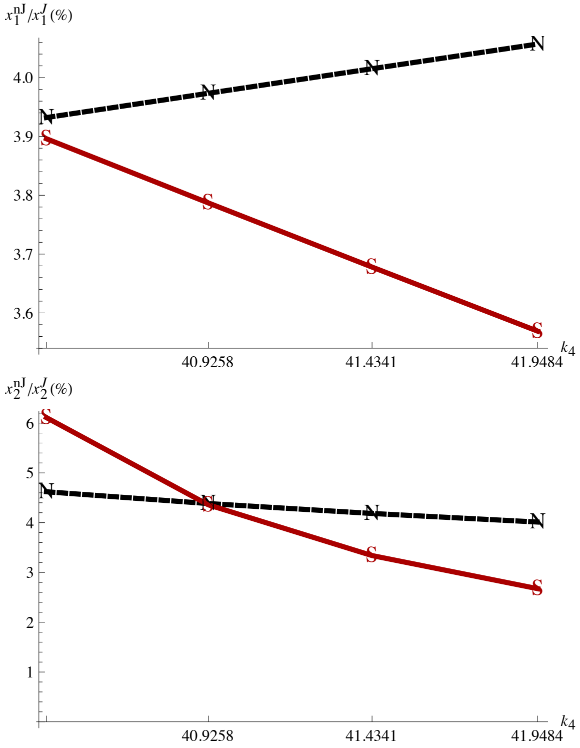


Figure s.4. Sensitivity analysis to different values of ξ calibrated from estimates of annual growth rates of the US productivity of labor ranging from 1.12% to 1.35%. Our calibration uses a 1.3% growth rate with the associated ξ = 41.4341. (See Section S.3.2.10.)

Figure s.4 represents the effects of variation in the productivity of labor ξ. The implications are similar to those from variations in x_0^{eS}.[39] If the education function is not sufficiently productive we cannot sustain growth with convergence, while for larger values of ξ we could find feasible paths that sustain higher growth rates while satisfying our conditions of convergence.

S.6.3 Sensitivity to Economic or Market Damages (θ_m).

Our calibration of θ_m is based on the economic or market damages from a temperature increase of 3.4ºC, estimated at 2.8% of global GDP. We have represented in Figure s.5 the optimal utility paths for a range of economic damages that goes from no damages to 28% of global GDP (ten times the value used in our calibration). As expected, increases in economic damages (and so increases in the absolute value of θ_m) result in lower welfare for Generation 2 in South, but the effects are negligible unless we shift to radically larger costs. Our calculations show that we could sustain 1% growth even for values of θ_m associated with economic damages of 42% of global GDP.

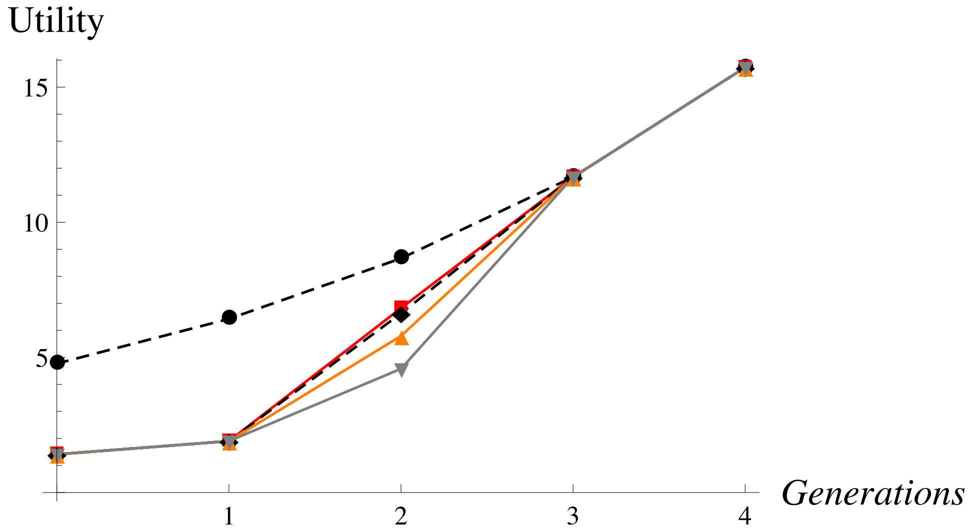


Figure s.5. Optimal utility paths for different values of θ_m calculated from different estimates of the economic damages associated with a 3.4ºC temperature increase. They range from no damages (the highest level of welfare) to economic damages equal to 28% of

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[39] Observe that the amount of human capital inherited by the first generation in South (x_1^S) is a datum for the optimization program as it is determined by the actual human capital devoted to education x_0^{eS} and the parameter ξ, capturing the productivity education ($x_1^S = N_0^S / N_1^S \, \xi \, x_0^{eS}$). This is indeed the reason behind our choice of optimizing the welfare of the second generation in South, despite the fact that the first generation in South is the worst-off generation.

global GDP (ten times the value used in our calibration). The dotted line represents the optimal path corresponding to our calibration.

