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Who should pay for climate? The effect of burden-sharing mechanisms on abatement policies and technological transfers [*]

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Abstract

Recent international environmental negotiations have highlighted the importance of establishing a commonly agreed approach to attribute climate change responsabilities. In this paper I investigate how choices on allocation mechanisms are likely to affect optimal abatement effort paths and technological transfers. I derive a North-South optimal growth model from the 2007 version of the RICE model allowing for pollution-abating technological transfers and use it to test three different allocation approaches, based on *sovereignty*, *egalitarian* and *polluter pays* principles. Numerical simulations typical of integrated assessment models show that: a) the presence of technical transfers always improves intertemporal global welfare; b) the optimal abatement and technical transfers paths depend on the chosen burden-allocation rule; c) the costs associated with the introduction of a 2-degree limit to temperature increase are in all probability too high to be politically acceptable.

JEL classification numbers: *Q54, F35, O13*

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1 Introduction

Changes in the terrestrial climate pattern are likely to have a wide range of detrimental consequences on the socio-economic system of both developed and developing countries, affecting their productive sectors and consumption habits. The international community has by now fully recognized the necessity to act collectively in order to limit the effects of an increase in global temperatures; a particular attention has been directed to the reduction of Greenhouse Gases (GHGs) emissions, considered the most important anthropogenic factor causing climate change [IPCC, 2007].

Although limited by the sharp non linearities characterizing the climate system, there is a broad acceptance of the main mechanisms relating emissions with carbon atmospheric concentration and the rise in global mean temperatures. A 2-degree Celsius increase from pre-industrial levels is usually regarded as the “safe” threshold to be respected, above which the impacts of climate change could become excessively harsh. The goal was publicly reaffirmed at the 15th Conference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC) held in Copenhagen in December 2009, where a vague recognition that “the increase in global temperature should be below 2 degrees Celsius” and that “deep cuts in global emissions are required according to science” was included in the Conference final statement [UNFCCC, 2009].

How could the global society face such a large-scale effort[1]? Since climate stability is a global public good which no individual country could unilaterally ensure and a global authority with the task of managing emissions is lacking, a compromise among national authorities is the only feasible solution to the issue [Barrett, 2008]. Such agreements are difficult enough to reach when potential participants are symmetric in the salient features of the problem. In addition, global climate change is an extremely asymmetric problem

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[1] Due to the complexity of climate behavior, there exists no certainty regarding the amount of emissions abatement needed to keep the temperature increase below 2 degrees. However, it was estimated that a stabilization of GHGs atmospheric concentration around 445-490 ppm (parts per million of CO2 equivalent) would be needed [IPPC, 2007; IEA, 2009].

since it involves countries which differ in almost every relevant aspect. That is, agreement must be sought among states who differ in their stage of development, prospective costs of unmitigated climate change, costs of mitigation and adaptation, and, most importantly, in terms of their perceived historical responsibility and ability to pay. Indeed, the clear distinction between developed and developing regions and the issues of fairness that this inevitably gives rise to, are the main factors holding back the attainment of a common agreement on emissions reduction and burden sharing.

On one side, developing countries tend to consider the access to energy services and consequent emissions as necessary means to expand their economic systems, ensuring higher standards of living for their population. They usually regard the international focus on climate change as an unfair way to curb their right to develop, especially in the light of the massive cumulative emissions from developing countries during the last two centuries. On the other side, industrialized countries are firstly reluctant to agree on stringent emissions reductions without an active role being played by developing countries in the global effort to abate emissions [Barrett, 2009]. Apart from the strategic issues and open-endedness of emissions that non-participation induces, there are large efficiency gains to be obtained from the participation of developing countries in global climate change mitigation [Nordhaus, 2008]. Secondly, high-income countries are reluctant to provide large transfers of finance or technology to help countries who will soon be economic and strategic competitors.

In a nutshell, given the asymmetric nature of global climate change and the issues of fairness and historical responsibility that this implies, I take the view that climate change mitigation is fundamentally a development problem and has to be linked to equity considerations. The main purpose of this paper is therefore to investigate the effects of the implementation of different fairness principles on the optimal abatement policies of both developed and developing regions. In particular, the analysis focuses on the role played by pollution-abating technological transfers in shaping a more equitable distribution of abatement commitments among countries. For this reason, I build a North-South optimal growth model with environmental externalities and run numerical simulations to test the effects of a set of burden-sharing formulas on domestic mitigation activities and international transfers. Special attention is devoted to the case in which a 2-degree increase in temperatures is imposed as upper bound.

The remainder of the paper is organized as follows. Section 2 offers an overview of the research strands in which the paper is inserted. Section 3 presents the theoretical structure of the base model, where no allocation of responsibilities is made. Section 4 incorporates three different burden-sharing mechanisms and analyzes the results of the numerical simulations. Section 5 concludes.

2 Motivation and literature

The paper relates to at least two parallel strands of research. The first one is dedicated to the investigation of the incentives for, and impact of, technology transfers in the context of climate change, by means of numerical simulations typical of integrated assessment modeling [Yang, 1999; Nordhaus and Yang, 2006; Aronsson et al., 2010]. The second one addresses the equity issues more directly by analyzing the implications of different proposals for the allocation of emissions reductions based on different conceptions of fairness and historical responsibility [Ringius, 2002; Vaillancourt and Waaub, 2004; Leimbach, 2003; Bosetti and Buchner, 2009; Cantore and Padilla, 2010]. What is missing from the literature is the combination of these two aspects of the problem. That is, an analysis of the mitigation efforts and technology transfers required to meet emissions reductions allocated under various conceptions of fairness and historical responsibility.

2.1 Fairness principles and allocation mechanisms

As highlighted in the introduction, progress on climate change mitigation and adaptation requires a clear and agreed distribution of responsibilities that could be considered as “fair” by a majority of countries. This turns out to be a particularly complex task, considering that there exist no universal criteria to evaluate the "fairness" of a proposal and different beliefs on equity can be an extremely powerful source of conflict. A further element of complication is given by the fact that three related but distinct levels of analysis exist, each focusing upon: (a) the general concepts of fairness; (b) the principles used to share costs (or benefits); (c) the operational criteria and indicators [Ringius et al., 2002]. A connection between the three layers is not straightforward because a certain burden-sharing formula can contain elements of more than one equity principle and can be implemented through a variety of operational instruments. Rose et al. (1998) also distinguish between "allocation-based" and "outcome-based" principles, the first being more focused on the distribution of property rights or emissions entitlements, and the second more concerned with sharing the relative costs of abatements or the loss and gains in welfare[2].

A large amount of different allocation schemes have been proposed in policy and academic circles in recent years [Rose et al., 1998; Ringius, 2002; IEA, 2009], each one interpreting and weighting in a different manner countries responsibilities in climate change, their capacity to pay or right to development. For instance, the UNFCCC has adopted the so-called "Common but Differentiated Responsibilities" (CDR) principle that was later used as an attribution scheme in the Kyoto Protocol, according to which only higher income nations - listed in "Annex I" - have quantified reduction commitments and national obligations are decided according to a mix of responsibility and capacity to pay.

