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Omar Chisari
Sebastián Galiani
Sebastián Miller

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Inter-American Development Bank
Department of Research and Chief Economist

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Omar Chisari*
Sebastián Galiani**
Sebastián Miller***

* UADE and Conicet
** University of Maryland
*** Inter-American Development Bank

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**Abstract***

This paper compares the optimal dynamic choices between policies of mitigation and adaptation for three economies: Brazil, Chile and the United States. The focus is on the optimal role of mitigation and adaptation for "environmentally small economies," i.e., economies that are witnessing an exogenous increase in emissions to which they are contributing very little. The simulations lead to three main conclusions. First, small economies should concentrate their environmental efforts, if any, on adaptation. This is not a recommendation that such economies indulge in free-riding. Instead, it is based on considerations of cost effectiveness, *ceteris paribus*. Second, small economies that are unable to spend enough on adaptation may end up spending less on mitigation owing to their impoverishment as a result of negative climate shocks. Third, higher mitigation expenditures may arise not only as a result of greater optimal adaptation expenditures, but also because of increased adaptation to the incentives for mitigation provided by richer countries.

**JEL classifications:** Q52, Q54
**Keywords:** Optimal mitigation and adaptation policies, Environmentally small economies

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## 1. Introduction

Anthropogenic climate change constitutes a perfect example of a large-scale market failure. According to the leading authority in this area, the Intergovernmental Panel on Climate Change (IPCC), it also poses a serious threat to humanity's welfare. The Fourth Assessment Report states that the concentration of greenhouse gases (GHGs) produced by our burning of fossil fuels is likely to cause a temperature rise of between 2 and 5 degrees Celsius by the end of the century, with consequences including drier soils, changes in weather extremes, the retreat of mountain glaciers, and rising sea levels (Solomon et al., 2007). These effects are expected to exhibit a great deal of geographical variation and may range from impacts that cause severe damage to productivity-enhancing changes. In spite of this consensus, the complexity of the climate makes any precise prediction of the relationship between specific concentrations of greenhouse gases and changes in global temperatures extremely difficult. Therefore, we are condemned to live with uncertainty. Despite the uncertainty surrounding many aspects of the problem, estimates of the net annual cost of a warmer world are in the neighborhood of from 2 to 3 percent of global GDP (Nordhaus, 2008; Smit and Pilifosova, 2001).

These changes are expected to have a strong impact on developing countries, which are typically responsible for only a small share of total emissions and whose societies tend to be dependent on resources that are extremely climate-sensitive (Adger et al., 2003). The Latin American and Caribbean countries are one example: their contribution to $CO_2$ in the atmosphere, the chief greenhouse gas generated by human activities, represents a scant 3.9 percent of the world total, whereas, for example, the United States is responsible for 23.8 percent (Energy Information Administration, various years).

Mitigation and adaptation are the two basic elements of the strategy to deal with climate change. Mitigation encompasses all actions that contribute to reducing greenhouse gases (GHG) emissions or increasing their capture from the atmosphere and thereby reduce the probability of negative future shocks due to climate change. Adaptation refers to actions to anticipate and/or compensate for the shocks of climate change. It is reasonable to expect that the countries' choices as to what kinds of policies to adopt will be driven by their relative costs and effectiveness.

Given the above statistics, a reduction in the growth rate of $CO_2$ would prove to be an ineffective strategy for the Latin American and Caribbean countries, but it would be a comparatively more effective one, for example, for the United States. This suggests that the optimal strategies may differ across countries, with larger ones (in terms of the emissions they produce) perhaps ending up choosing quite different policies from smaller ones.

The literature, however, has devoted most of its attention to the optimal choice of mitigation policies (see, for example, Copeland and Taylor, 1994; Stokey, 1998; Brock and Taylor, 2010; or Nordhaus, 2008). Adaptation policies are only recently starting to attract attention and to be recognized as a potentially useful instrument (Lecocq and Shalizi, 2007; de Bruin et al., 2009; Chisari and Galiani, 2010; and Hallegatte et al., 2011). Discussions of the optimal choice when both types of policy actions are simultaneously available are even thinner on the ground.