S.6.4 Alternative Values for the Climate Sensitivity Parameter.

Our analysis does not incorporate a climate model. However, we use the value of climate sensitivity to calibrate α_m, $\hat{S}^m$ and θ_m. For our calibration, we use the common value of 3ºC, the best estimate in the IPCC. However many scientists claim that this value is too low. Consequently we have computed the optimal paths associated with larger values, namely σ=3, 4, 5 and 6 (Figure s.6).[40] We observe that higher climate sensitivity values slightly decrease the welfare of the second generation in South, but the effects are small.

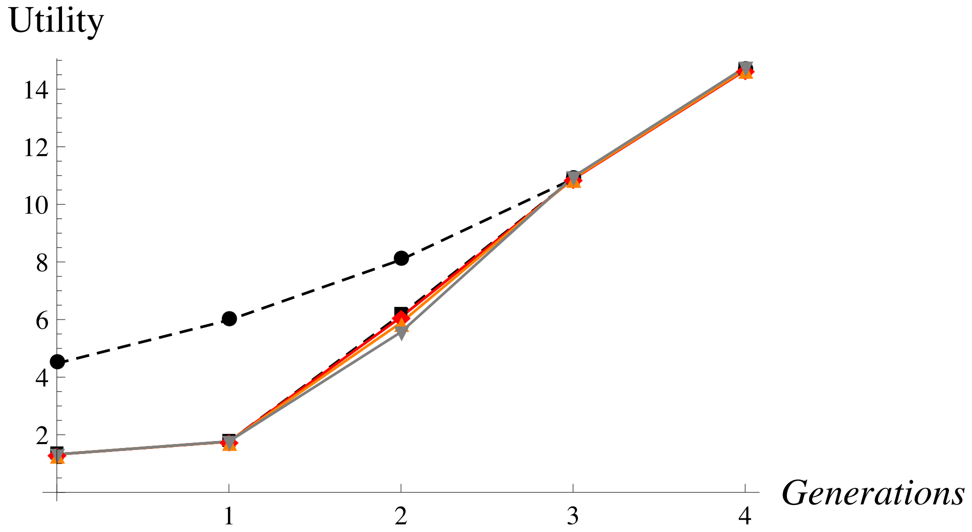

Figure s.6. Optimal paths for different climate sensitivity parameter values. Dashed lines represent the optimal path corresponding to a climate sensitivity of 3ºC, as used in our calibration. For North, we only depict the path from our calibration; nevertheless convergence occurs as well for the other cases, albeit at slightly different levels of utility.

S.6.5 Transition Path and Steady State in the Absence of Interregional Output Flows

In this section we compute the convergent path and the steady-state allocation in the absence of commodity flows between North and South. Tables s.10 and s.11 compare the cases with and without flows for a sustainable 1.18% annual growth rate.[41]

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[40] The IPCC Fourth Assessment Report (AR4) estimates that climate sensitivity is likely to be in the range 2 to 4.5°C, with a best estimate of about 3ºC, and this is the value most widely used by the current literature. However, the IPCC also indicates that values substantially higher than 4.5°C cannot be excluded, with estimates ranging from 1.5 to 9ºC. For example, Hansen et al. (2008) estimate a warming of 3ºC with only fast feedback processes and of 6ºC if slower feedback effects are included.

[41] Impeding output flows suppose an additional constraint to the maximization program and a 1.2% annual growth is not sustainable anymore. We use instead the paths for a

The steady state values of the variables (stocks for $t = 2$, and all economic variables for $t \geq 3$) do not depend on whether exports are allowed or not, but the values during the transition do. The differences between the ‘no output flows’ and ‘output flows’ regimes are more noticeable for $t = 2$, where net exports, from South to North, are large. As should be expected, in the presence of output flows, North reduces the fraction of its labor-leisure resource that it devotes to the production of output (by 46%) (see Table s.10), while increasing the fractions devoted to leisure, education and the investment in knowledge. On the other hand, South, the net exporter, increases the fraction of the labor-leisure resource that it spends on education and knowledge, mainly at the cost of leisure.