For the purposes of this paper, a comprehensive classification of allocation mechanisms is however not necessary, as the analysis will focus on three simple and popular approaches that are currently debated. These are presented in Table 1, together with the principles of fairness they stem from. The distinction of the selected principles between allocation- and outcome-based can be ambiguous, especially in the "polluter pays" case and the consequent mitigation burden sharing, which focuses on the relative contribution to climate change.

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[2] Rose et al. (1998) also point out the existence of a third group of principles called "process-based", which is not considered in the present analysis.

Table 1: Fairness principles and burden-sharing formulas

Fairness principle	Description	Burden-sharing formula
Sovereignty	Every country has the same right to pollute and to be protected from pollution.	*Grandfathering approach.* Emissions are abated keeping countries relative share of global emissions constant to the current level.
Egalitarian	Every individual has the same right to pollute and to be protected from pollution.	*Contraction and Convergence.* Per capita emissions converge to a common level, irrespective of present countries socio-economic conditions.
Polluter pays	Each country is to be held responsible for its total contribution to climate change.	*Brazilian Proposal.* Abatement costs are shared in proportion to countries cumulative emissions or historical contribution to temperatures increase.

Unlike Miketa and Schrattenholzer (2006), who list it within the allocation-based principles group, I model this approach as outcome-based. That is, the allocation mechanism concerns abatement costs, not emissions entitlements[3]. “Sovereignty” and “egalitarian” principles, on the other hand, are modeled as allocation-based mechanisms.

Over recent years, several studies have attempted to analyze the impacts of different burden-sharing formulas on emissions reduction dynamics by means of integrated assessment modeling[4]. Miketa and Schrattenholzer (2006) impose an emissions path leading to an atmospheric concentration of 550 ppm in the MERGE model, and derive countries entitlements by assuming a gradual convergence of emissions per capita, in one case, and emissions per unit of output, in the other. Leimbach (2003) focuses on the equal per

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[3] I consider this approach as more in line with the actual policy proposals that have been formulated [La Rovere et al., 2002].

[4] Integrated Assessment Models (IAMs) are optimal growth models dedicated to the study of economy-energy-environment interactions, based on numerical simulations [Nordhaus, 1994; Manne et al., 1995; Tol, 2002; Hope, 2006; Bosetti et al., 2007]. Although affected by a variety of shortcomings [Ackerman et al. 2009; Mastrandrea, 2009], IAMs are nonetheless very powerful analytical tools and are increasingly used to inform policy makers. This paper is inserted in the same literature, although the modeling approach adopted here can be considered as “conceptual” rather than “descriptive” (DeCanio, 2005). That is, the model proposed is built in a relatively simple fashion in order to grasp the crucial aspects of the development asymmetry surrounding climate change negotiations.

capita entitlements and the effects of introducing trade in pollution permits by means of the ICLIPS model, reaching the conclusion that allowing for trade increases both economic efficiency and equity. Bosetti and Buchner (2009) use the WITCH model together with the Data Envelopment Analysis, an efficiency valuation technique, to test a set of burden sharing mechanisms, showing that a scenario in which the concentration of CO2 stabilizes at 450 ppm and entitlements are allocated according to an equal-per-capita criterion dominates all the others in terms of efficiency. Vaillancourt and Waaub (2004) try a somewhat different exercise, using the AIM model. They select 11 different allocation criteria and then elaborate two different weight sets for these criteria according to the points of view of developed and developing countries. Imposing an emissions path leading to a CO2 concentration of 550 ppm, they show how using one set instead of the other would lead to very different allocation entitlements among regions, both now and in the future. Cantore and Padilla (2010) use RICE 99 to investigate the impact of the sovereignty principle, the equal per capita allocation and the Brazilian Proposal on a set of equity indices regarding income and emissions. They, as well, assume an emissions path that leads to a concentration of 550 ppm. None of the mentioned papers, however, allow for unilateral technical transfers between regions.

2.2 The role of technical transfers

Technical transfers directed to promote pollution abatement and sustainability in developing regions[5] have been considered as a crucial issue in international cooperation on climate change since the first phases of the negotiation process[6]. Their importance is highlighted by the inclusion of the Clean Development Mechanism (CDM) - through which Annex

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[5] In IPPC (2000) technology transfer is defined as “a broad set of processes covering the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders such as governments, private sector entities, financial institutions, non-governmental organizations (NGOs) and research/education institutions”.

[6] Article 4.1.c of the UNFCCC, signed in 1992, states that all countries should “promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases”.

I countries can voluntarily invest in abatement activities located in developing nations[7] - in the “flexibility mechanisms” envisioned in the Kyoto Protocol. Although the CDM statutory mandate is not to promote transfers, approximately half of the emissions reduction achieved through the Mechanism involves a transfer of technology, in terms of either equipment or knowledge (UNFCCC, 2010). More flows directed to transfer technologies for greenhouse gases mitigation are financed through bilateral Official Development Assistance and multilateral programs such as the Global Environment Facility (Peterson, 2008).

However, although unilateral technical transfers are regarded as crucial in climate change global mitigation strategy, the effort dedicated to investigate them in terms of economic modeling has been relatively small[8]. To my knowledge, Yang (1999) is the first attempt of analyzing the issue of unilateral transfers by means of integrated assessment modeling. Using a North-South framework very similar to the one used in this paper, Yang shows that unilateral transfers of pollution-abatement technology would benefit both the North and the whole world economy. In other words, the global features of climate change leads to the inclusion of the South mitigation effort into the optimal strategy of more developed countries. Similar results are obtained by Yang and Nordhaus (2006) with a multi-regional model. Kohn (2001) builds on the same theoretical framework by allowing for trade in a North-South static model and analyzing the case in which unilateral technical transfers by the North have to be contingent to equiproportional domestic abatement activities by the the South. More recently, Aronsson et al. (2010) introduce the effects of transfers on South total factor productivity and the existence of an informal labor sector. All the mentioned papers reach the results that allowing for unilateral voluntary technical transfers brings about an increase in global welfare.

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[7] The CDM is expected to reach approximately 2 billions of issued CERs (Certified Emission Reduction) by the end of 2012, each CER corresponding to one tonne of CO2 equivalent.

[8] More attention has been devoted to different forms of technology transfers, usually embedded in trade, foreign direct investments and energy R&D spillovers (De Cian, 2005; Bosetti et al., 2008). For an empirical survey, see Peterson (2008).

