NORTH-SOUTH CONVERGENCE AND THE ALLOCATION OF CO_2 EMISSIONS

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North-South convergence and the allocation of CO_2 emissions

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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% per year by 2080, while global CO_2 emissions are restricted to the Representative Concentration Pathway RCP3-PD scenario: a conservative path that leads to the stabilization of concentrations under 450 ppm CO_2, providing an expected temperature change not exceeding 2ºC.

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

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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% and 2.8% 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: Climate change, sustainability, North-South convergence, international negotiations.

JEL Classification: D63, F53, O40, O41, Q50, Q54, Q56

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 follows the Representative Concentration Pathway RCP3-PD, which represents the very low GHG concentration levels scenario in the IPCC's Fifth Assessment Report (AR5), and provides an expected temperature change not exceeding the 2ºC.

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, 2011) of the United Nations Framework Convention on Climate Change (UNFCCC) produced a non-binding agreement, reaffirmed in COP-18 (Doha) and COP-19 (Warsaw), to reach a deal by the COP-21 (Paris) in 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, following the RCP3-PD.

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 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 (Wagner 2011). We comment on the generalization to a multi-region world in the concluding section,

Our analysis is normative. We adopt two constraints:

(1) the usual resource and technology restrictions;

(2) the condition that world emissions follow the low emission path prescribed by the RCP3-PD, stabilizing temperature increase below 2ºC,

and look for paths of region-by-region emissions and 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.[1] 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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[1] Maximizing Generation 1's utility for a sustainable 1% annual growth rate implies a 3.5% increase in the utility of Generation 1 and a fall of 85.6% in the utility of Generation 2. Section S.6.6. in the Appendix presents the transition path from maximizing Generation 1's utility while growing at a sustainable 1% 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 those 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 proposal of convergence in three generations is based on Thomas Schelling's focal-point approach to bargaining (Schelling 1960; Colman 2006): there is a clear focal point in a bargaining problem, and this emerges as the agreement. We propose that 'preserving the date of convergence' may be a focal point in the climate-change bargaining problem.

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.

Our argument is political. 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 $y^{US} = \$46{,}179$ and $y^{Ch} = \$8{,}564$ (2010 figures, constant 2010 international dollars PPP) and $\left(g^{US}, g^{Ch}\right) = \left(0.02, 0.045\right)$, equation [1] solves to $T^* \approx 70$ years.[2] 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.[3] The only agreement that will not be rejected by one side or the other is to allocate emissions so that the growth rates preserve the estimated convergence date.

One might protest that agreeing upon what the date of convergence would have been under BAU is extremely difficult. But one does not have to look that far into the future. If in each five year period (say), the *ratio of growth factors* $\frac{1+g^{Ch}}{1+g^{US}}$ *is maintained* equal to what it would have been under BAU, then the date of convergence will be unchanged. To see this, imagine multiplying both growth factors by a constant r, and note that the date of convergence, now defined by the equation:

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

is exactly the same as before. Therefore, the problem of allocating emissions inter-regionally can be solved sequentially, without every having the estimate the putative convergence date.

We do not have a proof that *preserving the date of convergence* is a focal point. We propose that it may be so. In fact, proposing this may help make it so. Thus, we view

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[2] 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.

[3] We thank Robert Keohane for this point.

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.[4] Consider, first, a simpler world, with only one region, inhabited by one representative household at each period (generation), indexed by $t = 1,2,\dots$. 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 $u = (u_1, u_2, ...)$ which can be achieved, given current endowments and technology, and constraining economic activity to stay on a given path of carbon emissions. Pure sustainability directs us to solve this program:

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

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:

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

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

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[4] In other contexts, sustainability applies to maintaining some index of natural resources. Here we follow Solow's (1993) conception of sustainability: "I will assume that a sustainable path for the national economy is one that allows every future generation the option of being as well off as its predecessors" (p.168).

the *discounted utilitarian* approach of Nordhaus (2008, 2013) and Stern (2007), as discussed in Llavador, Roemer and Silvestre (2011, 2013) and Roemer (2011).

The application of the sustainabilitarian approach to a world with two regions is based upon a turnpike theorem that is proved for program [2] in Llavador, Roemer and Silvestre (2010). In the fleshed-out economic model of which programs [2] and [3] are abstract versions, 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 $\Gamma\left(\rho, e^*, S^{m*}\right) \subset \Re^3_+$ 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.[5] 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.

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.

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[5] 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.

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% 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 4.5% to 2.8%. 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, 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. South can benefit from knowledge diffusion as long as North has more knowledge than South (Eaton and

Kortum 1999; Keller 2004). Knowledge in South depreciates at a certain rate and increases by new knowledge produced by knowledge workers in South plus the knowledge diffused from North. This diffusion depends on the knowledge gap between North and South and also on the level of employment of knowledge workers in South, the so called Nelson-Phelps technological catch-up hypothesis (Nelson and Phelps 1966; Benhabib and Spiegel 2005).

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 human capital, physical capital, knowledge and biospheric quality inherited from period *t*, there will be, as a result of production in period $t+1$, new endowments of human capital, physical 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.[6] 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.) Educated leisure and knowledge also serve as proxies for the health level. 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.

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[6] 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.

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; Stern 2007). We believe this practice is too narrow in not appreciating the *direct* value to humans of education, knowledge and biospheric quality (Llavador, Roemer and Silvestre 2013). These arguments are *not solely* important because of their usefulness in commodity production.[7]

Date 0 is taken as 2010, and a generation is understood to live for 25 years. For the path of CO_2 emissions, we rely on the Representative Concentration Pathways (RCP), a set of consistent projections of the components of radiative forcing extending until 2100 prepared for the IPCC's Fifth Assessment Report (AR5).[8] In particular, we adopt a path based on RCP3-PD (a.k.a. RCP2.6), the only RCP that provides an expected temperature change not exceeding the 2ºC and is representative of scenarios of very low GHG concentration levels. Its radiative forcing level first peaks at 3.1 W/m^2 in the middle of the century and then returns to 2.6 W/m^2 by 2100, thus its name: "Peak & Decline" (van Vuuren et al 2007; van Vuuren et al 2011). Our setting requires constant annual emissions within a generation as well as stabilized emissions and concentration after year 2060. Hence we adapt the emissions in RCP3-PD to these requirements and run them in MAGICC 6.4.[9] Figure 1 pictures our path and shows that it is a very good approximation to the original RCP3-PD both in the levels of CO_2 concentration and in temperature change.

[Figure 1 here]

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[7] 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.

[8] The RCPs are described in the 2011 special issue of Climatic Change. For a summary see Meinshausen et al (2011) and van Vuuren et al (2011). The data can be obtained from http://www.pik-potsdam. de/~mmalte/rcps and also from MAGICC6 (http://www.magicc.org/)

[9] We keep emissions constant for all GHGs after 2060, except for land-use-change emissions, which decline following the original path.

The projected populations of the global North and South are taken from United Nations (2013). Population is assumed to be unchanging after 2060.

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 2010, estimated from standard sources.

As mentioned earlier, knowledge diffuses 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 2085), 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% *per year*, *starting from the* $t = 0$ (*year* 2010) *reference level*, *with North and South converging in* 75 *years* ($t = 3$), *while keeping global* CO_2 *emissions at the levels based on RCP3-PD. At convergence, North and South reach a common steady state where all economic variables grow at a constant rate. In particular, the per capita levels of the stock of knowledge, investment in knowledge and emissions are then equalized across regions. During the transition, Northern utility grows at* 1% *per year and after convergence, both regions grow at that rate forever.*[10]

However, there are no feasible solutions to the program at which both North and South grow at sustainable rates equal to or higher than 1.1% *per year.*

Figure 2 illustrates the utility paths; $t = 0$ provides the data of the 2010 reference level. The transition generations are $t = 1,2$, and the steady state is reached at $t = 3$ and continues forever at the constant growth rate.

[Figure 2 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 1.08% per year. 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*

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[10] 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.

higher than 1% *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* 2010), *North has a lower emissions-to-output ratio, and higher emissions per capita than South.*

[Figure 3 here]

The optimal values for the allocation of emissions are presented in Figure 3. 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 3.4 times as large as those in South, whereas the emissions-to-output ratio in South are 1.6 times 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 per year to reduce to a 16% of the initial values.

The steady-state values display the following properties.[11]

- *Both North and South devote to investment in physical capital* 6.8% *of their labor-leisure resource, a figure* 70% *higher than the reference value of* 4% *in North, but substantially lower than the reference* 16% *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 twice*

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[11] Values for the economic variables along the transition and in the steady state are reported in the Appendix (see section S.4).

(resp., three and a half times) that of the reference year. And in the steady state South devotes to education a fraction of the labor-leisure resource 48% *higher than the reference level.*

- *The fractions of the labor-leisure resource devoted to leisure as well as those devoted to the production of output in either region do not substantially differ from the reference values. The same observation applies to consumption in North. But South must devote to consumption, resp. investment, a fraction of its labor-leisure resource* 37% *higher, resp.* 57% *lower, than the reference value. This is unsurprising and consistent with the observation, often made, that China is investing too much and consuming too little.*

During the transition, $t = 1,2$, the optimal path entails output exports from North to South at $t = 1$ on the order of 6.1% of domestic output in North or 4.7% of domestic output in South, and, at $t = 2$, from South to North of about 9.8% of domestic output in South and around 100% of domestic output in North, i. e., the amount imported by North is basically 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.[12]

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.[13] 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% 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

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[12] 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 our main results with respect to the inclusion of this constraint.

[13] 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.

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 \$2,620 per metric ton of carbon or \$715 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).