We seek to contribute to a more balanced discussion by presenting a model that is in the spirit of the Dynamic Integrated Climate-Economy (DICE) model (see Nordhaus, 2008) that includes both mitigation and adaptation expenses, as well as parameters that capture relevant decisions and aspects from different types of countries. Although this is already an improvement on most past studies, which include only mitigation policies, we go further by allowing for the possibility that the effects of these (mostly mitigation) policies will differ from country to country depending on the size of each country's contribution to total emissions relative to that of the rest of the world.

In order to depict the optimal trajectories for mitigation and adaptation expenditures under different scenarios, we calibrate the model for environmentally large, medium-sized and small economies (the criteria for this classification will be specified at the end of Section 3.2). The simulations provide us with the following insights. First, small economies will tend to concentrate their environmental efforts, if any, on adaptation. Although, in absolute terms, larger countries may spend more on both mitigation and adaptation, the mitigation/adaptation ratio will be greater for larger economies. Second, small economies unable to spend enough on adaptation may be forced to spend even less on mitigation because of their increased impoverishment under climate shocks. Third, higher mitigation expenditures may arise not only as a result of greater optimal adaptation expenditures, but also because of increased adaptation to the incentives to mitigate provided by richer countries.

These findings provide a new perspective on the Nordhaus-type solution, which requires that the marginal costs of reducing GHGs be equalized in each sector and country, while at the same time ensuring that in every year the marginal cost is equal to the marginal benefit in terms of less future damage. As Nordhaus himself notes (Nordhaus, 2008: 88): "If inefficient implementation occurs (say, through inefficient allocation of permits, differential standards, exclusions, inefficient taxation, or regional exemptions), then the costs will rise and the benefit-cost ratio of even the optimal policy could easily decline …" The first and second results mentioned in the preceding paragraph suggest that there are tensions between the high level of coordination required by those policies and the optimal responses of economies having different environmental profiles, or "sizes," and structural characteristics.

The rest of the paper is organized as follows: the next section presents a brief discussion of the literature on the subject. Section 3 presents the model along with the criteria used for classifying a country as "environmentally small." The idea is to present the basic qualitative characteristics of the model and describe the properties of the steady state. Section 4 presents the results of the model's calibration and several simulations of comparative dynamics. Section 5 concludes.

## 2. Literature Review

The DICE model was first introduced by Nordhaus (1994). It includes economic growth as well as geophysical functions, taking into account emissions, concentrations, climate change, damage, and emissions controls. However, a more recent version of this model (one on which we draw heavily) can be found in Nordhaus (2008), who carried out one of the most exhaustive studies of the economic impact of human activity on climate. He finds that mitigation expenditures ultimately lower total emissions (which in turn affect temperatures, which in turn influence how much of aggregate production is lost), but the possibility of countries' adapting or adjusting in response to climatic stimuli is not systematically explored. We will present a far simpler model than Nordhaus has used in order to focus on the effects of both mitigation and adaptation policies in economies of different environmental sizes.

Our paper also fits in nicely with other works on this subject. For example, Lecocq and Shalizi (2007: 34) recognize that optimal policies may vary depending on the environmental size of the economy: "… since the extent of mitigation is for the most part exogenous for individual country policy makers, to what extent does the optimal adaptation strategy depend on this exogenous parameter? This … requires a numerical estimation of the model which is not attempted in this paper." Our model addresses this question by including this parameter, which enables us to consider the case of a pollutant stock with a negative depreciation rate, since the emissions of the rest of the world are higher than the environment's natural rate of absorption.