This paper contributes to the literature in two ways. First of all, I combine the research strands outlined above by analyzing the effects that different burden-sharing rules are likely to have on abatement and technical transfers strategies. In order to investigate these effects I derive a stylized North-South model from the 2007 version of the RICE[9] (Regional Integrated Model of Climate and the Economy) [Yang, 2008], allow for pollution-abating technical transfers, and test three different mechanisms through which the burden of climate change mitigation could be distributed among regions. To my knowledge, this has never been attempted previously. The numerical results show that optimal policies are significantly altered by the choices on the allocation mechanism to be adopted, both in the North and the South. In the second place, I put special attention on the scenario in which a limit of two degrees of increase with respect to pre-industrial levels is imposed on global temperatures, usually not included in the literature on technical transfers. In this case, numerical results seem to suggest that such a threshold is not likely to be respected, given the exceptionally large domestic mitigation costs and technical transfers that it would entail.

3 The base model

Two regions exist in the stylized world economy of this paper: a North (N) and a South (S). The productive sectors of the two economies are negatively affected by the presence of a stock pollutant in the atmosphere, which accumulates depending on the amount of greenhouse gas emissions. In their turn, emissions are a byproduct of the production process. Accordingly, both economies have the option to decrease polluting emissions in any given period by diverting a part of their resources to unproductive abatement activities. In

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[9] The RICE [Nordhaus and Yang, 1996] is a regional, dynamic, general-equilibrium model in which economic processes are integrated with a climate module through greenhouse gas emissions on one side, and negative externalities from an increase in global temperatures on the other. It can be considered as the multi-regional version of the DICE (Dynamic Integrated Climate and Economy model) [Nordhaus and Boyer, 2000].

addition to that, the North can also transfer part of its income to abate South emissions[10].

In both economies a single good $Q_i(t)$ is produced according to a standard Cobb-Douglas technology:

$$Q_i(t) = \Omega_i(t) A_i(t) K_i(t)^{\gamma} L_i(t)^{1-\gamma}, \quad 0 < \gamma < 1 \tag{1}$$

for i=N,S. $K_i(t)$ is the physical capital stock, $L_i(t)$ is the labor force, $A_i(t)$ is the total productivity of factors[11] and $\Omega_i(t)$ represents climate damage, which is a nonlinear function of the increase in temperatures:

$$\Omega_i(t) = \frac{1}{1 + a_{1,i} T(t)^{a_{2,i}}} \tag{2}$$

where $T(t)$ is the temperature increase with respect to pre-industrial levels, and $a_{1,i}$ and $a_{2,i}$ are parameters. Global temperatures are modeled to rise if an increase of the concentration of the pollutant in the atmosphere occurs (See Appendix). Polluting emissions, in their turn, are determined in the following way:

$$E_N(t) = \sigma_N(t)[1 - \mu_N(t)]Q_N(t) \tag{3}$$

$$E_S(t) = \sigma_S(t)[1 - \mu_S(t) - \nu(t)]Q_S(t) \tag{4}$$

Parameter $\sigma_i(t)$ is the exogenously given emissions/output ratio in the absence of abatement activities. It is assumed to decrease in time[12]. Pollution abatement is managed through the parameter $\mu_i(t) \in [0, 1]$, which represents the domestic control rate. A value of $\mu_i(t)$ equal to zero means that no effort is put in abatement activities, while a value

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[10] This is the only economic exchange that occurs between the two regions, as trade is not included in the analysis.

[11] Both regions total factor productivities increase in time in an exogenous fashion. See Appendix.

[12] This is a common assumption in models that do not include endogenous technical change, such as DICE and RICE. The time-decreasing path of $\sigma_i(t)$ is supposed to represent the progressive relative reduction in the impact on environment that economies seem to experience through their development process. See Appendix for the values used in simulations.

equal to 1 represents a complete decarbonization of the economies[13]. In addition to $\mu_i(t)$, South emissions can also be abated by a flow of technological transfers coming from the North, that are represented by the parameter $\nu_i(t) \in [0,1]$. In this way, general purpose transfers are avoided, as the South economy is forced to employ the financial flows from the donor in emissions abatement activities and is unable to pursue any other purpose than that (Yang and Nordhaus, 2006).

The net output of both economies is negatively affected by the diversion of resources to domestic mitigation activities, through an abatement cost function of $\mu_i(t)$. North output is also reduced by the cost of technical transfers, while South output is completely unaffected by them. The equations defining regional net output $Y_i(t)$ are the following:

$$Y_N(t) = Q_N(t)[1 - b_{1,N}\mu_N(t)^{b_{2,N}}][1 - c_1\nu(t)^{c_2}] \tag{5}$$

$$Y_S(t) = Q_S(t)[1 - b_{1,S}\mu_S(t)^{b_{2,S}}] \tag{6}$$

where $b_{1,i}$, $b_{2,i}$, c_1 and c_2 are the parameters that define the cost that countries have to bear when abating domestic pollution or transferring technology.

Net output $Y_i(t)$ is then distributed between consumption $C_i(t)$ and investments in physical capital $I_i(t)$ through the simple accounting equation:

$$Y_i(t) = C_i(t) + I_i(t) \tag{7}$$

Finally, the individual instantaneous utility is modeled to be a logarithmic function of per capita consumption. The instantaneous utility of North and South regions is therefore equal to the logarithm of individual average consumption multiplied by the total amount

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[13] This could be considered as an excessive simplification of reality. With such a theoretical framework economies are supposed to be able to instantaneously abate emissions through $\mu_i(t)$ (similarly to the "dirtiness of technology" parameter in Stokey (1998)). In reality, however, decarbonization can only be obtained by a prolonged and resource-consuming process of research and development of cleaner technologies. The literature on endogenous technical change has in part overcome the issue (Buonanno et al., 2003; Popp, 2004). For simplicity, these advancements will not be considered here but could be fruitfully included in further work on the topic.

of the population[14]:

$$U_i(t) = L_i(t) \ln \left(\frac{C_i(t)}{L_i(t)} \right) \tag{8}$$

As Yang (1999) and Nordhaus and Yang (2006), I focus the analysis on the cooperative efficient solution, in which externalities from climate change are fully internalized by a global social planner. The planner maximizes the intertemporal sum of the discounted utilities of the two regions using utilitarian weights:

$$W = \sum_{t=0}^{\infty} \beta^t (U_N(t) + U_S(t)) \tag{9}$$

where β^t is the discount factor[15].