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% 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 following the RCP3-PD with a expected temperature change not exceeding the 2ºC. We emphasize that the regional allocation of actual emissions is given as part of the optimal solution, rather than being decided *a priori* 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 (Aldy and Stavins 2012; Rose et al. 1998; Vaillancourt et al. 2008; 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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Figures

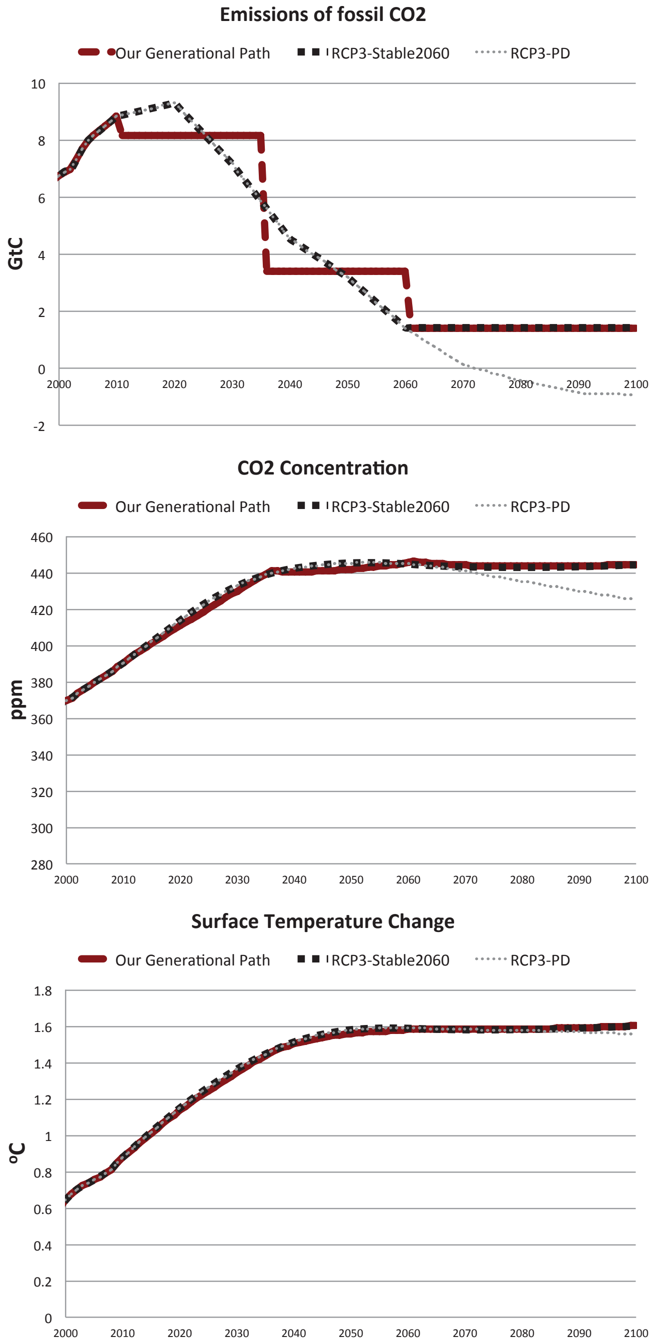
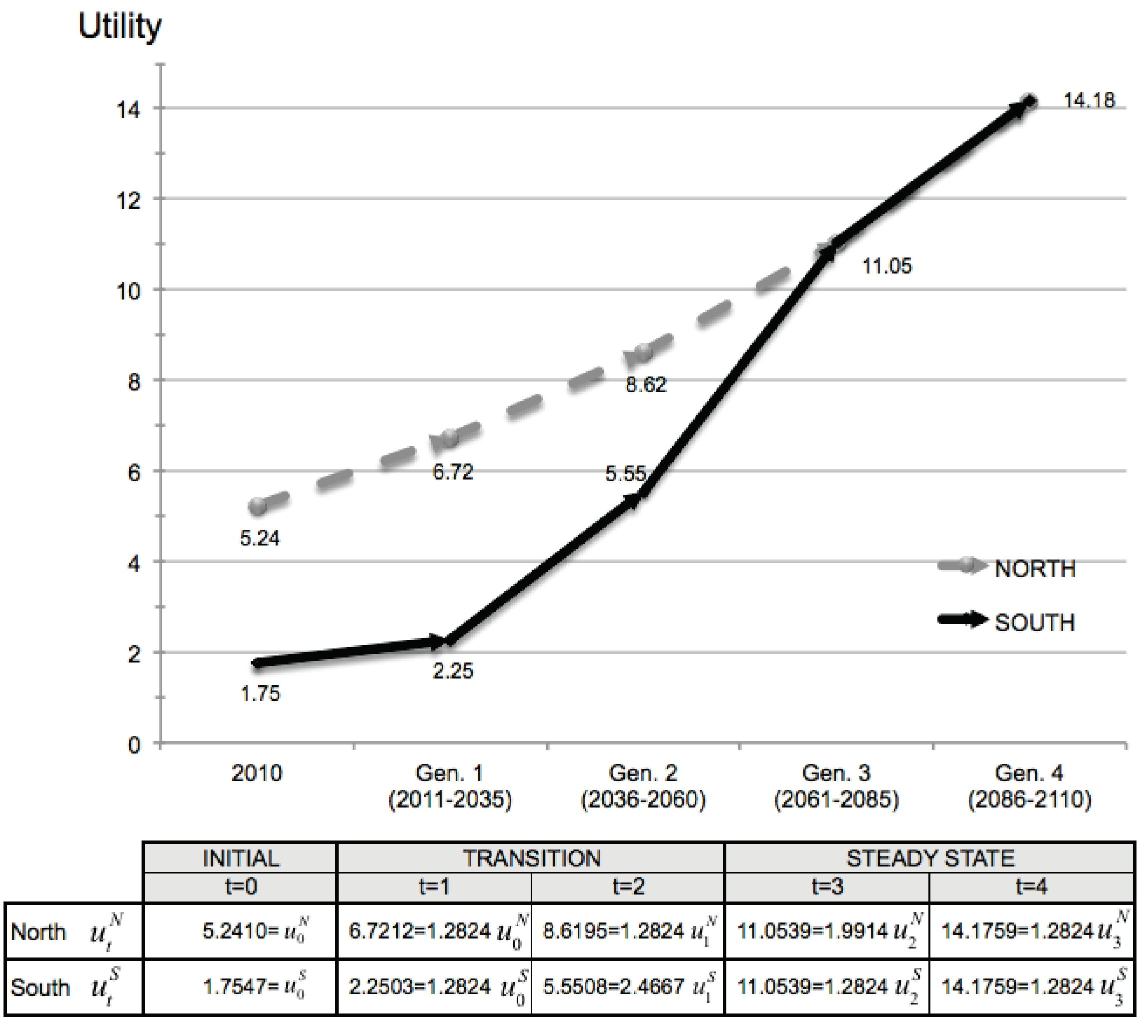


Figure 1: The graphs plot together three paths: the original RCP3-PD; *RCP3-stable2060*, which only differs from RCP3-PD by stabilizing emissions after 2060; and our *Generational Path*, which assigns to each generation its average annual emissions according to *RCP3-stable2060*. CO_2 concentrations and temperature changes are obtained by running MAGICC 6.4 for each one of the three emissions paths.



	INITIAL	TRANSITION		STEADY STATE	
	t=0	t=1	t=2	t=3	t=4
North u_t^N	5.2410= u_0^N	6.7212=1.2824 u_0^N	8.6195=1.2824 u_1^N	11.0539=1.9914 u_2^N	14.1759=1.2824 u_3^N
South u_t^S	1.7547= u_0^S	2.2503=1.2824 u_0^S	5.5508=2.4667 u_1^S	11.0539=1.2824 u_2^S	14.1759=1.2824 u_3^S

Figure 2. Utility paths for a guaranteed growth rate of 1% per year (28.24% per generation).

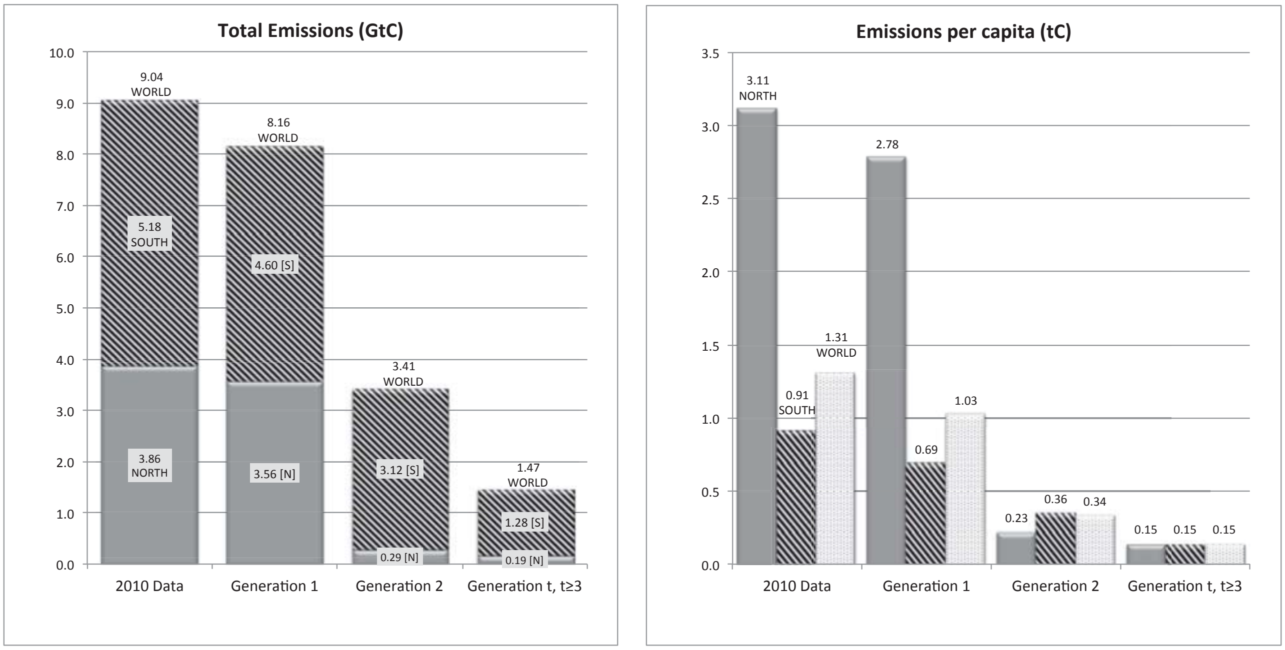


Figure 3. Total and per capita annual CO_2 emissions (North, South and World). Year 2010 values from World Resource Institute (2013).