				Labor allocation (fraction of total labor-leisure available)							Labor (in efficiency units)		
				Education	Knowledge	Output	Investment	Consumption	Net Exports	Leisure	Education	Knowledge	Leisure
North	INITIAL	$t = 0$		**0.033**	**0.016**	**0.28**	**0.052**	**0.229**	**0**	**0.67**	**0.067**	**0.034**	**1.363**
	TRANSITION	$t = 1$	No Output Flows	**0.034**	**0.037**	**0.288**	**0.074**	**0.214**	**0**	**0.641**	**0.09**	**0.099**	**1.7**
			Output Flows	**0.031**	**0.039**	**0.268**	**0.068**	**0.221**	**0**	**0.662**	**0.082**	**0.103**	**1.757**
		$t = 2$	No Output Flows	**0.036**	**0.038**	**0.272**	**0.054**	**0.218**	**0**	**0.654**	**0.129**	**0.137**	**2.368**
			Output Flows	**0.04**	**0.042**	**0.186**	**0.064**	**0.244**	**0**	**0.733**		**0.136**	**2.398**
	STEADY STATE	$t \geq 3$		**0.033**	**0.034**	**0.283**	**0.067**	**0.217**	**0**	**0.65**	**0.175**	**0.181**	**3.485**
South	INITIAL	$t = 0$		**0.02**	**0.007**	**0.323**	**0.151**	**0.173**	**0**	**0.65**	**0.027**	**0.01**	**0.885**
	TRANSITION	$t = 1$	No Output Flows	**0.06**	**0.038**	**0.281**	**0.075**	**0.207**	**0**	**0.62**	**0.056**	**0.035**	**0.571**
			Output Flows	**0.115**	**0.037**	**0.278**	**0.075**	**0.19**	**0.014**	**0.57**	**0.106**	**0.034**	**0.524**
		$t = 2$	No Output Flows	**0.073**	**0.063**	**0.332**	**0.155**	**0.177**	**0**	**0.532**	**0.129**	**0.111**	**0.938**
			Output Flows	**0.038**	**0.032**	**0.311**	**0.083**	**0.206**	**0.022**	**0.618**		**0.109**	**2.081**
	STEADY STATE	$t \geq 3$		**0.033**	**0.034**	**0.283**	**0.067**	**0.217**	**0**	**0.65**	**0.175**	**0.181**	**3.485**

Table s.10. The allocation of labor-leisure resources with and without interregional output flows for a sustainable 1.18% annual growth rate.

1.8% annual growth, the maximum sustainable growth rate with and without transfers satisfying our conditions.

				Stock of Physical Capital S_t^{kJ}	Stock of Knowledge S_t^{nJ}	Human Capital x_t^{eJ}	Consumption per Capita c_t^J	Consumption per Capita Growth c_t^J / c_0^J	Investment per Capita i_t^J
North	INITIAL	$t = 0$		95.281	22.100	0.067	34.094	1	7.739
	TRANSITION	$t = 1$	No Output Flows	259.932	60.744	0.090	52.591	1.543	18.34
			Output Flows	219.094	62.709	0.082	49.159	1.442	15.227
		$t = 2$	No Output Flows	270.565	90.079	0.129	66.841	1.96	16.55
			Output Flows				65.181	1.912	17.19
	STEADY STATE	$t = 3$		365.887	121.814	0.175	76.394	2.241	23.5
		$t = 4$		494.791	164.730	0.237	103.307	3.03	31.78
South	INITIAL	$t = 0$		14.739	0.370	0.027	2.177	1	1.8994
	TRANSITION	$t = 1$	No Output Flows	53.315	24.426	0.056	10.708	4.92	3.865
			Output Flows	68.236	23.493	0.106	12.711	5.84	5.003
		$t = 2$	No Output Flows	270.565	90.079	0.129	22.871	10.508	19.963
			Output Flows				48.978	22.502	19.777
	STEADY STATE	$t = 3$		365.887	121.814	0.175	76.394	35.098	23.5
		$t = 4$		494.791	164.730	0.237	103.307	47.463	31.78

Table s.11. The evolution of stocks (physical capital, knowledge and human capital) and flows (consumption and investment) with and without interregional output flows for a sustainable 1.18% annual growth rate.

S.6.6 Transition Path when Maximizing the Utiliy of Generation 1 in South.