A large and interesting debate has taken place during recent years regarding the "right" weights to be used when different regional utilities are aggregated by a social planner. The choice regarding weights can be reconducted to whether efficiency or equity objectives are judged to be more important, and has crucial implications in terms of welfare and distribution. A significant number of IAMs use the so-called Negishi weights to equalize marginal productivities of physical capital across regions[16] (Manne et al., 1995; Bosetti et al., 2007; Yang, 2008). If not applied, a global social planner would transfer resources from high-income countries to low-income ones to take advantage of the higher marginal productivity of capital, thus increasing global social welfare. Consequently, in order to abstract the climate change problem from the more complex issue of underdevelopment and convergence, Negishi weights are applied by imposing a higher weight to more developed regions utility. This theoretical structure has been, not surprisingly, criticized by researchers more

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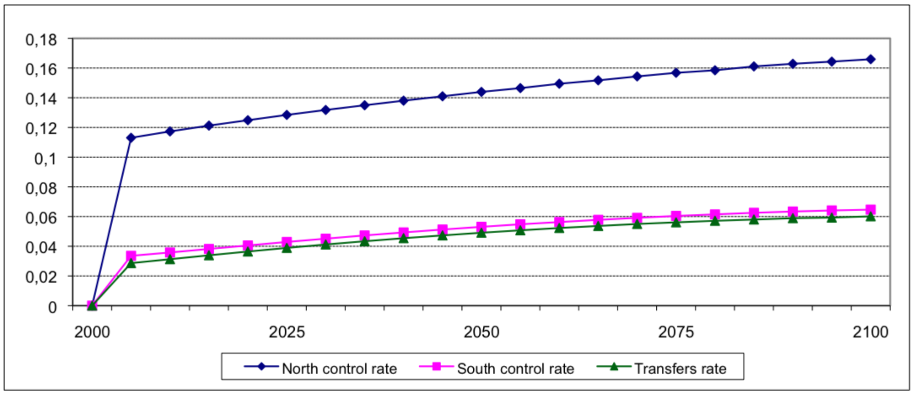
[14] Population dynamics is exogenous. Population in the North is assumed to increase and then stabilize at approximately 1 billion individuals by 2100, while population in the South stabilizes just over 7 billions. These projections are roughly coincident with IAASA projections, available at www.iiasa.ac.at.

[15] The social rate of time preference is assumed to be constant and equal to 5% per year. Therefore, $\beta \approx 0.95$.

[16] Equalizing the marginal productivity of capital is equivalent to equalize the marginal utility of consumption (Stanton, 2011).

Figure 1: Control rates and transfers in the base case



concerned with fairness issues that argue instead for the introduction of equity weights[17] (Azar, 1999; Anthoff et al, 2009; Stanton, 2011). I abstract from this discussion by assuming relatively "neutral" utilitarian weights. That is, the utilities of both regions are valued equally and aggregated without imposing any weight adjustment.

The numerical calibration of the model draws extensively from the 2007 version of the RICE model (Yang, 2008). Values for North and South parameters are weighted averages of RICE regional parameters, and their initial values are aggregated values of RICE regional ones[18]. The values of the parameters that enter the functions of abatement cost and technical transfer are taken from Yang (1999)[19]. The base year of the model is 2000, and the simulations are ran for 40 periods, each period representing 5 years. Only the first 21 periods, corresponding to the period 2000-2100, are shown in the results. All values are in 2000 US$.

A first set of simulations is run with no specific allocation of emissions and no temperature limit. The resulting paths of the domestic control rates, $\mu_N(t)$ and $\mu_S(t)$, are shown in

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[17] Some very well-known integrated assessment models such as PAGE (Hope, 2006) and FUND (Tol, 2002) use equity weights.

[18] Six regions populate the RICE model: United States, European Countries and Japan compose the North region of this paper; China, Former Soviet Union and the Rest Of the World compose the South.

[19] See Appendix.

Figure 2: Emissions in the base case

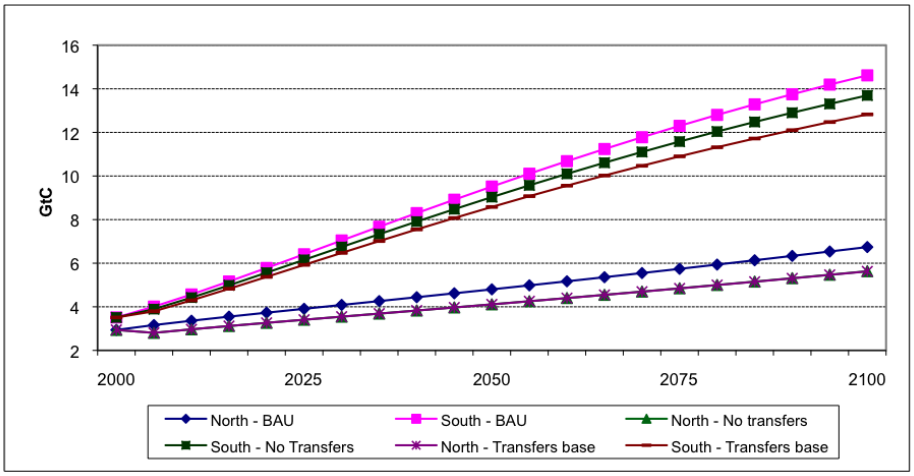

Figure 1 together with the transfers control rate $\nu(t)$. Both countries embark on abatement activities from the second period onwards (in the first period $\mu_i(t)$ is set to be equal to zero), slowly increasing over time the share of resources devoted to them. The transfer control rate shows a similar trend. In financial terms, the total amount of transfers gradually rises to reach a value of approximately 40 billion dollars in 2100. Emissions steadily grow both in the North and in the South, driven by the increase in output. In Figure 2 the path of emissions in the base case with transfers is compared to the business-as-usual scenario (BAU) and the case in which countries abate domestically but no transfer is allowed[20]. Not surprisingly, emission trends are lower for both regions when abatement activities are permitted. The introduction of transfers produces a further decrease of emissions in the South, while they do not have a particularly strong impact on North emissions. Global temperature increases approximately by 2.6 degrees with respect to pre-industrial levels by 2100 (and by almost 5 degrees in the last period of simulation). These results are in line with Yang (1999), although his results indicate slightly higher values for $\mu_N(t)$ and total transfers.

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[20] Technically, the business-as-usual scenario is obtained by setting $\mu_i(t)$ and $\nu(t)$ equal to zero in all the periods; the "no transfers" case, on the other hand, has a free $\mu_i(t)$ and $\nu(t)$ set equal to zero.

4 The allocation of emissions and mitigation costs

4.1 Three burden-sharing formulas

The previous section deals with the case in which no burden-sharing rule is clearly specified, and therefore the resulting allocation of emissions can be considered as "optimal". However, climate change negotiations are inherently affected by political and equity consideration and in such a context the specification of clear and agreed rules, even if not perfectly efficient, turns out to be crucial. For this reason, I now introduce some allocation mechanisms in the model dynamics to investigate their effects on domestic control rates $\mu_i(t)$, technical transfers, emission paths and overall welfare. In particular, the analysis focuses around the grandfathering approach, the convergence of per capita emissions, and the Brazilian proposal on historical emissions. The approach adopted to insert allocation mechanisms in the model differs from the one usually used in the literature, which consists in imposing a specific path of future emissions (e.g. the one that leads to a stabilization of CO2 atmospheric concentration at 550 ppm) and then, in each period, allocate the available emissions among regions according to the selected burden-sharing formula (Miketa et al., 2006; Bosetti and Buchner, 2009; Cantore and Padilla, 2010). In this paper no fixed scenario is chosen, letting emissions to be determined endogenously by the intertemporal optimization process.