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

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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-2010 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

$$\left(c_t^J\right)^{\alpha_c}\left(x_t^{lJ}\right)^{\alpha_l}\left(S_t^{nJ}\right)^{\alpha_n}\left(\hat{S}^m - S_t^m\right)^{\alpha_m}, \qquad \text{(s.0)}$$

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

$$f\left(x_t^{cJ}, S_t^{kJ}, S_t^{nJ}, e_t^J, S_t^m\right) \equiv k_1\left(x_t^{cJ}\right)^{\theta_c}\left(S_t^{kJ}\right)^{\theta_k}\left(S_t^{nJ}\right)^{\theta_n}\left(e_t^J\right)^{\theta_e}\left(S_t^m\right)^{\theta_m}, \quad t \geq 1, \qquad \text{(s.0)}$$

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. Note 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

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

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

$$(1-d^n)\frac{N_{t-1}^N}{N_t^N}S_{t-1}^{nN}+k_3 x_t^{nN} \geq S_t^{nN}, \quad t \geq 1, \qquad \text{(s.2)}$$

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.2) 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 may spill 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).[1] 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*

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[1] 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.

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

$$S_t^{nS} = (1-d^n)\frac{N_{t-1}^S}{N_t^S}S_{t-1}^{nS} + k_3 x_t^{nS} + k_{3d}\left[S_{t-1}^{nN} - S_{t-1}^{nS}\right]x_t^{nS} \qquad \text{if} \quad S_{t-1}^{nN} - S_{t-1}^{nS} > 0\,, \tag{s.4}$$

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.[2]

S.1.5 Education Production Function

The education production function transforms labor-leisure time in efficiency units of labor and leisure.[3] 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

$$x_t^J \le \xi x_{t-1}^{eJ}\frac{N_{t-1}^J}{N_t^J}, \quad t \ge 1, \quad J = N, S\,, \tag{s.5}$$

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

Given the generational growth rate ρ and the global emission-concentration path $\left\{\left(e_1^*, S_1^{m*}\right), \left(e_2^*, S_2^{m*}\right), \left(e^*, S^{m*}\right)\right\}$, 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:

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

$$\left.\begin{aligned}
&\left(c_1^S\right)^{\alpha_c}\left(x_1^{lS}\right)^{\alpha_l}\left(S_1^{nS}\right)^{\alpha_n}\left(\hat{S}^m - S_1^{m*}\right)^{\alpha_m} - (1+\rho)u_0^S \ge 0,\\
&\left(c_1^N\right)^{\alpha_c}\left(x_1^{lN}\right)^{\alpha_l}\left(S_1^{nN}\right)^{\alpha_n}\left(\hat{S}^m - S_1^{m*}\right)^{\alpha_m} - (1+\rho)u_0^N \ge 0,\\
&\left(c_2^N\right)^{\alpha_c}\left(x_2^{lN}\right)^{\alpha_l}\left(S_2^n\right)^{\alpha_n}\left(\hat{S}^m - S_2^{m*}\right)^{\alpha_m} - (1+\rho)^2 u_0^N \ge 0,\\
&\left(c_3\right)^{\alpha_c}\left(x_3^l\right)^{\alpha_l}\left(S_3^n\right)^{\alpha_n}\left(\hat{S}^m - S^{m*}\right)^{\alpha_m} - (1+\rho)^3 u_0^N \ge 0,
\end{aligned}\right\}\text{utility growth,}$$

---

[2] Of course, the law of motion (s.4) of the stock of knowledge in South when $S_{t-1}^{nN} = S_{t-1}^{nS}$ coincides with (s.3) and parallels (s.2).

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

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

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

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

$$\left.\begin{aligned}
&e_1^*-\frac{N_1^N}{N_1^N+N_1^S}e_1^N-\frac{N_1^S}{N_1^N+N_1^S}e_1^S\geq 0,\\
&e_2^*-\frac{N_2^N}{N_2^N+N_2^S}e_2^N-\frac{N_2^S}{N_2^N+N_2^S}e_2^S\geq 0,
\end{aligned}\right\}\text{emissions}\,,^{4}$$

---

[4] For $t=1, 2$, e_t^* denotes the average annual world emissions per capita of CO_2.

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

$$\left.\begin{array}{l}
\left(x_2^e, S_2^k, S_2^n\right) \in \Gamma\left(\rho, e^*, S^{m*}\right),\\
S_3^n - (1+g)S_2^n \geq 0,\\
c_3 - \gamma_1\left(\rho, e^*, S^{m*}\right) \geq 0,\\
x_3^l - \gamma_2\left(\rho, e^*, S^{m*}\right) \geq 0,
\end{array}\right\}\text{steady state ,}^{5}$$

with initial conditions $\left(x_0^{eN}, S_0^{kN}, S_0^{nN}\right)$, $\left(x_0^{eS}, S_0^{kS}, S_0^{nS}\right)$, u_0^N and u_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 $x_3^l \equiv x_3^{lN} = x_3^{lS}$.

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.[6] 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)

---

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

[6] See Section 3 in the main text.

S.3 Calibration

S.3.1 Values

The precise definitions of parameters and initial values are provided in Sections S.3.2.1 and S.3.2.2 below. Details for the calibration and source of the parameter values in Table s.1 and the initial values of the stocks and flows for the reference year (2010) in tables s.2-s.5 are in Sections S.3.2.3-S.3.2.11.

Parameter	Value	Parameter	Value
α_c	0.318	ξ	41.434
α_l	0.636	d^k	0.787
α_n	0.017	d^n	0.787
α_m	0.028	$\hat{S}^m$	1,249.090
k_1	15.987	θ_c	0.670
k_2	13.118	θ_k	0.284
k_3	558.309	θ_n	0.046
k_{3d}	5.583	θ_e	0.091
$\hat{\lambda}$	0.010	θ_m	-0.036

Table s.1. Calibrated parameter values.

Stocks	Value	Units
S_0^{kN}	101.572	thousands of 2010-international \$ per capita
S_0^{kS}	34.359	thousands of 2010-international \$ per capita
S_0^{nN}	26.953	thousands of 2010-international \$ per capita
S_0^{nS}	0.837	thousands of 2010-international \$ per capita
S_0^m	390.430	ppm
x_0^{eN}	0.072	USA-1950-efficiency units per capita
x_0^{eS}	0.028	USA-1950-efficiency units per capita

Table s.2. Initial values of the stocks in the reference year (2010).

Flows	Value	Units
y_0^N	46.179	thousands of 2010 international dollars per capita
y_0^S	8.564	thousands of 2010 international dollars per capita
c_0^N	39.576	thousands of 2010 international dollars per capita
c_0^S	4.280	thousands of 2010 international dollars per capita
i_0^N	6.604	thousands of 2010 international dollars per capita
i_0^S	4.280	thousands of 2010 international dollars per capita
e_0^N	311.2	tC per capita
e_0^S	0.913	tC per capita

Table s.3. Initial values of the flows in the reference year (2010).

Variable	Value	Units
x_0^N	2.170	1950-US efficiency units per capita
x_0^S	1.340	1950-US efficiency units per capita
x_0^{lN}	1.454	1950-US efficiency units per capita
x_0^{lS}	0.871	1950-US efficiency units per capita
x_0^{cN}	0.609	1950-US efficiency units per capita
x_0^{cS}	0.429	1950-US efficiency units per capita
x_0^{eN}	0.072	1950-US efficiency units per capita
x_0^{eS}	0.028	1950-US efficiency units per capita
x_0^{nN}	0.036	1950-US efficiency units per capita
x_0^{nS}	0.012	1950-US efficiency units per capita

Table s.4. Labor allocation in the reference year (2010).

Variable	Value	Units
N_0^{USA}	312,247	thousands
N_0^{China}	1,367,406	thousands
e_0^{USA}	3.112	tC per capita
e_0^{China}	0.913	tC per capita

Table s.5. USA's and China's population and emissions in the reference year (2010).

The calibrated values of the utility arguments yield the initial utility levels u_0^N y u_0^S.

S.3.2 Data and Calibration Procedures

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: $S_t^{kJ} \le (1-d^k)\dfrac{N_{t-1}^J}{N_t^J} S_{t-1}^{kJ} + k_2 i_t^J$.

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: $x_t^J \le \xi \dfrac{N_{t-1}^J}{N_t^J} x_{t-1}^{eJ}$.

S.3.2.4 Population

We follow the United Nations (2013) population forecast. We assign the average forecasted population for 2011-2035 to Generation 1, and the average forecasted population for 2036-2100 to Generation 2. World population is 6.9 billion people in 2010, increases to 7.9 billion people for Generation 1, and stabilizes at 10 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 2010	1,240,935	17.9%	5,675,249	82.1%	312,247	6,916,183
Generation 1	1,278,338	16.2%	6,635,766	83.8%	345,122	7,914,104
Generation 2	1,295,940	12.8%	8,790,833	87.2%	426,333	10,086,772

Table s.6. World population paths

S.3.2.5 Path of Emissions and Carbon Concentrations

We adopt a path of CO_2 emissions based on the Representative Concentration Pathway RCP3-PD. The values for emissions and concentration 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 2010	9.0424	3.8615	5.1809	390.43	1.31
Generation 1	8.1515	endogenous	endogenous	439.21	1.03
Generation 2	3.4146	endogenous	endogenous	445.63	0.34
Generation *t*, *t* $\geq$3	1.4679	endogenous	endogenous	444.56	0.15

Table s.7. Our postulated paths for the world annual CO_2 emissions and end-of-generation concentrations, based on RCP3-PD. Year 2010 values from WRI(2013). World emissions per capita are constructed from World Total emissions and the population data in Table s.6.

The RCPs are a new set of consistent projections of the components of radiative forcing extending until 2100 that have been prepared to serve as input for climate modeling in the development of new scenarios for the IPCC's Fifth Assessment Report.[7]

The RCP3PD pathway (a.k.a. RCP2.6) is the only RCP that provides an expected temperature change not exceeding the 2ºC and is representative of scenarios of very low GHG concentration levels. Its radiative forcing level first peaks at 3.1 W/m^2 in the middle of the century and then returns to 2.6 W/m^2 by 2100, thus its name: "Peak & Decline" (van Vuuren et al. 2007; van Vuuren, Stehfest, et al. 2011). Our setting requires constant annual emissions within a generation as well as stabilized emissions and concentration after year 2060. After adapting RCP3-PD to these requirements, we run MAGICC 6.4.*8* Figure s.1 depicts our path and the RCP3-PD (without and with stabilized emissions after 2060). The values for CO_2 concentration and the change in temperature do not substantially vary if we adopt our emission path instead of the RCP3-PD emissions with stabilization after 2060.