We have computed the optimal path for the maximization of the utility of Generation 1 in South, the worst-off generation. The program is then:

maximize Λ_1^S subject to:

$$\left(c_1^S\right)^{\alpha_c}\left(x_1^{lS}\right)^{\alpha_l}\left(S_1^n\right)^{\alpha_n}\left(\hat{S}^m - S_1^{m*}\right)^{\alpha_m} - \Lambda_1^S \geq 0,$$

$$\left.\begin{aligned}
&\left(c_2^S\right)^{\alpha_c}\left(x_2^{lS}\right)^{\alpha_l}\left(S_2^{nS}\right)^{\alpha_n}\left(\hat{S}^m - S_2^{m*}\right)^{\alpha_m} - \left(1+\rho\right)\Lambda_1^S \geq 0,\\
&\left(c_1^N\right)^{\alpha_c}\left(x_1^{lN}\right)^{\alpha_l}\left(S_1^{nN}\right)^{\alpha_n}\left(\hat{S}^m - S_1^{m*}\right)^{\alpha_m} - \left(1+\rho\right)\Lambda_0^N \geq 0,\\
&\left(c_2^N\right)^{\alpha_c}\left(x_2^{lN}\right)^{\alpha_l}\left(S_2^n\right)^{\alpha_n}\left(\hat{S}^m - S_2^{m*}\right)^{\alpha_m} - \left(1+\rho\right)^2\Lambda_0^N \geq 0,\\
&\left(c_3\right)^{\alpha_c}\left(x_3^l\right)^{\alpha_l}\left(S_3^n\right)^{\alpha_n}\left(\hat{S}^m - S^{m*}\right)^{\alpha_m} - \left(1+\rho\right)^3\Lambda_0^N \geq 0,
\end{aligned}\right\}\text{utility growth,}$$

and the remaining economic and climate constraints in the optimization program of

section S.2.

Figure s.7 and Table s.11 present the transition path for a 1.2% annual growth rate and compare it with the one obtained when maximizing the utility of Generation 2 in South (see section S.4). The convergence of South and North in Generation 3 is independent of the maximization program. Maximizing Generation 1's utility for a sustainable 1.2% annual growth rate implies a relatively small increase in the utility of Generation 1 of 6%, especially compared with the fall of 59% in the utility of Generation 2. This is the reason why we opted to maximize the utility of Generation 2 in South, obtaining the smoother transition path, as represented by the red, solid path in Figure s.7.

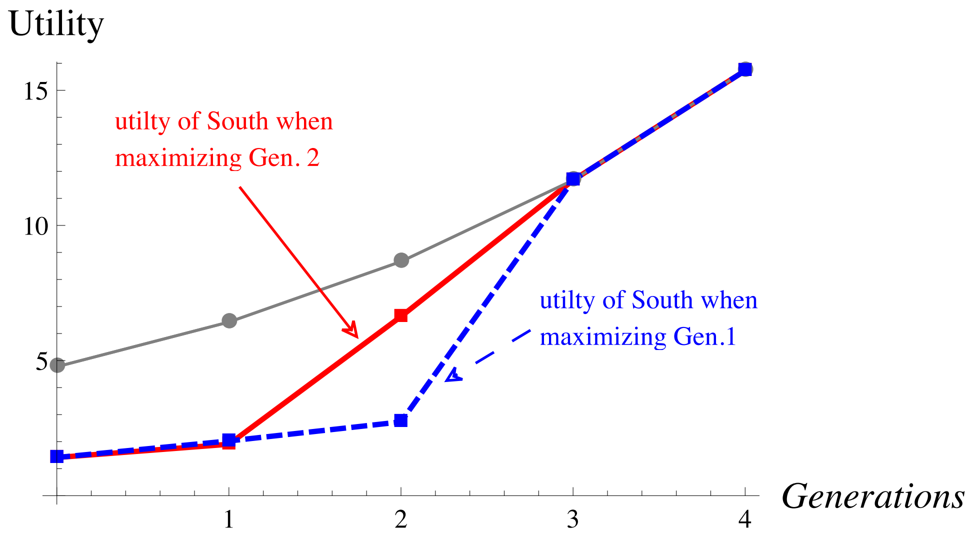
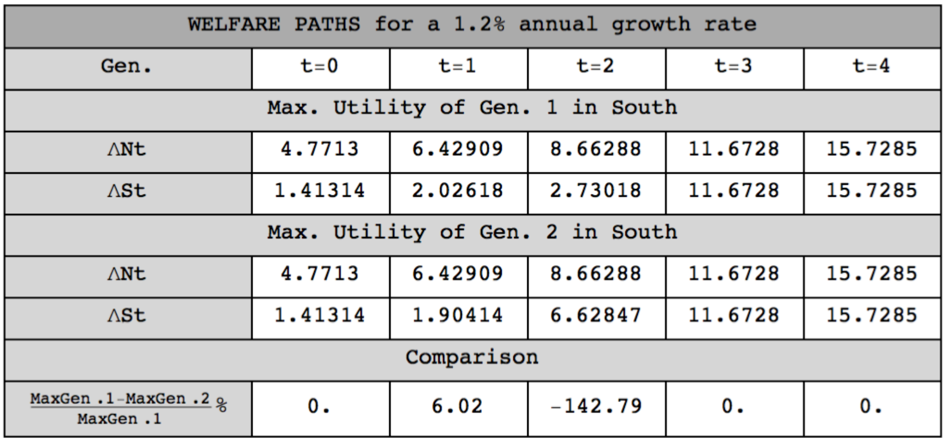