(1) *Grandfathering.* The first case deals with the application of the sovereignty principle to climate change negotiations, according to which each country has the same right to pollute or to be protected from pollution externalities and the level of current emissions represents a status quo right. The sovereignty approach is the one judged to be the most likely for post-Kyoto commitments according to a poll conducted among climate change experts by Bohringer and Loschelw (2005). This can be regarded as an especially unfair criterion if the right to development of poorer countries is considered. However, as Kohn

(2001) argues, the inclusion of transfers in the framework makes it more equitable and inserts some elements of the “ability to pay” approach. In the grandfathering case emissions entitlements are thus distributed according to the current relative contribution to global emissions. In the initial simulation period (2000) the North accounts for approximately 46% of global emissions and the South for the remainder. These initial shares are kept constant throughout the simulation.

(2) *Equal per capita emissions.* In this case, the right to pollute or to be protected from pollution is assumed to pertain to individuals rather than nations. For this reason, an equal share of entitlements is assigned to each individual and regions are allowed to produce emissions proportionally to the level of their population. This is a vastly popular proposal both among policy-makers of developed countries and academic researchers[21]. Given the strong inequality in the current distribution of per capita emissions [IEA, 2009] and the drastic modification to trends in pollution that an implementation of the egalitarian principle would entail, I follow Meyer (2000) and Miketa and Schrattenholzer (2006) by allowing a period of time for the transition to take place. A smooth convergence process is imposed through the formula:

$$\frac{E_i(t+1)}{\sum_i E_i(t+1)} = \frac{E_i(t)}{\sum_i E_i(t)} - \left(\frac{E_i(t)}{\sum_i E_i(t)} - \frac{L_i(t)}{\sum_i L_i(t)}\right)\left(\frac{t}{t_{conv}}\right) \tag{10}$$

The last term on the right-hand side of the equation manages the speed of convergence, with t_{conv} specifying the date in which the convergence process terminates. The default value for t_{conv} in this paper is 2075, as in Llavador et al. (2010)[22].

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[21] Leimbach (2003) argues that “the moral superiority of the equal per capita allocation of emission permits follows from the global commons property of the atmosphere as a sink for anthropogenic greenhouse gases and its limited sink capacity.”

[22] This can be considered as the most realistic assumption. Given the fact that the major part of the convergence takes place in the first periods, reducing its speed as it approaches t_{conv}, 2050 would have required an effort by developed countries that I consider unlikely to take place.

(3) *Cumulative emissions.* This approach, which has become widely known as the Brazilian Proposal [La Rovere et al., 2002], is more concerned with the historical path of emissions rather than their current levels. The climate system is inherently characterized by time lags, as past emissions remain for decades in the atmosphere and contribute to the present increase in temperatures. For this reason many, especially from developing countries, advocate for the inclusion of historical emissions in the criteria to allocate future emissions as a means to grasp some elements of current development asymmetries. The cumulative emissions approach is however slightly more complicated to model than the previous ones, as there exists a wide variety of scientific and policy choices to make when calculating countries contribution to climate change. These are related to the attribution period, the evaluation date, the indicator to be used[23], and other elements [Den Elzen et al. 2005; Dellink et al., 2009]. Also, a problem regarding data availability and emissions estimation clearly exists. In the present paper, somewhat arbitrarily, the chosen starting period to calculate emissions is 1900, and the indicator is the amount of CO2 emissions from energy use. Using these specifications in year 2000 the North can be considered responsible for 634 GigaTonnes of CO2 emissions, the South for 449 [World Resources Institute, 2011]. In the simulations each region share of total abatement cost in every period is imposed to be equal to the relative contribution to historical emissions up to then. In every period new historical emissions from 1900 are calculated, allowing for a time-varying evaluation date able to catch the effects of the realistic future increase in South emissions. This is a somewhat different modeling structure with respect to scenarios (1) and (2), as it does not impose any particular dynamics on the emission entitlements and can therefore be considered an outcome- rather than allocation-based approach.

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[23] A chain of causality exists in global warming [Enting and Law, 2002]. Indicators for climate change could be located in any point of the chain, changing countries relative contribution. In general, a trade off exists between accuracy of measurement (early in cause-effect chain) and accuracy of impact (later in the chain): emissions are easily estimated but are quite a poor indicator of climate change responsibility, while temperature increase is a much more telling indicator but it is hard to disentangle each country role in it. Industrialized countries are likely to show a larger share of responsibility as one moves down the chain, since their emissions have been circulating in the atmosphere for long time by now.

Table 2: Welfare values

	No allocation		**Grandfather**		**Per capita**		**Cumulative**	
	optimal	2deg	optimal	2deg	optimal	2deg	optimal	2deg
Global	1,37070 *(0,00003)*	1,36779 *(0,00459)*	1,36953 *(0,00262)*	1,36668 *(0,00974)*	1,36921 *(0.00001)*	1,36697 *(0,00436)*	1,37066 *(0,00004)*	1,36642 *(0,00545)*
North	0,72760 *(-0,00002)*	0,72550 *(0,00014)*	0,72699 *(-0,00004)*	0,72535 *(-0,00176)*	0,72596 *(-0,00001)*	0,72441 *(-0,00072)*	0,72763 *(-0,00001)*	0,72581 *(-0,00090)*
South	0,64310 *(0,00005)*	0,64228 *(0,00445)*	0,64254 *(0,00266)*	0,64133 *(0,01150)*	0,64325 *(0,00002)*	0,64255 *(0,00507)*	0,64302 *(0,00005)*	0,64060 *(0,00635)*
Temp	2.623	1.991	2.450	1.995	2.476	1.986	2.647	1.970

Table 2 shows the scaled welfare values resulting from scenario simulations, and the projected rise in temperatures[24]. First of all, consider the numbers in brackets, which represent the difference between the scenario welfare value and the welfare value of the same scenario *without* transfers (i.e. with $\nu_i(t)$ set equal to zero in all periods). These figures suggest that allowing for North-South transfers always produce an increase in global welfare, whatever allocation mechanism is chosen. This is especially true when the limit of 2 degrees in temperatures is imposed. As it could be expected, the overall variation in utility is a combination of changes in North and South welfare values. The former are almost always negative, indicating that, from the North perspective, the benefits from the additional mitigation that takes place in the South because of the transfers are in general lower than the associated domestic costs; the latter are always positive and more than compensate North negative values.