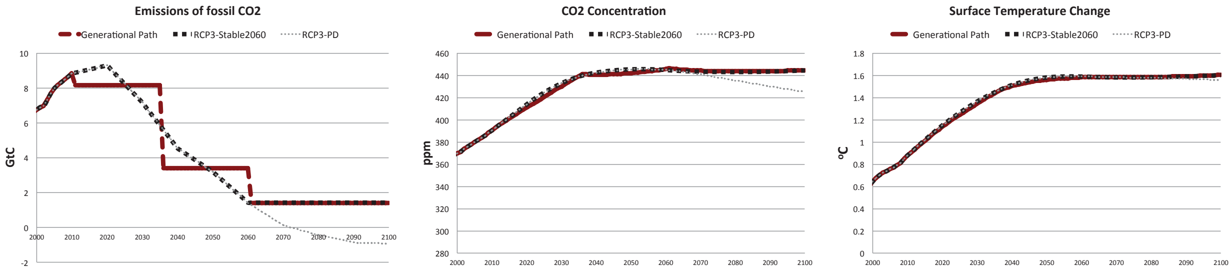

Figure s.1. The left graph plots three emissions paths: the original RCP3-PD; *RCP3-stable2060*, which only differs from RCP3-PD by stabilizing emissions after 2060; and our *Generational Path*, which assigns to each generation its average annual emissions according to *RCP3-stable2060*. CO_2 concentrations and temperature changes are obtained by running MAGICC 6.4 for each one of the three emissions paths.

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[7] The RCPs are described in the 2011 special issue of Climatic Change. For a summary see Meinshausen et al. (2011) and van Vuuren et al. (2011). The data can be obtained from http://www.pik-potsdam. de/~mmalte/rcps and also from MAGICC6 (http://www.magicc.org/)

[8] We keep emissions constant for all GHGs after 2060, except for land-use-change emissions, which decline following the original RCP3-PD path.

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 $\alpha_n/\alpha_c = 0.055$ 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 1996-2009.[9]

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

$$\Delta T = \sigma \frac{\ln\left(S^e / S^m_{1850}\right)}{\ln 2}, \tag{s.6}$$

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*.[10] Expression (s.6) 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

$$\widehat{S}^m(\Delta T) = \frac{S^m_{1850}}{1.16} 2^{\Delta T/\sigma} \tag{s.7}$$

We take $S^m_{1850} = 280$ ppm and adopt the common best-guess for the climate sensitivity of $\sigma = 3$.[11]

We consider that an increase in temperature of 6º-8ºC (relative to pre-industrial level) would have catastrophic impacts.[12] From (s.7) 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

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[9] Expenditures on R&D are obtained from the National Science Foundation (2013) and those of investment in computer components and software from the Bureau of Economic Analysis (2013). Since the BEA only provides aggregate data for Equipment and Software, we take the share of Private Software on Private Software and Equipment to construct Public Investment in Software.

[10] 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.

[11] Section S.6.4 runs a sensitivity analysis for higher values of the climate sensitivity parameter.

[12] 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).

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).[13] Again from (s.7) a 5ºC temperature increase corresponds to an S^m value of 766.33 $\equiv \tilde{S}^m$. Accordingly, we consider a 6% decrease in consumption equivalent to suffering an atmospheric CO_2 concentration of $\tilde{S}^m$ instead of 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 $\dfrac{\alpha_m}{\alpha_c} = \dfrac{\ln 0.94}{\ln\left(\hat{S}^m - \tilde{S}^m\right) - \ln\left(\hat{S}^m - S^m_{1850}\right)}$. 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

$$f\left(x_t^c, S_t^k, S_t^n, e_t, S_t^m\right) \equiv k_1\left(x_t^c\right)^{\theta_c}\left(S_t^k\right)^{\theta_k}\left(S_t^n\right)^{\theta_n}\left(e_t\right)^{\theta_e}\left(S_t^m\right)^{\theta_m}$$

in the following inputs: the 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 1960-2010, corresponding to 0.86 and 0.14, respectively. Hence, $\theta_c = 0.670$, $\theta_k = 0.284$ and $\theta_n = 0.046$, 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.7) yields

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[13] 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).

$$\widehat{f}(x_t^c, S_t^k, S_t^n, e_t, \Delta T) = \left(\frac{280}{1.16} 2^{\Delta T/3} \right)^{\theta_m} \widehat{a}(.)\text{, where} \equiv \widehat{a}(.) = k_1 (x_t^c)^{\theta_c} (S_t^k)^{\theta_k} (S_t^n)^{\theta_n} (e_t)^{\theta_e} .$$

We assume, following Nordhaus (2010, p. 11723), that a 3.4ºC increase in temperature implies a 2.8% loss of GDP, i. e., $\left(\frac{280}{1.16} 2^{3.4/3} \right)^{\theta_m} \widehat{a}(.) = 0.972 \left(\frac{280}{1.16} 2^{0/3} \right)^{\theta_m} \widehat{a}(.)$, or $2^{1.13 \times \theta_m} = 0.972$, 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 2010 values:[14]

$$k_1 = \frac{y_{2010}^{USA}}{\left(x_{2010}^{c,USA}\right)^{\theta_c} \left(S_{2010}^{k,USA}\right)^{\theta_k} \left(S_{2010}^{n,USA}\right)^{\theta_n} \left(e_{2010}^{USA}\right)^{\theta_e} \left(S_{2010}^{m}\right)^{\theta_m}} =$$

$$\frac{46.18}{0.609^{0.670}\, 101.570^{0.284}\, 26.950^{0.046}\, 4.952^{0.091}\, 390.430^{-0.036}} = 15.9867.$$

S.3.2.8 The Stock of Physical Capital

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

$$(1 - d^k) S_{t-1}^{kJ} \frac{N_{t-1}^J}{N_t^J} + k_2 i_t^J \geq S_t^{kJ} .$$

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 $k_2 = \frac{1 - \left(1 - \hat{d}^k\right)^{25}}{1 - \left(1 - \hat{d}^k\right)} = 13.118$.

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 U.S. Gross Capital Formation data adjusted for imports and exports for the period 1960-2010 (World Bank

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[14] GDP is denoted in thousands of constant 2010 dollars per capita from the World Development Indicator (World Bank 2013). USA emissions are obtained from the World Resources Institute (2013). See sections s.3.2.8-12 below for the values of the other stocks and flows in the year 2010.

2013), and taking 1960 as initial year. For the initial value, $S_{1960}^{kN} = i_{1960}^{kN} \Big/ \left(\hat{d}^k + g^{kN}\right) = 27.62$ thousands of constant 2010-dollars per capita, where i^{kN} represents gross capital formation, and g^{kN} represents the average yearly growth rate of investment between 1960-1970 (computed at 4.33%). The value for the stock of physical capital in the year 2010 is $S_0^{kN} = 101.57$ thousands of 2010-international dollars per capita. (We use deflactors information from the WDI to convert to 2010 international dollars.)

Initial stock of physical capital for South

We assign South the stock of physical capital per capita in China. We start from Albala-Bertrand and Feng (2007), who provide a figure of 11,243.3 billion 1952-Yuan for the capital stock in 2005, or 14.74 thousands of constant 2005-international dollars per capita (once dividing by population and using CPI data from Officer and Williamson (2008) and PPP from the World Bank). Then we update the value to 2010 by the PIM, using Gross Capital Formation in China from the WDI (World Bank, 2013), and obtain $S_0^{kS} = 34.359$ thousands of 2010-international dollars per capita.[15]

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

$$S_t^{nS} = \left(1 - d^n\right) S_{t-1}^{nS} \frac{N_{t-1}^S}{N_t^S} + k_3 x_t^{nS} + k_{3d} \left(S_{t-1}^{nN} - S_{t-1}^{nS}\right) x_t^{nS}, \tag{s.8}$$

where

$$k_3 = \frac{d^n}{\hat{d}^n} \bar{w}, \ k_{3d} = \hat{\lambda} k_3, \tag{s.9}$$

$\bar{w}$ 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

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[15] We follow (2006)Bai et al. (2006) in considering Gross Capital Formation as an accurate measure of the change in China's reproducible capital stock.

knowledge capital may be substantial.[16] 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 $\bar{w} = i_{1970-2010}^n / x_{1970-2010}^n = 42.56$ of 2010-dollars (expenditure in knowledge from NSF (2003) and BEA (2013), labor allocation from BLS (2012), and CPI from WDI).

The calibration of $\hat{\lambda}$ is more problematic.[17] 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 depreciation rate of $\hat{d}^n = 0.06$, an annual diffusion rate of $\hat{\lambda} = 0.01$, and an estimation of $\bar{w} = 42.56$, we compute $k_3 = 558.309$, and $k_{3d} = 5.583$, in accordance with (s.9).

Initial stock of knowledge for North

The time series of the stock of knowledge in North is constructed by the PIM, using USA data for 1960-2005 and taking 1960 as the initial year. For the stock of knowledge in 1960 we take $S_{1960}^{nN} = i_{1960}^{nN} / \left(\hat{d}^n + g^{nN}\right) = 0.396 / \left(0.06 + 0.049\right) = 3.624$ thousands of constant 2010-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 2010 is $S_0^{nN} = 26.950$ (in thousands of 2010-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 the PIM, using the annual knowledge equation with technology diffusion given in (s.8). We take 1/3 of the GDP per capita in 1980 (i. e., 222 international dollars per capita) as the initial value for the stock of knowledge in China.[18] The date is unusually recent for applying the PIM, but it can be justified by the particular circumstances of China.[19] Year 1980 roughly coincides with the new development path set by Deng Xiaoping after the failure of the "Great Leap" experiment.[20] 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

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

[17] 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%.

[18] Currency is always in constant 2010 PPP international dollars.

[19] The choice of the initial value has a moderate effect for the stock in 2010. Choosing as initial value R&D investment in 1980 would decrease the year 2010 stock around $30 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 2010 stock in less than $30 per capita.