Another closely related work is that of de Bruin, Dellink, and Tol (2009), where adaptation is included in both DICE and Regional Integrated Climate-Economy (RICE) models. What sets our work apart from theirs is the functional form we choose for the damage function, which enables us to separate out the contributions of different factors to different countries' temperature increases and to focus on environmentally small economies. Although they consider multiple regions when they study adaptation using RICE models, they make no distinction among the region-specific factors that contribute to temperature increases, which suggests that their analysis can be further expanded and that the discussion can profit from the numerical explorations that we perform in this paper.

Adaptation can be driven by the market, as happens in the case of agriculture (Mendelsohn, 2000), for example, when more resistant varieties are introduced. However, in a macroeconomic optimal growth model such as the type of used in the literature, adaptation has to be understood as either private or public investment. For instance, in 1936, the United States Department of Agriculture (USDA) began campaigning for the introduction of a hybrid variety of corn that proved to be more heat resistant, and, even before that, had been engaged in its own research on the subject, while also subsidizing the dissemination of knowledge and seed samples (Sutch, 2011). The USDA also invested heavily in irrigation infrastructure throughout the twentieth century. Dams and irrigation canals helped to mitigate the effects of severe droughts, thus overcoming the collective action problem stemming from their character as a public good (Hansen et al., 2011).

To sum up, most of the papers that address the potential of either adaptation or mitigation (or both) policies as a means of reducing the impact of climate change treat all economies as being similar. Our main contribution to the climate change literature is then to differentiate among countries, not only by their economic size, but also by their relative degree of responsibility in terms of this problem.

## 3. The Model

### *3.1. The Basic Model*

We present an optimal growth model that includes a climate component. It has several characteristics that are to some extent inspired by the DICE model, but it also includes our own modelization of climate shocks and of mitigation and adaptation expenses.

Since we are not concerned with distributional issues, the model is a standard Ramsey model of a representative agent who maximizes the present value of its infinite flow of consumption, although we add the stock of emissions as a state variable into the optimization program.

These emissions are assumed to affect productivity by reducing total output, which is in turn responsible for creating them. This enables us to study the conditions under which governments incur mitigation and adaptation expenses and to run simulations that depict their optimal trajectories for countries of different sizes in terms of the environmental dimensions discussed above, along with some comparative statics exercises.

Assume that the representative agent of this economy chooses a sequence of consumption to maximize:[1]

$$(1.1) \quad \int_0^{\infty} u(c(t))e^{-rt}dt$$

where $u(.)$ satisfies the standard assumptions of being monotonically increasing in $c$, but at a diminishing rate ($\partial u/\partial c > 0,$ and $\partial^2 u/\partial^2 c < 0$). The flow of future consumption is discounted at a constant rate $r > 0$.

We assume that the production function of the economy has the regular properties of neoclassical production functions. The representative agent's consumption $c$ is produced with a single input $k$, capital, using the production function $F(k)$. Again, this function satisfies the standard conditions of being increasing and strictly concave, $\partial F/\partial k > 0$, $\partial^2 F/\partial^2 k < 0$.

The differences from a standard growth model arise in the constraints that the representative agent faces. The first concerns the evolution of capital, where the harmful effects of emissions make themselves felt: we model them as downscaling output by a fraction

[1] For the sake of notational simplicity, we omit the time subscript from all variables.

$\Theta(S)\epsilon(0,1)$. For now, theta will only depend on $S$, the stock of GHGs in the atmosphere of the planet (which thus depends on the emissions of all countries), in a way similar to that of Nordhaus (2008). To capture the fact that an increase in emissions further diminishes output, we assume that $\Theta(S)$ satisfies $\partial\Theta/\partial S < 0$. However, we will not necessarily assume concavity of $\Theta(S)$, since that would mean that it could be zero for some level of pollution (and could imply that it will become zero for some level of $S$). The first constraint is therefore:

$$(2.1)\quad \frac{dk}{dt} = \Theta(S)F(k) - \delta k - c$$

In other words, capital increases with savings (i.e., the difference between output $F(k)$ and consumption $c$), and decreases at the constant depreciation rate $\delta$. We can clearly see how climate change operates on capital accumulation by destroying a share $[1 - \Theta(S)]$ of production. To make matters simpler, let us assume for now that there is no population growth. We will remove this assumption later on, when we run our simulations, and we will see that the rate of population growth is a highly relevant variable. This is because, if population (either local or that of the rest of the world) grows even when capital per capita stays constant (as in the steady state), total output and hence total emissions will be higher. For simplicity, we also assume that there is no technological progress.