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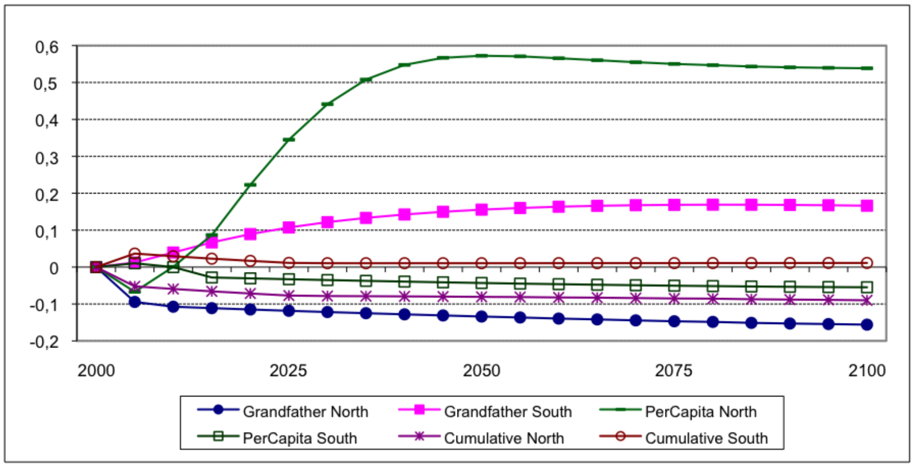
[24] The Global, North and South welfare values are obtained through the intertemporal optimization of the sum of discounted utilities using utilitarian weights (Equation 9). Given the logarithmic functional form of welfare, even small changes in values are to be considered as significant. Numbers in brackets represent their variation with respect to the case where technical transfers are not allowed. *Temp* is measured as the variation between the scenario expected temperature in 2100 and the pre-industrial levels.

Figure 3: Change in $\mu_i(t)$ with respect to the "no allocation" scenario

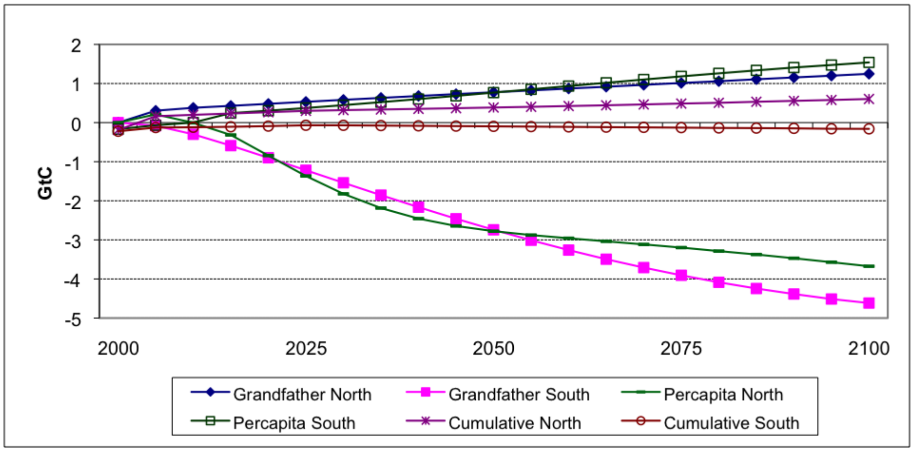


4.2 The optimal scenario

I will first of all concentrate on the "optimal" case, as to say the scenario in which no limit on temperature increase is imposed. Figures 3 and 4 show the differences in the domestic control rates $\mu_i(t)$ and the polluting emissions between the three selected burden-sharing formulas and the "no allocation" scenario. Figure 5 illustrates the different trends in technical transfers.

The grandfathering and the equal per capita entitlements scenarios are the ones in which domestic control rates and emissions paths are subject to the most relevant variations. In the grandfathering case, the trend of the North domestic control rate $\mu_N(t)$ is lower than the "no allocation" scenario, while $\mu_S(t)$ is higher. By the end of the century, North and South domestically abate, respectively, 20% less and 20% more than in the reference scenario. As a consequence, North emissions are allowed to grow, while South emissions decrease by almost 5 Gigatonnes by 2100. This reduction is financed partly by the South abatement activities and partly by the massive increase in the optimal transfers, shown in the right panel of Figure 5. That is, when an excessive burden is put on the shoulders of developing countries, as it happens when the grandfathering approach is adopted, the

Figure 4: Change in emissions with respect to the “no allocation” scenario

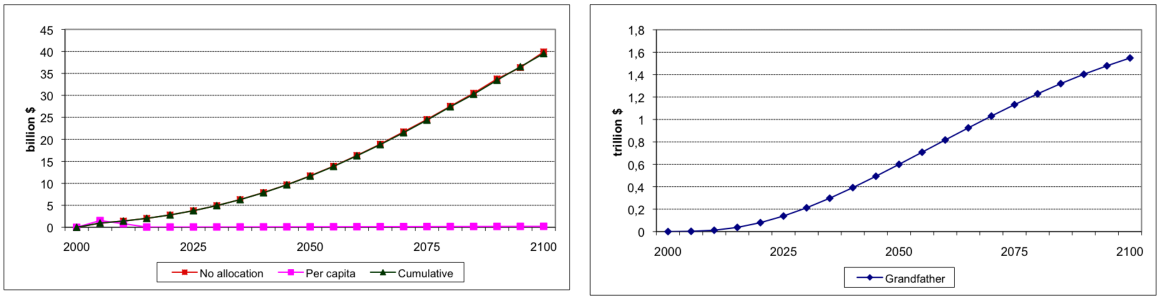


optimal cooperative solution involves a huge amount of flows of financial resources from the North to the South. This result supports the opinion according to which allowing for transfers transforms the grandfathering approach in a combination of the sovereignty and the “ability to pay” principles (Kohn, 2001).

When entitlements are allocated by way of a convergence process of per capita emissions the optimal results are, not surprisingly, specular to the previous scenario. The North is required to embark in remarkably high abatement activities that result in a strong reduction of emissions; at the same time the South is allowed to let its emissions grow without almost any restraints. Both $\mu_S(t)$ and $\nu(t)$ remain close to zero throughout the simulation period, as in this scenario nor domestic abatement nor pollution-abating technical transfers are needed in the South. This result is clearly due to the large (and expanding) gap in population levels between the two regions.

The Brazilian Proposal scenario yields more unexpected results. In international climate change negotiations, developing countries have repeatedly and strongly argued for the inclusion of historical emissions in the set of criteria through which abatement burdens are allocated. This is usually seen as a way to impose a higher burden on the shoulders of those countries that have been emitting industrial greenhouse gases into the atmosphere

Figure 5: Technical transfers



(a)

(b)

for at least two centuries, and to alleviate the "development costs" that poorer countries would suffer if they required to divert resources in abatement activities. However, this does not seem to be the case, at least according to the stylized simulated model used here. On the contrary, the implementation of the Brazilian Proposal gives the impression of favoring the North, that can reduce its domestic control rate thus increasing emissions, while the opposite happens in the South. The main explanation for this feature lies on the fact that in a cooperative solution with no allocation the share of abatement costs assigned to the developed region is much higher than if cumulative emissions were taken into account. That is, the implementation of the Brazilian Proposal in a cooperative setting *increases* the relative burden of the South, instead of reducing it. This can be seen in Figure 6 where the share of the South in total abatement costs is shown[25]. In both the "no allocation" case and the scenario with a convergence of per capita entitlements, the South share is very close to zero. In the grandfathering case it is roughly equal to one (although, if transfers were included in the figure, the North would be the one sustaining the great majority of overall costs). Finally, when abatement costs are allocated according to historical responsibility, the South share places itself in an intermediate position, allowing the North to abate relatively less than in the reference scenario.