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

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.[21] For the time series of investment in knowledge, we use data on R&D investment from Gao and Jefferson (2007), the China Statistical Data Book (Ministry of Science and Technology in China, MOST 2000), and the China Statistical Yearbook on Science and Technology (National Bureau of Statistics of China 2012).[22] 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 2010 of $S_0^{n,S} = 0.837$ thousands of 2010-international dollars per capita.

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.5)), 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

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

for some given $\bar{t}$, which 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 (2013), and supported by other recent findings (see e. g. Christian, 2010, Wei, 2008, or Gu and Wong, 2010).[23]

The rate $\hat{x}_{t-1}^e / \hat{x}_t$ is the product of the rate of education in labor and the rate of labor in total time. We assume that 10% of total labor is devoted to education (a figure roughly constant since 1990, Bureau of Labor Statistics (BLS), 2013), and that labor accounts for 1/3 of total time. It follows that

$$\xi = (1.013)^{25}\left(\frac{1}{3}\times 0.1\right) = 41.434. \qquad \text{(s.10)}$$

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.

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[21] 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).

[22] 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).

[23] 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.

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 2013). Hence, $x_t^N = 1.013^{t-1950}$ in 1950-USA efficiency units, and therefore $x_0^N = 1.013^{60} = 2.17$. 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 output (Standard Occupation Classification (SOC) of the U.S. Bureau of Labor Statistics (2012; 2013)).

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 (2013) the average years of school of the total population aged 15 and over for USA and China: 13.09 and 8.11 years, respectively.[24] Therefore, $x_0^S = 2.17 \times (8.11/13.09) = 1.34$, 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. For the allocation of working time, we take the 2005-2010 averages from the China Statistical Yearbook (National Bureau of Statistics of China 2012): 6% in education, 2.5% in knowledge, and the remaining 91.5% in the production of output.[25]

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 use the values for the USA and China, respectively (World Bank 2013). For consumption and investment we use "Final Consumption Expenditure" and "Gross Capital 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-s.10. They correspond to a sustainable 1% annual growth rate. Table s.8 describes the allocation of CO_2 emissions and their relationship with production. Table s.9 displays the fractions of each period's labor-leisure resource allocated to the various uses, whereas Table s.10 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 in 2010.[26]

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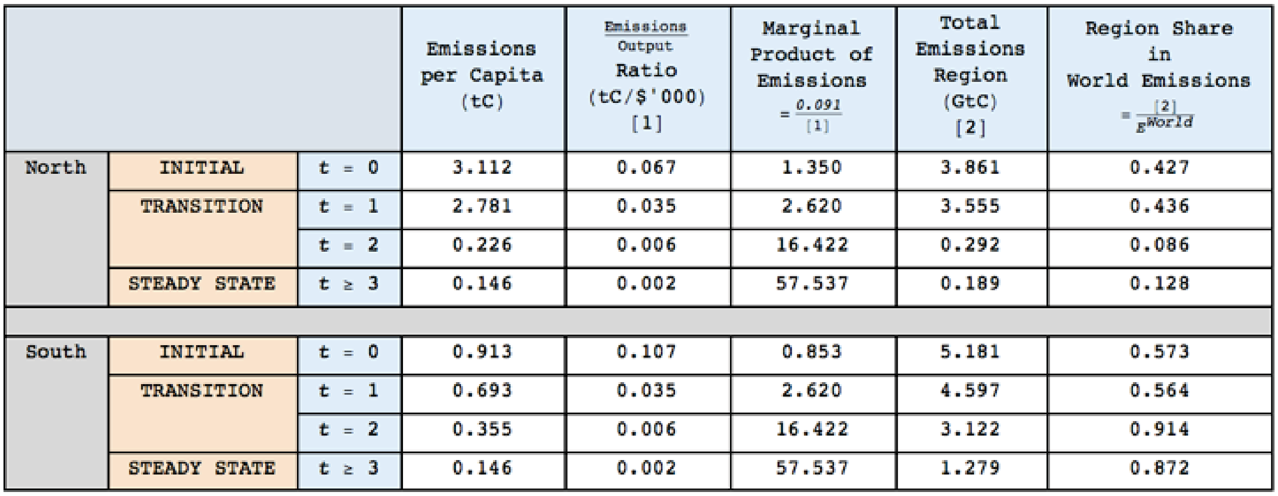
[24] More sophisticated analyses, like those of Wang and Yao (2001) and Perkins and Rawski (2008), find similar values for China.

[25] 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.

[26] 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.



			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	3.112	0.067	1.350	3.861	0.427
	TRANSITION	t = 1	2.781	0.035	2.620	3.555	0.436
		t = 2	0.226	0.006	16.422	0.292	0.086
	STEADY STATE	t ≥ 3	0.146	0.002	57.537	0.189	0.128
South	INITIAL	t = 0	0.913	0.107	0.853	5.181	0.573
	TRANSITION	t = 1	0.693	0.035	2.620	4.597	0.564
		t = 2	0.355	0.006	16.422	3.122	0.914
	STEADY STATE	t ≥ 3	0.146	0.002	57.537	1.279	0.872

Table s.8. 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 (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 $\frac{x_t^{cJ}}{x_t^J}\frac{c_t^J}{\text{output}}$	Net Exports $\frac{x_t^{cJ}}{x_t^J}\frac{T_t}{\text{output}}$	Leisure $\frac{x_t^{lJ}}{x_t^J}$	Education x_t^{eJ}	Knowledge x_t^{nJ}	Leisure x_t^{lJ}
North	INITIAL	$t = 0$	0.033	0.016	0.280	0.040	0.24	0	0.670	0.072	0.036	1.454
	TRANSITION	$t = 1$	0.026	0.038	0.311	0.082	0.209	0.019	0.625	0.076	0.109	1.801
		$t = 2$	0.041	0.042	0.154	0.059	0.256	0	0.764	0.126	0.128	2.358
	STEADY STATE	$t \geq 3$	0.031	0.032	0.286	0.068	0.218	0	0.651	0.163	0.165	3.406
South	INITIAL	$t = 0$	0.021	0.009	0.320	0.160	0.160	0	0.650	0.028	0.012	0.871
	TRANSITION	$t = 1$	0.086	0.034	0.263	0.069	0.207	0	0.617	0.086	0.034	0.615
		$t = 2$	0.047	0.039	0.328	0.099	0.196	0.032	0.586	0.126	0.103	1.570
	STEADY STATE	$t \geq 3$	0.031	0.032	0.286	0.068	0.218	0	0.651	0.163	0.165	3.406

Table s.9. The allocation of labor-leisure resources. (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	$t=0$	101.570	26.950	0.072	39.576	1.000	6.604
	TRANSITION	$t=1$	299.721	66.249	0.076	53.953	1.363	21.247
		$t=2$	266.563	85.571	0.126	67.843	1.714	15.522
	STEADY STATE	$t=3$	344.330	110.535	0.163	70.092	1.771	21.922
		$t=4$	444.784	142.783	0.211	90.540	2.288	28.317
	INITIAL	$t=0$	34.360	0.837	0.028	4.280	1.000	4.280
	TRANSITION	$t=1$	74.660	24.353	0.086	15.671	3.662	5.214
		$t=2$	266.563	85.571	0.126	38.400	8.972	19.405
	STEADY STATE	$t=3$	344.330	110.535	0.163	70.092	16.377	21.922
		$t=4$	444.784	142.783	0.211	90.540	21.154	28.317

Table s.10. 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.2), for North, and (s.3)-(s.4), 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 2010-international dollars. This appendix obtains the generational laws (s.2), (s.3) and (s.4) 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

$$\hat{S}_{t\tau}^{nN} = (1-\hat{\delta}^n)\frac{N_{t,\tau-1}^N}{N_{t\tau}^N}\hat{S}_{t,\tau-1}^{nN} + \bar{w}x_t^{nN}, \tau = 1,\ldots,25, \qquad \text{(s.11)}$$

which incorporates simplifying assumptions (i)-(iii), where $\hat{S}_{t\tau}^{nN}$ denotes the per capita stock of knowledge in North in year τ, with $S_{t-1}^{nN} = \hat{S}_{t0}^{nN}$ and $S_t^{nN} = \hat{S}_{t,25}^{nN}$ (i. e., the generational stock is that of the last year of the generation.[27] The iteration of (s.11) gives

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

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

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

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

...

$$\hat{S}^{nN}_{t\tau} = (1-\hat{\delta}^n)^\tau\frac{N^N_{t-1}}{N^N_t}S^{nN}_{t-1} + \frac{1-(1-\hat{\delta}^n)^\tau}{\hat{\delta}^n}\bar{w}x^{nN}_t, \tau = 1,\ldots,25, \tag{s.12}$$

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.2) for

$$1-d^n = (1-\hat{d}^n)^{25}, \tag{s.13}$$

and

$$k_3 = \frac{1-(1-\hat{d}^n)^{25}}{\hat{d}^n}\bar{w} = \frac{d^n}{\hat{d}^n}\bar{w}. \tag{s.14}$$

South. An argument parallel to the preceding one leads to (s.3).