Figure s.7. Optimal paths for the two optimization programs: maximizing the utility of the first or the second generation in South. The dotted, blue line represents utility of South when optimizing for the first generation. The solid, red line represents the utility of South when optimizing for the second generation.



WELFARE PATHS for a 1.2% annual growth rate					
Gen.	t=0	t=1	t=2	t=3	t=4
Max. Utility of Gen. 1 in South					
ΛNt	4.7713	6.42909	8.66288	11.6728	15.7285
ΛSt	1.41314	2.02618	2.73018	11.6728	15.7285
Max. Utility of Gen. 2 in South					
ΛNt	4.7713	6.42909	8.66288	11.6728	15.7285
ΛSt	1.41314	1.90414	6.62847	11.6728	15.7285
Comparison					
$\frac{\text{MaxGen .1}-\text{MaxGen .2}}{\text{MaxGen .1}}\%$	0.	6.02	-142.79	0.	0.

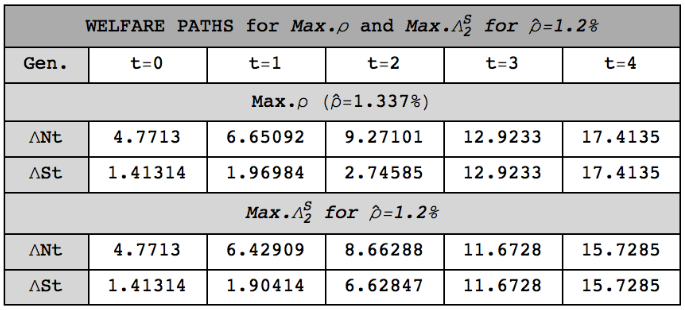
Table s.11 Optimal paths when maximizing the utility of the first or the second generation in South

S.7 Transition Path for the Maximum Sustainable Growth Rate

In this section we report the results from maximizing the growth rate that can be sustained for all generations in all regions, conditional on the economic and climate constraints (as specified in section S.2):

$$\max \rho \qquad \text{s.t.} \quad u_t^J \geq (1+\rho)u_{t-1}^J \qquad \text{for } t = 1,2,3;\ J = N,S,$$

and subject to convergence in three generations, and the sustainability and feasibility constraints.[42]



WELFARE PATHS for *Max.*ρ and *Max.*Λ_2^S *for* $\hat{\rho}$*=1.2%*					
Gen.	t=0	t=1	t=2	t=3	t=4
Max.ρ ($\hat{\rho}$=1.337%)					
ΛNt	4.7713	6.65092	9.27101	12.9233	17.4135
ΛSt	1.41314	1.96984	2.74585	12.9233	17.4135
Max.Λ_2^S *for* $\hat{\rho}$*=1.2%*					
ΛNt	4.7713	6.42909	8.66288	11.6728	15.7285
ΛSt	1.41314	1.90414	6.62847	11.6728	15.7285

a) Optimal paths.

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[42] Observe that if we denote by $\bar{\rho}$ the maximum growth rate, then the optimal path is equivalent to the path we would obtain from maximizing the utility of Generation 1 in South or Generation 2 in South for that given growth rate $\bar{\rho}$.