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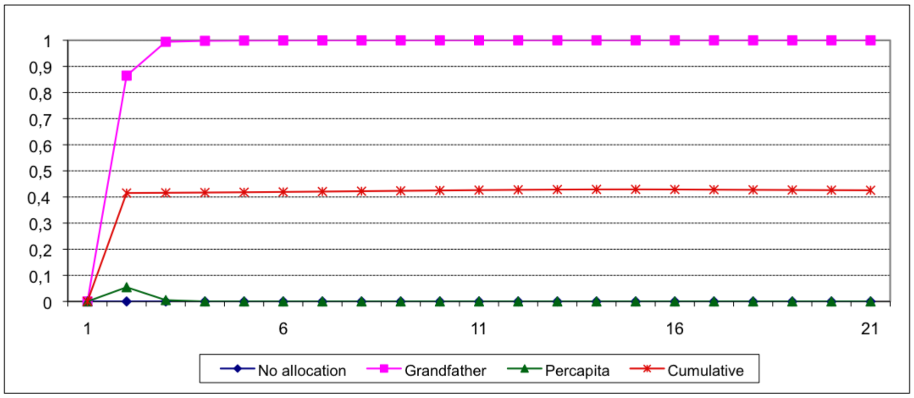
[25] Figure 6 refers just to domestic abatement costs. Transfers are not included in the computation.

Figure 6: South share in total abatement costs



4.3 The 2-degree limit scenario

The scenarios shown in the previous subsection put no limit to global atmospheric temperature. As a consequence, in 2100 the temperature increase with respect to pre-industrial levels is roughly equal to 2.5 degrees Celsius, depending on the selected allocation mechanism, and to approximately 5 degrees in 2195 (last period of the simulation). These "optimal" results are clearly dependent on the calibration of the climate damage function. However, the dynamic behavior of terrestrial climate is still essentially unknown and deterministic models like the one used here may turn out to be unable to grasp the full consequences of such a rise in temperatures. For this reason, as highlighted in the introduction, policy-makers have identified a benchmark threshold to be respected, i.e. an increase of 2 degrees with respect to pre-industrial levels. I thus now introduce in the model an upper limit on temperatures[26] in order to analyze its effects in terms of abatement efforts and technical transfers.

The results are striking. Both regions manage to reduce their emissions to zero thus completely decarbonizing their economies by the end of the century, and the 2-degree limit is respected (Table 2). However, this result comes with extremely high costs. Figure

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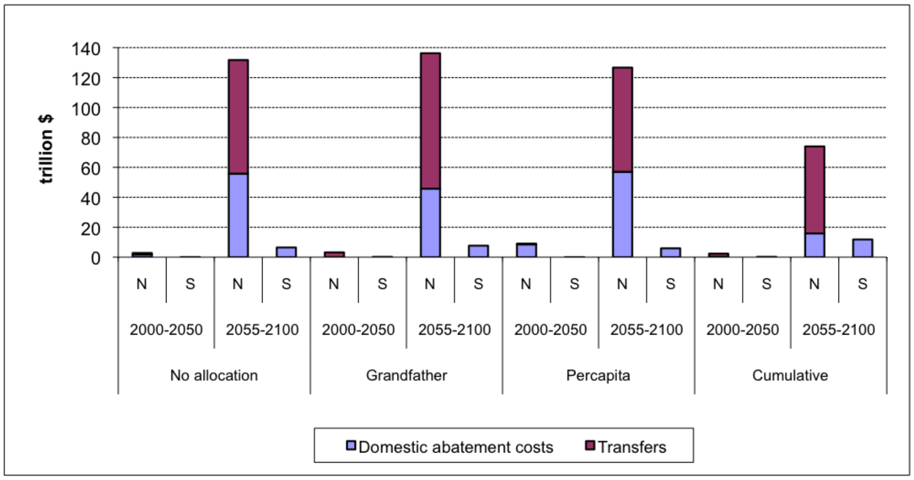
[26] The temperature limit of 2 degrees is simply introduced as an upper bound for the variable representing atmospheric temperature increase with respect to pre-industrial levels, to be satisfied throughout the intertemporal maximization process.

Figure 7: Cumulative abatement costs and transfers in the 2-degree limit case



7 illustrates the projected cumulative abatement costs in the two halves of the century (2000-2050 and 2055-2100). Pollution-abating transfers are added to North costs columns. Abatement efforts are now in the range of trillions US$, and mainly concentrated in the second half of the century. The major share of the burden is now clearly on the shoulders of the more developed region, irrespective of the selected allocation mechanism. A variable portion of the total costs suffered by the North consists in technical transfers to the South, who therefore decarbonize primarily through abatement activities financed by the North.

These projection are most probably to be regarded as infeasible, at least in political terms, as they would require a disproportionate commitment from developed countries. Considering that the U.S. preferred to opt out from the quite mild obligations contained in the Kyoto Protocol, it would be hard to imagine them complying with the commitments shown in Figure 7, especially when this would mean transferring such a vast amount of resources to countries that will soon be strategic competitors. According to the stylized model used here, satisfying a 2-degree temperature limit seems to be confined in the realm of infeasible and unrealistic outcomes.

5 Conclusions

The purpose of this paper has been to investigate the effects on abatement and technical transfers policies of a range of possible burden-sharing mechanisms: (i) allocation of emission entitlements according to the current relative share of global emissions, (ii) convergence of per capita emission entitlements to a common level by 2075, and (iii) allocation of total abatement costs in proportion to the relative contribution to historical emissions. In order to do this, I have built a North-South optimal growth model with climate change externalities, where both domestic abatement and transfers of abatement technologies are allowed. The numerical simulations regarding a cooperative solution have given some interesting and at times unexpected results.

First of all, when a technical transfers parameter is introduced in the model so that the North can devote its own resources to pollution abatement in the South, the presence of transfers allows the global planner to increase its objective function in every single scenario tested, confirming their crucial role in international environmental negotiations. However, different methods of distributing the burden of climate change mitigation are likely to produce relevant variations on the emission paths, abatement efforts and technical transfers with respect to the "no allocation" reference scenario. A particularly unexpected result regards the Brazilian Proposal on historical emissions, which seems to favor the more developed region instead of the developing one.

The imposition of a 2-degree limit on temperatures increase yields lower welfare values than the "optimal" case, in every scenario considered and for both the North and the South economies. But the most prominent result in this case is the gigantic amount of resources directed to pollution abatement that a cooperative solution would involve, either through domestic abatement or through transfers. Such a large effort is in all probability to be considered unrealistic in the current state of environmental negotiations.