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.4), which in equality form can be written

$$S^{nS}_t = \left(1-d^n\right)S^{nS}_{t-1}\frac{N^S_{t-1}}{N^S_t} + k_3x^{nS}_t + k_{3d}\left[S^{nN}_{t-1} - S^{nS}_{t-1}\right]x^{nS}_t. \tag{s.15}$$

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 $S^{nN}_{t-1} - S^{nS}_{t-1}$ inherited from the previous generation and the investment $\bar{w}\hat{x}^{nS}_t$ in knowledge in South in that year, i. e.,

$$\hat{S}^{nS}_{t\tau} = \left(1-\hat{d}^n\right)\frac{\hat{N}^S_{t,\tau-1}}{\hat{N}^S_{t\tau}}\hat{S}^{nS}_{t,\tau-1} + \bar{w}\,x^{nS}_t + \hat{\lambda}\left[1-\hat{d}^n\right]\left[S^{nN}_{t-1} - S^{nS}_{t-1}\right]\bar{w}\,x^{nS}_t,\ \tau = 1,\ldots,25, \tag{s.16}$$

where we adopt the simplifying assumptions $\hat{N}^{nS}_{t0} = N^{nS}_{t-1}$ and, for $\tau \geq 1$, $N^{nS}_{t\tau} = N^{nS}_t$, and, as before, $\hat{S}^{nS}_{t0} = S^{nS}_{t-1}$, $\hat{S}^{nS}_{t,25} = S^{nS}_t$. The iteration of (s.15) gives

$$\hat{S}^{nS}_{t1} = \left(1-\hat{d}^{n}\right)\frac{N^{S}_{t-1}}{N^{S}_{t}}S^{nS}_{t-1} + \bar{w}x^{nS}_{t} + \hat{\lambda}\left[1-\hat{d}^{n}\right]\left[S^{nN}_{t-1} - S^{nS}_{t-1}\right]\bar{w}x^{nS}_{t};$$

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

…

$$\hat{S}^{nS}_{t\tau} = \left(1-\hat{d}^{n}\right)^{\tau}\frac{N^{S}_{t-1}}{N^{S}_{t}}S^{nS}_{t-1} + \bar{w}x^{nS}_{t}\sum_{\theta=0}^{\tau-1}\left(1-\hat{d}^{n}\right)^{\theta} + \hat{\lambda}\left[S^{nN}_{t-1} - S^{nS}_{t-1}\right]\bar{w}x^{nS}_{t}\sum_{\theta=0}^{\tau-1}\left(1-\hat{d}^{n}\right)^{\theta}, \tau = 1,\ldots,25,$$

…

$$\begin{aligned}
S^{nS} \equiv \hat{S}^{nS}_{t25} &= \left(1-\hat{d}^{n}\right)^{25}\frac{N^{S}_{t-1}}{N^{S}_{t}}S^{nS}_{t-1} + \bar{w}x^{nS}_{t}\sum_{\theta=0}^{24}\left(1-\hat{d}^{n}\right)^{\theta} + \hat{\lambda}\left[S^{nN}_{t-1} - S^{nS}_{t-1}\right]\bar{w}x^{nS}_{t}\sum_{\theta=0}^{24}\left(1-\hat{d}^{n}\right)^{\theta} \\
&= \left(1-\hat{d}^{n}\right)^{25}\frac{N^{S}_{t-1}}{N^{S}_{t}}S^{nS}_{t-1} + \frac{1-\left(1-\hat{d}^{n}\right)^{25}}{\hat{d}^{n}}\bar{w}x^{nS}_{t} + \hat{\lambda}\frac{1-\left(1-\hat{\delta}^{n}\right)^{25}}{\hat{\delta}^{n}}\left[S^{nN}_{t-1} - S^{nS}_{t-1}\right]\bar{w}x^{nS}_{t},
\end{aligned}$$

which is (s.15) for $1-d$ as given by (s.13), k_3 as given by(s.14), 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.2 and s.3 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, 0.04).

Furthermore, Figure s.3 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% annual growth satisfying all our conditions (the lowest path in Figure s.2). 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 in utility.

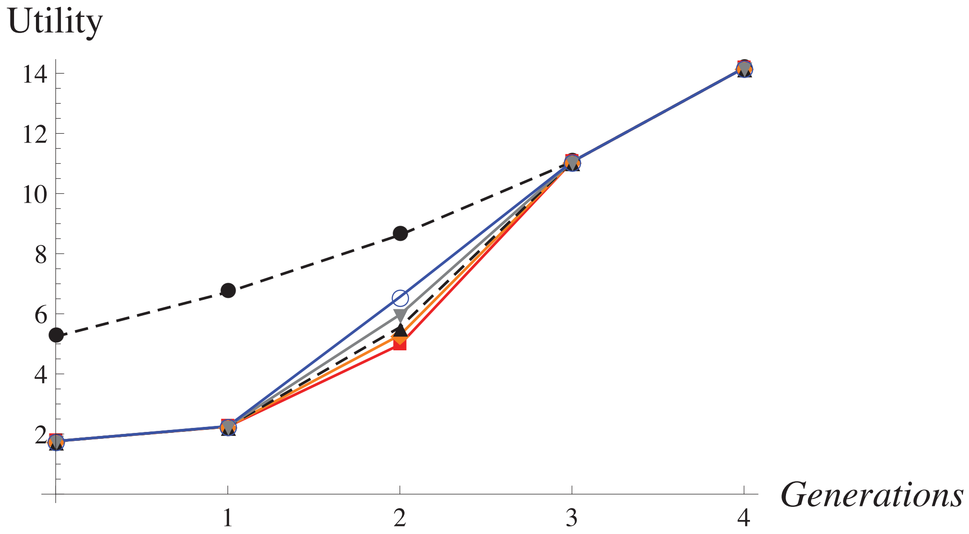

Figure s.2. Sensitivity analysis to different values of $\hat{\lambda}$. Convergent utility paths for $\hat{\lambda} = 0$, 0.005, 0.01, 0.02, 0.04. Our calibrated value is $\hat{\lambda} = 0.01$, with path is represented by the dashed lines.

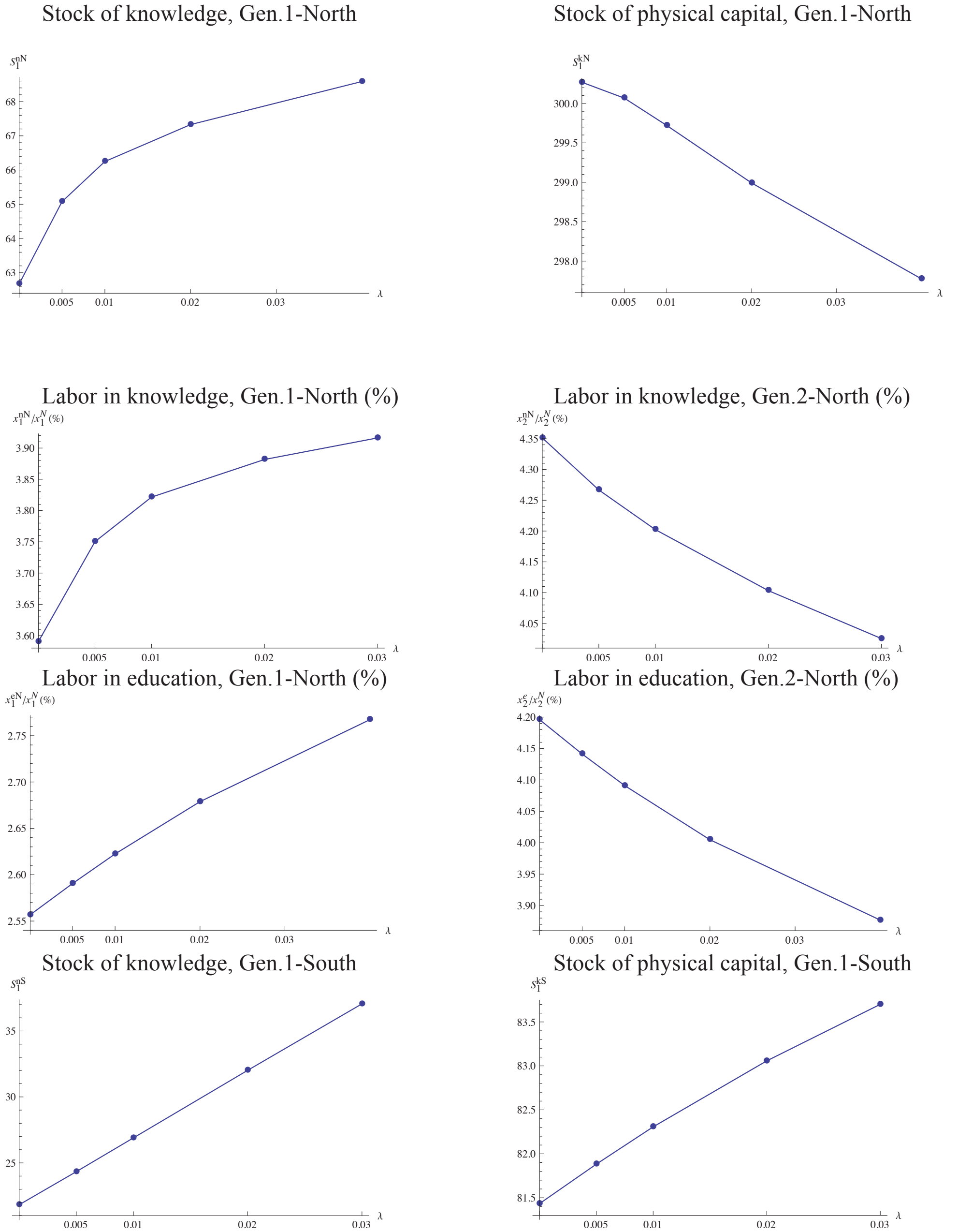

Figure s.3. Sensitivity analysis to different values of $\hat{\lambda}$. The dependence of relevant stocks and flows of $\hat{\lambda}$ along the optimal paths.

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 education in South to be 6% of the total labor force in 2010. Figure s.4 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 5.8% and 6.2% of total labor. For values below 5.6%, convergent paths cannot be obtained for a sustained annual growth rate of 1%. While values above 6.2% could sustain rates of growth much higher than 1%.

Convergent paths for $x_0^{eS}\Big/\left(x_0^S - x_0^{lS}\right) = 0.058$, 0.06, and 0.062.