The second constraint concerns the evolution of GHGs from the point of view of the economy under study. In line with Copeland and Taylor (1994), we assume that every unit of $F(k)$ generates $\gamma$ units of emissions; and in the same fashion as Brock and Taylor (2010), we capture the fact that the environment regenerates itself by introducing a constant regeneration rate $\delta_s$. These two assumptions shape the second constraint:

$$(3.1)\quad \frac{dS}{dt} = -\delta_s S + \gamma F(k)$$

Equation (3.1) captures the fact that emissions are an inevitable consequence of the production process, and equation (2.1) shows their negative influence on future capital.

An important point should be made regarding $\delta_s$: it usually accounts for the fact that the environment is able to reabsorb part of the stock of the pollutant, so that $\delta_s > 0$. In the case of the model developed by Nordhaus, that role is played by the seas. However, in our simulations we consider a large (greater than 1 in magnitude) and negative $\delta_s$ for small economies, which captures the fact that they face an exogenous positive net rate of growth of the stock of GHGs in the atmosphere that depends on the rest of the world's emissions. In fact, in our simulations, $\delta_S$ will be a function of other variables:

$$\delta_S = \zeta - E_S(Y_{RW} * N_{RW} * e_{RW} + Y_C * N_C * e_C)$$

that is, $\delta_S$ may be a function of the natural absorption of the environment, $\zeta$, which is an exogenous negligible rate, less the total emissions of the world, $E_S$. In this specification, $E_S$ depends on total emissions around the planet, calculated as the sum of the emissions of the rest of the world per unit of output, $e_{RW}$, times the per capita income of the rest of the world, $Y_{RW}$, times the population of the rest of the world, $N_{RW}$, and of those same values for the country concerned, indicated with $C$. Then, it is apparent that the influence exerted by a given country in terms of climate change will be small (compared to that of the rest of the world) if its population, its per capita income and/or its coefficient of emissions are small. A small country may see that, even if it were to reduce its emissions to zero, $\delta_S$ would still be negative, which could induce it to consider $\delta_S$ as a large exogenous negative parameter. As mentioned in the introduction, the country's incentive to reduce its own emissions will be low when the emissions of the rest of the world are disproportionately high and are determined exogenously.

Seen from this perspective, international agreements could give proper incentives for mitigation to small economies if they were matched with a credible reduction of the emissions of the rest of the world, i.e., reductions in the component that is under their control, $e^{RW}$, if they *dramatically* reduce the cost of mitigation or by providing incentives in terms of economic rewards.

Given all these considerations, the problem faced by the representative consumer is to maximize (1.1) subject to (2.1) and (3.1). Consumption is the control variable, while emissions and capital are the state variables of the optimization program. The associated Hamiltonian is:

$$(4.1) \quad H = u(c)e^{-rt} + \lambda[\Theta(S)F(k) - \delta k - c] + \mu[-\delta_S S + \gamma F(k)]$$

and the necessary conditions for a maximum are:[2]

$$(5.1) \ [c]: \ \frac{du}{dc}e^{-rt} - \lambda = 0$$

[2] It is also necessary that the transversality condition be satisfied: $\lim_{t\to\infty} \lambda k = 0$

$$(6.1)\ \ [k]:\ \ \lambda[\Theta(S)F'(k)-\delta]+\mu\gamma F'(k)=-\frac{d\lambda}{dt}$$

$$(7.1)\ \ [S]:\ \ \lambda\Theta'(S)F(k)-\mu\delta_S=-\frac{d\mu}{dt}$$

We now manipulate these expressions in order to describe the impact of mitigation and adaptation policies on the steady-state level of capital. First of all, we note that, by totally differentiating (5.1), we get:

$$\frac{d^2u}{d^2c}*\frac{dc}{dt}*e^{-rt}-r\frac{du}{dc}e^{-rt}\ -\frac{d\lambda}{dt}=0$$

and then, considering the steady state and using (5.1) again, we arrive at:

$$(8.1)\ \ -\frac{d\lambda}{dt}=r\lambda$$

Replacing this expression in (6.1), we get:

$$\lambda[\Theta(S)F'(k)-\delta]+\mu\gamma F'(k)=r\lambda$$

Solving for $\mu$ yields:

$$(9.1)\quad \mu=\frac{\lambda[r+\delta-\Theta(S)F'(k)]}{\gamma F'(k)}$$

By taking derivatives with respect to time again we have:

$$(9.1')\quad -\frac{d\mu}{dt}=\frac{r\lambda[r+\delta-\Theta(S)F'(k)]}{\gamma F'(K)}$$

And, by replacing $\mu$ and $\frac{d\mu}{dt}$ given by (9.1) and (9.1′) in (7.1), it can immediately be shown that, in the steady state

$$(10.1)\quad \Theta(S)F^{\prime\prime}(k)-(r+\delta)=-\frac{\Theta^{\prime}(S)F(k)\gamma F^{\prime\prime}(k)}{r+\delta_S}=\epsilon>0$$

must hold. We call $k^{***}$ the level of capital that satisfies this equality. Notice that (10.1) also implies that $\mu<0$, which is consistent with the fact that emissions $S$ are a stock that the economy wants to reduce.

We now show that $k^{***}$ (the optimal value of the steady-state stock of capital per capita in this setup) is lower than the level of capital corresponding to the emissions-free case. To do this, we consider the ideal case of $\Theta(S) = 1$ , a situation that is akin to assuming that the economy is "immunized" from the environment. In this context, it is straightforward to determine the steady-state climate-change-free level of capital, which we denote $k^*$:

$$(10.1') \quad F'(k^*) - (r + \delta) = 0$$

A comparison of $(10.1)$ and $(10.1')$ shows that, in our setting, capital has to be reduced: that is to say, $k^{***} < k^*$. This occurs as a consequence of two effects which we will define separately.

The first is an *average effect*, caused by the fact that $\Theta(S) < 1$ (which diminishes the marginal product of capital) and $F(k)$ is strictly concave. Under our assumptions, it can be readily determined that, even if $\Theta'(S)$ were equal to zero, the level of capital satisfying inequality $(10.1)$, $k^{**}$, would be lower than $k^*$. This is simply because $F'(k^{**}) = \frac{r+\delta}{\theta(S)} > F'(k^*) = (r + \delta)$ implies $k^{**} < k^*$.

The second effect is a *marginal effect* which will drive capital to an even lower steady state than $k^{**}$. To identify this effect, it suffices to note that the representative agent of the economy is aware of the marginal impact of additional capital on production and thus on the total stock $S$, and hence $\Theta'(S)$ becomes relevant (as shown by the right-hand side of (10.1)). This implies that we actually need to consider $k^{***}$, which is the amount of capital that satisfies $F'(k^{***}) = \frac{r+\delta+\epsilon}{\Theta(S)} > \frac{r+\delta}{\Theta(S)} = F'(k^{**})$. This inequality implies that $k^{***} < k^{**}$. It can then be seen that the marginal effect stems from assuming $\Theta'(S) < 0$, which simply captures the (somewhat still controversial) idea that increasing emissions monotonically increases the damage suffered by the economy. In turn, this derivative determines the sign of the right-hand side of condition $(10.1)$, $\epsilon$, and results in the inequality that yields an even lower steady-state level of capital.