Table 3 sums up the results, showing the ranking of the allocation mechanisms in terms of welfare. The first best choice for a global social planner is to choose no particular burden

Table 3: Allocation mechanism ranking

	Optimal			**2 degrees limit**		
	Global	**North**	**South**	**Global**	**North**	**South**
1	No allocation	Cumulative	Per capita	No allocation	Cumulative	Per capita
2	Cumulative	No allocation	No allocation	Per capita	No allocation	No allocation
3	Grandfather	Grandfather	Cumulative	Grandfather	Grandfather	Grandfather
4	Per capita	Per capita	Grandfather	Cumulative	Per capita	Cumulative

sharing mechanism, so to have an "optimal" allocation of emissions and costs. This applies to both the optimal and the 2-degree limit runs. The ranking of the remaining scenarios is however different in the two cases: if the temperature limit is respected, the highest utility is yielded by the equal per capita scenario; otherwise the historical responsibility scenario is to be preferred. As for regional rankings, some counterintuitive results are obtained. The North appears to obtain higher welfare levels with the cumulative emissions approach in both the optimal and 2-degree limit runs. As discussed in section 4.2 this is due to the fact that allocating abatement costs according to cumulative emissions increases the South share of abatement costs instead of reducing it. The grandfather approach generates an even more beneficial distribution of costs for the North, but the large quantity of transfers attached makes the scenario less ideal. The South, on the other hand, would unmistakably be better off with the "equal emissions per capita" approach.

The paper is obviously subject to some limitations. Some of them are typical of the majority of integrated assessment models, such as the deterministic framework that does not account for uncertainty in climate sensitivity; the dependence of results on the chosen discounting; the assumptions regarding the future evolution of population or technical progress; and others. The most relevant here concern the exogenous dynamics of the total factor productivity $A_i(t)$, which is the main driver of growth, and the emissions/output ratio $\sigma_i(t)$ (see Appendix). Regarding the latter, the absence of mechanisms to endogenize technical change indubitably affect the explicatory power of the model. All the above mentioned issues could be fruitfully considered in future research.

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Appendix: Model Equations and calibration

Notation

$Q_i(t)$	Gross output
$Y_i(t)$	Net output
$\Omega_i(t)$	Damage function
$C_i(t)$	Consumption
$A_i(t)$	Total factor productivity
$K_i(t)$	Physical capital stock
$L_i(t)$	Population
$I_i(t)$	Investments in physical capital
$E_i(t)$	Emissions
$CE_i(t)$	Cumulative emissions
$\sigma_i(t)$	Emissions-output ratio
$\mu_i(t)$	Domestic control rate
$\nu(t)$	Technical transfer rate
$B_i(t)$	Abatement costs
δ_K	Physical capital depreciation rate
$M(t)$	Atmospheric GHG concentration
$T_1(t)$	Atmospheric temperature change
$T_2(t)$	Oceanic temperature change
$F(t)$	Total radiative forcing
$f(t)$	Exogenous radiative forcing

Economic module

$i = N, S$

Production function (gross output):

$$Q_i(t) = \Omega_i(t)A_i(t)[K_i(t)^{\gamma}L_i(t)^{1-\gamma}] \tag{.1}$$

Net output:

$$Y_N(t) = Q_N(t)[1 - b_{1,N}\mu_N(t)^{b_{2,N}}][1 - c_1\nu(t)^{c_2}] \tag{.2}$$

$$Y_S(t) = Q_S(t)[1 - b_{1,S}\mu_S(t)^{b_{2,S}}] \tag{.3}$$

Accounting equation:

$$C_i(t) = Y_i(t) - I_i(t) \tag{.4}$$

Percapita consumption:

$$c_i(t) = \frac{C_i(t)}{L_i(t)} \tag{.5}$$

Dynamics of capital:

$$K_i(t+1) = I_{K_i} + (1 - \delta_K)K_i(t) \tag{.6}$$

Emissions:

$$E_N(t) = \sigma_N(t)[1 - \mu_N(t)]Q_N(t) \tag{.7}$$

$$E_S(t) = \sigma_S(t)[1 - \mu_S(t) - \nu(t)]Q_S(t) \tag{.8}$$

Instantaneous welfare function:

$$U_i(t) = L_i(t)\ln[c_i(t)] \tag{.9}$$

Objective function:

$$W = \textstyle\sum_{t=0}^{\infty} \beta^t(U_N(t) + U_S(t)) \tag{.10}$$

Climatic module

$$M(t) = m + \beta(E_N(t) + E_S(t)) + (1 - \delta_M)M(t-1) \tag{.11}$$

$$T_1(t) = T_1(t-1) + \tfrac{\tau_2[F(t) - \lambda T_1(t-1)] - R_2[T_1(t-1) - T_2(t-1)]}{R_1 \tau_2} \tag{.12}$$

$$T_2(t) = T_2(t-1) + \tfrac{T_1(t-1) - T_2(t-2)}{\tau_2} \tag{.13}$$

$$F(t) = \tau \tfrac{log(M(t)/m)}{log2} + f(t) \tag{.14}$$

$$\Omega_i(t) = 1/[1 + \psi_{1,i} T_1(t) + \psi_{2,i} T_1(t)^2] \tag{.15}$$

Allocation mechanisms

Grandfathering:

$$\frac{E_i(t+1)}{\sum_i E_i(t+1)} = \frac{E_i(t)}{\sum_i E_i(t)} \tag{.16}$$

Percapita emissions convergence:

$$\frac{E_i(t+1)}{\sum_i E_i(t+1)} = \frac{E_i(t)}{\sum_i E_i(t)} - \left(\frac{E_i(t)}{\sum_i E_i(t)} - \frac{L_i(t)}{\sum_i L_i(t)}\right)\left(\frac{t}{t_{conv}}\right) \tag{.17}$$

Cumulative emissions:

$$\frac{B_i(t+1)}{\sum_i B_i(t+1)} = \frac{CE_i(t)}{\sum_i CE_i(t)} \tag{.18}$$

Calibration

Almost all parameter values are derived by from the 2007 six-regions version of the RICE model [Yang, 2008] by aggregation or by computing weighted averages. The parameters that appear in the abatement cost and technical transfer functions are taken from Yang (1999). For simplicity, only the most relevant parameter values are given here:

$b_{1,N}$=0.07 $b_{2,N}$=2.887 $b_{1,S}$=0.12 $b_{2,N}$=2.887 c_1=1.015 c_2=2.887

	A_N	A_S	σ_N	σ_S
1	8.639	0.947	0.128	0.490
2	9.317	1.060	0.117	0.463
3	10.018	1.179	0.109	0.439
4	10.740	1.304	0.101	0.417
5	11.484	1.434	0.095	0.396
6	12.247	1.569	0.089	0.378
7	13.028	1.708	0.084	0.361
8	13.825	1.850	0.080	0.345
9	14.636	1.996	0.076	0.331
10	15.461	2.143	0.072	0.317
11	16.297	2.293	0.069	0.305
12	17.143	2.444	0.067	0.294
13	17.997	2.596	0.064	0.283
14	18.857	2.748	0.062	0.273
15	19.723	2.899	0.060	0.264
16	20.592	3.050	0.058	0.256
17	21.462	3.200	0.056	0.248
18	22.334	3.349	0.055	0.241
19	23.204	3.495	0.054	0.234
20	24.073	3.639	0.052	0.227
21	24.938	3.781	0.051	0.221