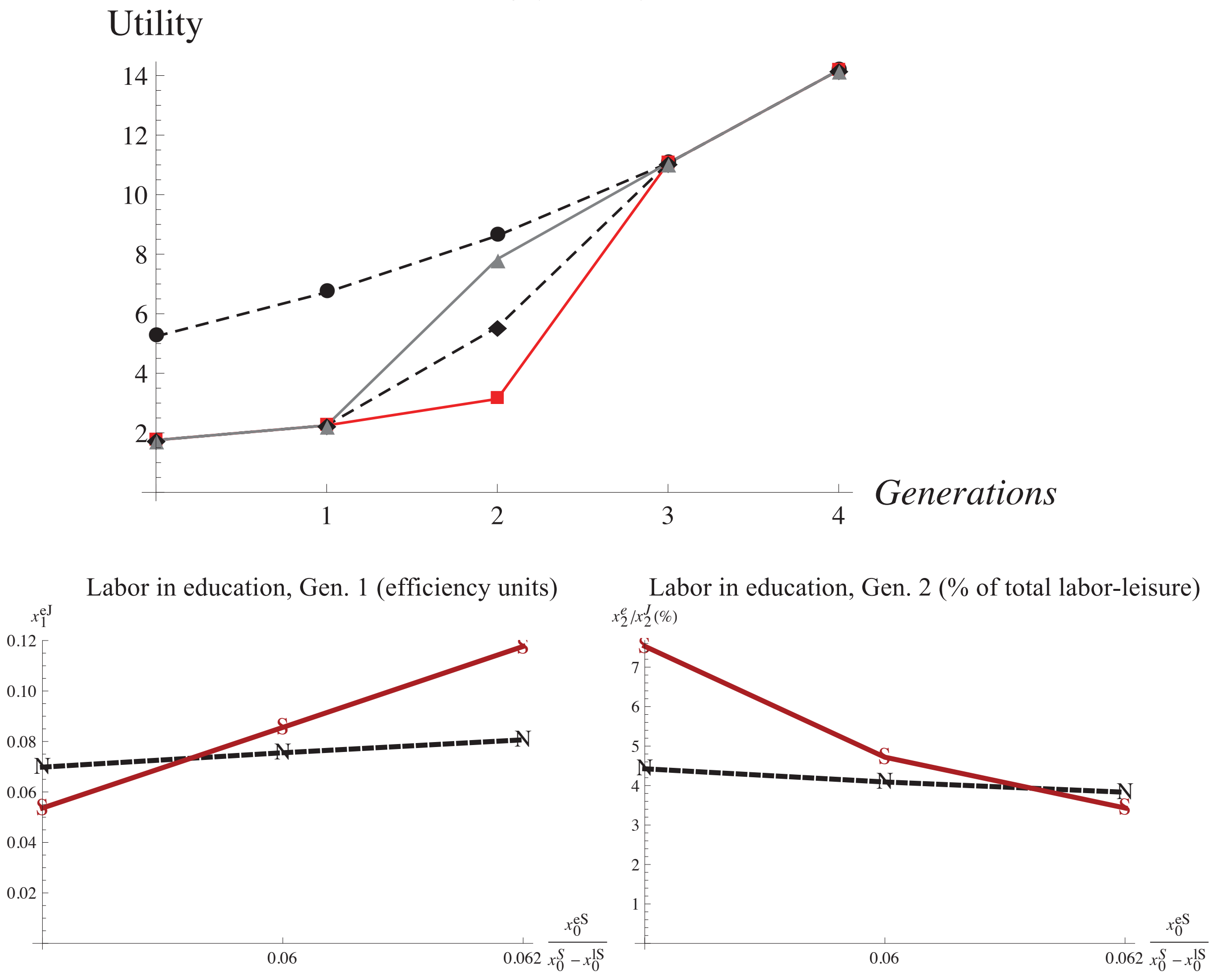

Figure s.4. Sensitivity analysis to different values of the fraction of labor force devoted to education in South for the initial period. The first graph presents the convergent utility paths (with generations in the horizontal axis). Higher values of $x_0^{eS}\Big/\left(x_0^S - x_0^{lS}\right)$ correspond to higher levels of the utility of Generation 2 in South. The bottom graphs show its effect on the amount of labor in education (in efficiency units and as percentage of the total labor force). Our calibration obtains a value of $x_0^{eS}\Big/\left(x_0^S - x_0^{lS}\right) = 0.060$.

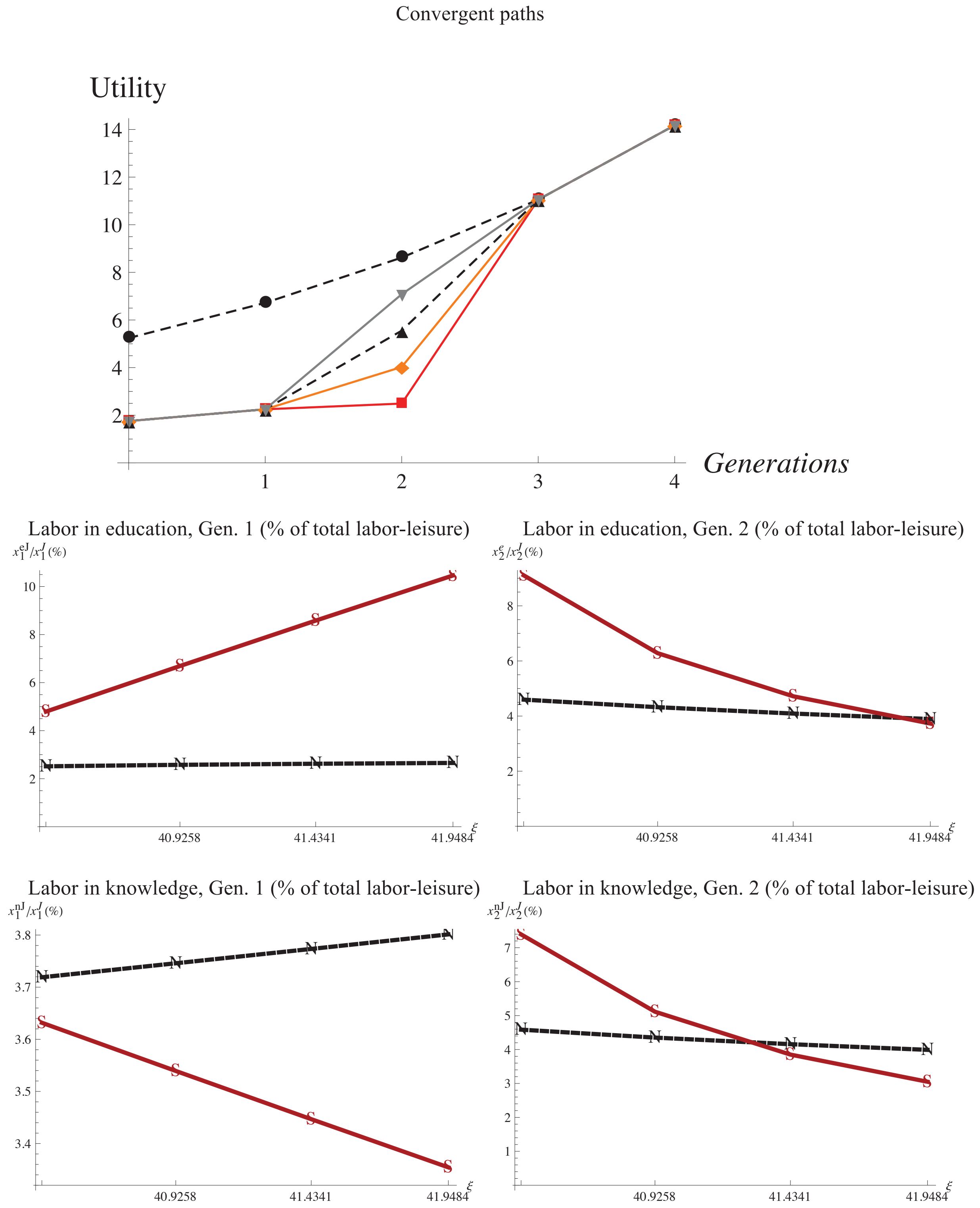

Figure s.5. Sensitivity analysis to different values of ξ calibrated from estimates of annual growth rates of the US productivity of labor ranging from 1.12% to 1.35%. Our calibration uses a 1.3% growth rate with the associated $\xi = 41.4341$. (See Section S.3.2.10.)

Figure s.5 illustrates the effects of alternative values of the productivity of labor ξ. The implications are similar to those from variations in x_0^{eS}.[28] If the education function is not sufficiently productive we cannot sustain growth with convergence. On the other hand, larger values of ξ can sustain higher growth rates while satisfying our conditions of convergence.

S.6.3 Sensitivity to Economic 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.6 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 a 1% annual growth even for values of θ_m associated with economic damages of 42% of global GDP.

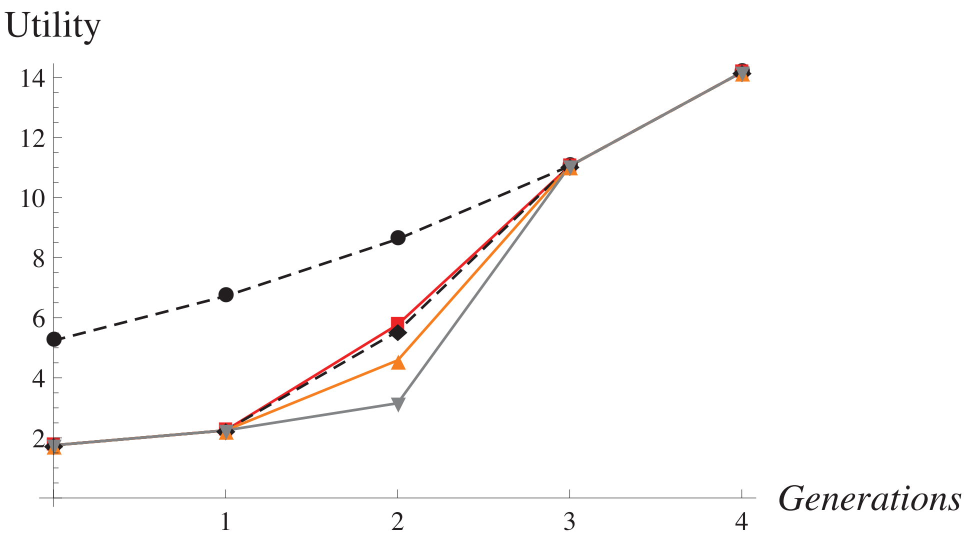

Figure s.6. Optimal utility paths for different values of θ_m calculated from different estimates of the economic damages associated with a 3.4ºC temperature increase. They range from no damages (the highest level of welfare) to economic damages equal to 28% of global GDP (ten times the value used in our calibration). The dashed line represents the optimal path corresponding to our calibration.

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[28] 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, which captures the productivity education ($x_1^S = N_0^S / N_1^S \xi x_0^{eS}$). This is the reason for 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.

S.6.4 Alternative Values for the Climate Sensitivity Parameter.