In the next section we will consider two ways of reducing the harmful impact of emissions: adaptation and mitigation expenditures. We could say, in broad terms, that mitigation helps to counterbalance the *marginal effect* $(k^{**} - k^{***})$, whereas adaptation helps to reduce the *average effect* $(k^* - k^{**})$: this is because mitigation will slow down the growth rate of emissions, while adaptation will decrease their impact.

### *3.2. Model with Mitigation and Adaptation*

We shall now suppose that the economy that we are studying is capable of making expenditures for the purposes of both mitigation and adaptation. The state equations become:

$$(2.2)\quad \frac{dk}{dt} = \Theta(S - za)F(k) - \delta k - c - \eta m^2 - \rho a^2$$

and:

$$(3.2)\quad \frac{dS}{dt} = -\delta_S S + \gamma(bm)F(k)$$

Notice that, while adaptation $a$ reduces the effect of pollution on output by increasing theta through a parameter $z$ (thus, softening the average effect), mitigation lowers the amount of pollution generated per unit of output (which means it acts upon the marginal effect, since $\frac{\partial\gamma}{\partial m} < 0$). However, expenditure in either case is non-decreasing, as it is seen from equation (2.2) that the marginal expenditure on mitigation is $2\eta m \geq 0$ and that of adaptation is $2\rho a \geq 0$.

The Hamiltonian then becomes:

$$(4.2)\quad H = u(c)e^{-rt} + \lambda[\Theta(S - za)F(k) - \delta k - c - \eta m^2 - \rho a^2] + \mu[\gamma(bm)F(k) - \delta_S S]$$

Although the optimality conditions will be the same as in the basic model, we now need to state the Kuhn-Tucker conditions for both $m$ and $a$:

$$(5.2)\ -2\lambda\eta m - b\mu\gamma'(bm)F(k) \leq 0$$
$$(5.2')\ [-2\lambda\eta m - b\mu\gamma'(bm)F(k)]m = 0$$
$$(6.2)\ \lambda[-z\Theta'(S - za)F(k) - 2\rho a] \leq 0$$
$$(6.2')\ \lambda a[-z\Theta'(S - za)F(k) - 2\rho a] = 0$$

By investigating equations 5.2 and 5.2′, we can see that, if the expenditure on mitigation is positive, its optimal level would be:

$$m = -\frac{b\mu\gamma'(bm)F(k)}{2\lambda\eta}$$

Thus, expenditure on mitigation will be larger if the shadow price of pollution $\mu$ (in absolute values) is higher, or if the marginal productivity of mitigation (measured by $b$) increases. However, we can expect this parameter to be small in an environmentally small economy.

On the other hand, if the marginal cost of mitigation (measured by $2\eta$) or the marginal utility of present consumption ($\lambda$) increases, or if output per capita $F(k)$ is not big enough, then there will be few incentives for the economy to spend on mitigation. On the contrary, in developed economies, output per capita is larger and $\lambda$ is smaller, and hence, our simulations for that type of countries will show a higher propensity to make expenses in mitigation.

In the case of adaptation expenditures, from equations (6.2) and (6.2′) it can be seen that their optimal level, if different from zero, will be:

$$a = -\frac{z\Theta'(S - za)F(k)}{2\rho}$$

This means that, in a steady state, adaptation expenditures will be larger the larger their marginal productivity, their effect on the palliation of the decrease in output (for $\Theta'_a > 0$) and output itself. Again, this explains why adaptation expenditures are larger in developed economies. On the other hand, a country will spend less on adaptation the larger its marginal cost is.

It is worth noticing that, even if $\gamma = 0$ (which means the economy is not responsible for the emission of GHGs), it may be an optimal choice for the economy to spend money on adaptation. This is not the case, however, for mitigation expenditures since (5.2) would be negative and the optimal level of *m* would be zero.

In the simulations that we ran, there are cases in which either mitigation or adaptation, or both, are absent until some point in the future. Equations (5.2) to (6.2′) show that these instruments may remain unused, but the level of these expenditures may become positive when economies become richer, either because consumption rises (which induces an increase in mitigation) or capital per capita increases (thus, prompting expenditure on adaptation).