Maximum growth vs. 1.2% annual growth rate					
Generation	t=0	t=1	t=2	t=3	t=4
$\frac{\text{Max}\rho - \text{MaxGen .2}}{\text{Max}\rho}$ % (South)	0.	3.34	-141.4	9.68	9.68
$\frac{\text{Max}\rho - \text{MaxGen .2}}{\text{Max}\rho}$ % (North)	0.	3.34	6.56	9.68	9.68

b) Utility gains and loses.

Table s.12 Optimal path for the maximum growth versus the optimal path for maximizing the utility of the second generation in South for a 1.2% annual growth rate.

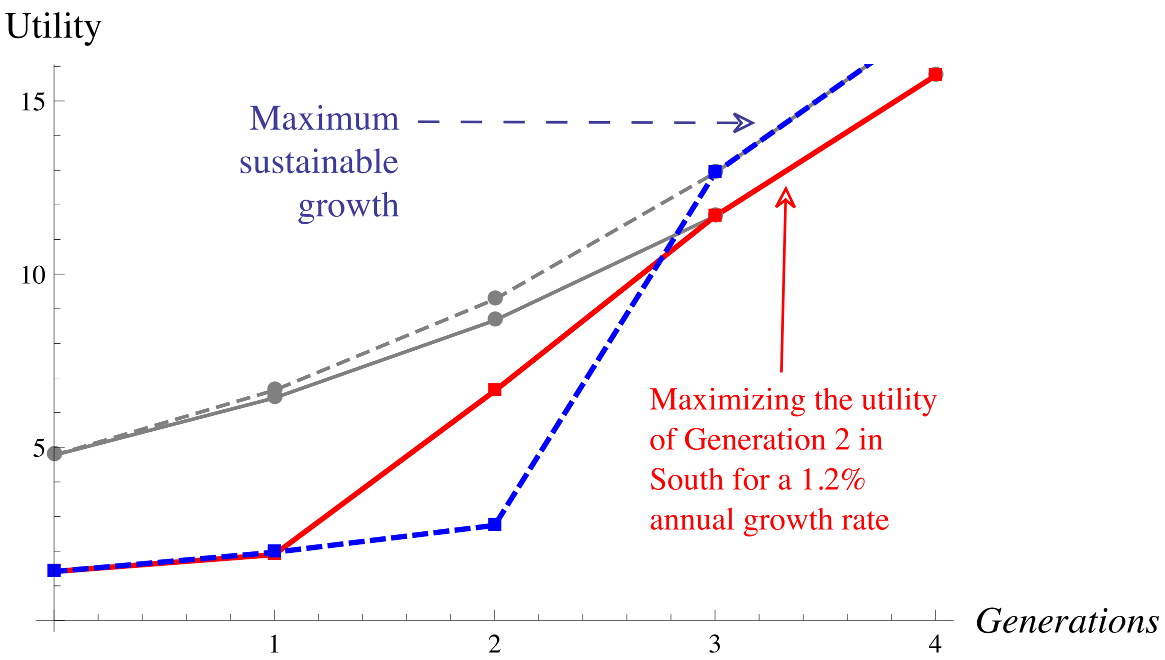
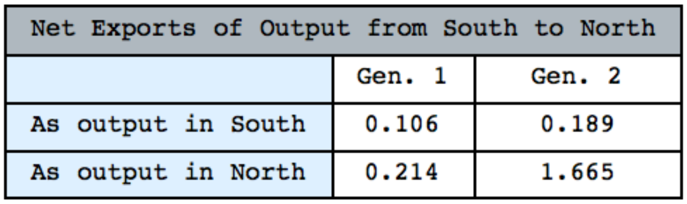


Figure s.8. Maximizing growth (dashed lines) versus optimizing the utility of the second generation in South for a 1.2% annual growth rate (solid lines).

The maximum sustainable growth rate is a 1.337% per annum. Figure s.8 and Table s.12 present the utility paths for the maximum growth rate and compare them with the 1.2% annual growth rate path in the text. The growth maximization path generate a small increase in the utility of Generation 1 in South (of around 3%), a moderate increase in the utility of Generation 2 in North and all generations after 2 (around 7% and 10%, respectively), and impose a very large cost for Generation 2 in South of around 141% (see Table s.12.b).

Moreover, the transition path for the maximum sustainable growth rate (an annual 1.337%) entails huge exports of the commodity from South to North: on the order of 166% of domestic output in North or 21% of domestic output in South for Generation 2 (see Table s.13).



Net Exports of Output from South to North		
	Gen. 1	Gen. 2
As output in South	0.106	0.189
As output in North	0.214	1.665

Table s.13 Net commodity exports from South to North along the transition path for the maximum growth program.

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