Our analysis does not explicitly incorporate a climate model, as global emissions follow the RCP3-PD pathway (see Section S.3.2.5). However, the climate sensitivity parameters enters in the calibration of α_m, $\hat{S}^m$ and θ_m. We adopt the value of 3ºC, the best estimate in the IPCC. Because it has been claimed that this value is too low, we have also computed the optimal paths associated with larger values, namely $\sigma = 4$, 5 and 6 (Figure s.7).[29] We observe that higher climate sensitivity values slightly decrease the welfare of the second generation in South, but the effects are small.

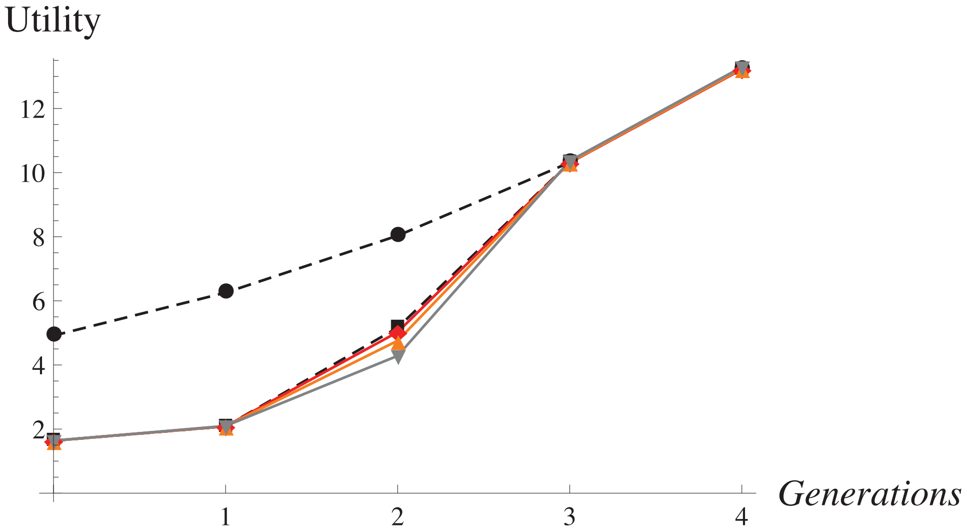

Figure s.7. Optimal paths for different climate sensitivity parameter values. The dashed lines display the optimal path corresponding to a climate sensitivity of 3ºC, as used in our calibration. For North, we only depict the path from our calibration; convergence also occurs for the other cases, albeit at slightly lower 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.11 and s.12 compare the cases with and without flows for a sustainable 1% annual growth rate.

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 it should be expected, in the presence of output flows, the net exporter increases the share of labor-leisure resource devoted to the production of output (see Table s.11), while reducing the fractions devoted to leisure, education and the investment in knowledge.

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[29] 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.

				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	0.280	0.040	0.240	0	0.670	0.072	0.036	1.454
	Transition	$t = 1$	No Output Flows	0.033	0.039	0.290	0.076	0.214	0	0.638	0.096	0.112	1.837
			Output Flows	0.026	0.038	0.311	0.082	0.209	0.019	0.625	0.076	0.109	1.801
		$t = 2$	No Output Flows	0.032	0.033	0.281	0.062	0.219	0	0.654	0.126	0.128	2.565
			Output Flows	0.041	0.042	0.154	0.059	0.256	0	0.764		0.128	2.358
	Steady state	$t \geq 3$		0.031	0.032	0.286	0.068	0.218	0	0.651	0.163	0.165	3.406
South	Initial	$t = 0$		0.021	0.009	0.320	0.160	0.160	0	0.650	0.028	0.012	0.871
	Transition	$t = 1$	No Output Flows	0.078	0.035	0.277	0.073	0.204	0	0.61	0.078	0.035	0.608
			Output Flows	0.086	0.034	0.263	0.069	0.207	0	0.617	0.086	0.034	0.615
		$t = 2$	No Output Flows	0.052	0.042	0.305	0.103	0.201	0	0.601	0.126	0.102	1.46
			Output Flows	0.047	0.039	0.328	0.099	0.196	0.032	0.586		0.103	1.57
	Steady state	$t \geq 3$		0.031	0.032	0.286	0.068	0.218	0	0.651	0.163	0.165	3.406

Table s.11. The allocation of labor-leisure resources with and without interregional output flows for a sustainable 1% annual growth rate.

				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	$t = 0$		101.570	26.950	0.072	39.576	1.000	6.604
	TRANSITION	$t = 1$	No Output Flows	263.074	68.374	0.096	51.752	1.308	18.454
			Output Flows	299.721	66.249	0.076	53.953	1.363	21.247
		$t = 2$	No Output Flows	266.563	85.571	0.126	57.348	1.449	16.108
			Output Flows				67.843	1.714	15.522
	STEADY STATE	$t = 3$		344.330	110.535	0.163	70.092	1.771	21.922
		$t = 4$		444.784	142.783	0.211	90.54	2.288	28.317
South	INITIAL	$t = 0$		34.360	0.837	0.028	4.280	1.000	4.280
	TRANSITION	$t = 1$	No Output Flows	81.388	24.908	0.078	16.019	3.743	5.727
			Output Flows	74.660	24.353	0.086	15.671	3.662	5.214
		$t = 2$	No Output Flows	266.563	85.571	0.126	37.687	8.805	19.323
			Output Flows				38.4	8.972	19.405
	STEADY STATE	$t = 3$		344.330	110.535	0.163	70.092	16.377	21.922
		$t = 4$		444.784	142.783	0.211	90.54	21.154	28.317

Table s.12. 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% annual growth rate.

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

In this section, instead of maximizing the utility of generation 2 in South, we maximize the utility of generation 1 in South, which is the worst-off generation. The program is:

maximize Λ_1^S subject to:

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

$$\left.\begin{aligned}
&\left(c_2^S\right)^{\alpha_c}\left(x_2^{lS}\right)^{\alpha_l}\left(S_2^{nS}\right)^{\alpha_n}\left(\hat{S}^m - S_2^{m*}\right)^{\alpha_m} - \left(1+\rho\right)\Lambda_1^S \geq 0,\\
&\left(c_1^N\right)^{\alpha_c}\left(x_1^{lN}\right)^{\alpha_l}\left(S_1^{nN}\right)^{\alpha_n}\left(\hat{S}^m - S_1^{m*}\right)^{\alpha_m} - \left(1+\rho\right)u_0^N \geq 0,\\
&\left(c_2^N\right)^{\alpha_c}\left(x_2^{lN}\right)^{\alpha_l}\left(S_2^n\right)^{\alpha_n}\left(\hat{S}^m - S_2^{m*}\right)^{\alpha_m} - \left(1+\rho\right)^2 u_0^N \geq 0,\\
&\left(c_3\right)^{\alpha_c}\left(x_3^l\right)^{\alpha_l}\left(S_3^n\right)^{\alpha_n}\left(\hat{S}^m - S^{m*}\right)^{\alpha_m} - \left(1+\rho\right)^3 u_0^N \geq 0,
\end{aligned}\right\}\text{utility growth,}$$

and the remaining economic and climate constraints in the optimization program of section S.2.

Figure s.8 and Table s.13 present the transition path for a 1% 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 from the maximization program. Maximizing Generation 1's utility for a sustainable 1% annual growth rate implies a relatively small increase in the utility of Generation 1 (less than 4%), especially compared with the fall in the utility of Generation 2 (that is basically cut in half). 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.8.

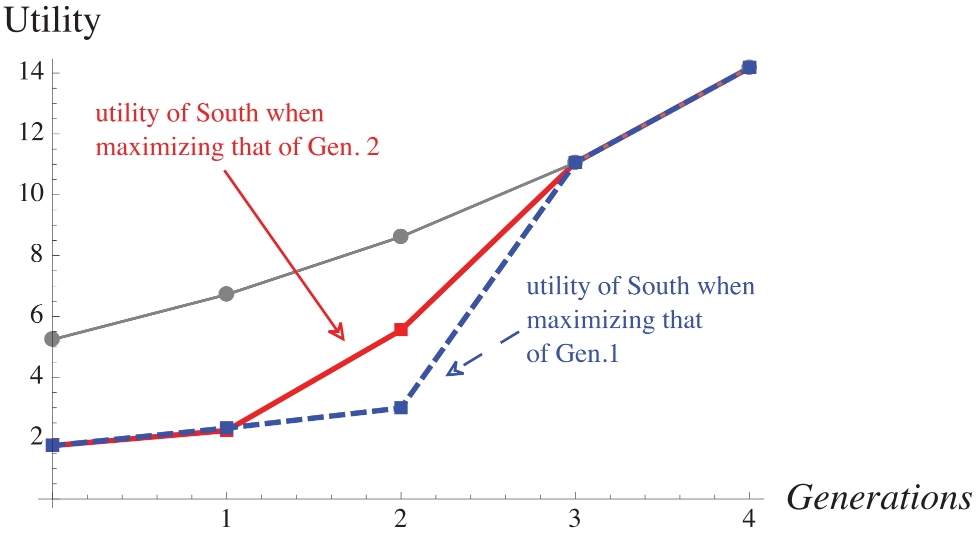

Figure s.8. Optimal paths for the two optimization programs: maximizing the utility of the first or the second generation in South. The dashed, blue line represents utility of South when maximizing that of the first generation. The solid, red line represents the utility of South when maximizing that of the second generation.

WELFARE PATHS for a 1% annual growth rate					
Gen.	t=0	t=1	t=2	t=3	t=4
Max. Utility of Gen. 1 in South					
ΛNt	5.241	6.72123	8.61952	11.0539	14.1759
ΛSt	1.75472	2.33224	2.99093	11.0539	14.1759
Max. Utility of Gen. 2 in South					
ΛNt	5.241	6.72123	8.61952	11.0539	14.1759
ΛSt	1.75472	2.25031	5.55083	11.0539	14.1759
Comparison: % change from MaxGen2 to MaxGen1					
$\frac{\text{MaxGen.1}-\text{MaxGen.2}}{\text{MaxGen.1}}\%$	0.	3.51	−85.59	0.	0.

Table s.13 Optimal paths when maximizing the utility of the first vs. the second generation in South

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