Also, if, over time, there is an exogenous increase in the stock of pollution $S$ from the point of view of the economy that we are studying (because the net value of $\delta_S$ is negative when we consider the difference between global emissions and local absorption), this will have a negative impact on the economy's actual output and capital accumulation (for $\Theta'_S < 0$). In this case, it is plausible that the economy will become poorer and will spend less on both mitigation and adaptation, or that it will at least postpone these expenditures.

Now that we have introduced the relevant parameters for expenditure on mitigation and adaptation, we are able to define our criteria for classifying a given economy as being "environmentally small". In our simulations, an environmentally small economy will be one with parameters that satisfy all of the following informal conditions:

1) $\delta_S < 0$

2) $\delta_S$ depends almost entirely on the rest of the world's GDP growth, population and emissions coefficients.

3) $b \cong 0$ and $\gamma \cong 0$

*4)* $\Theta_{Sk} > 0$ . This shows that the marginal impact of S is smaller the higher the stock of capital. That is, the economy is more resistant to climate change the more capital it possesses, but the per capita stock of capital $k$ is small (evidence of this can be found in Schumacher and Strobl (2008) and can be a useful structural property of economies).

## 4. Calibration of the Model and Simulations

To illustrate some of the expected results of our model, we calibrated it and ran a series of simulations for three countries: Brazil, Chile and the United States. Brazil cannot be categorized as a small economy on the basis of its GDP, and it is the 17$^{th}$ largest polluter, as its $CO_2$ emissions account for 1.3 percent of the world's total emissions. However, we will see that this level of emissions may not be high enough to warrant classifying Brazil as an environmentally large economy, for its expenditures will initially be concentrated on adaptation. As the simulations show, however, this economy will increase its mitigation expenditures after some years, mainly because it is expected to growth at a faster rate than the rest of the world and because its decision-makers begin to realize that the country accounts for a sizeable percentage of total emissions. Although Brazil is becoming a larger economy, its mitigation expenditures remain fairly low, however, because most of the damage that it sustains as a result of climate change is still attributable to the rest of the world's emissions.

Chile qualifies as a small economy in any classification that we may consider, so it should not be surprising that most of the results of our simulations fit those predicted by the model for this country. This economy does not make any mitigation effort, since it never becomes a significant source of emissions, and our simulations show that it will concentrate its efforts on adaptation.

On the other hand, the United States is one of the planet's biggest economies in terms of both production and pollution, and its capital stock and GDP are among the largest in the world in per capita terms. This is why it internalizes a large amount of the consequences of pollution and thus uses resources to both reduce and soften the impact of it. The simulations show that this economy will spend on mitigation from the very outset of the time interval. However, one of the simulations also shows that, when the rest of world reduces its emissions, this economy takes advantage of the situation by reducing its own mitigation efforts.

### *4.1. Calibration*

This model can easily be written in GAMS to run simulations of different scenarios.[3] In these simulations, utility takes the CRRA form with constant elasticity $\sigma$. The stock of emissions is proxied by the Earth's average temperature, so the higher that temperature is, the more production will be hurt. In the same sense, mitigation expenditures help to reduce the average rate of increase in the Earth's temperature.

The law of motion for total GHG in the atmosphere (see (5) in Appendix 2) states that the average temperature will depend on the per capita emissions production (*betp)* and the size of the population of both the country under study and of the rest of the world (*betrow*), parameterized with a constant $\varphi$ calibrated to transform emissions in temperature increases so that, under usual conditions, a 3°C increase in the Earth's average temperature would be obtained at the end of a 50-year period.

Since we do not use a natural absorption rate ($\delta_S$) for the simulations, this model (unlike the model discussed in the first sections of this paper) does not have a steady state. Even if this could be a strong assumption for physical capital, it is not for an autonomous and slowly evolving stock of natural capital.

Unlike Nordhaus and Boyer (2000), who use a multiple regression model in which the impact on average temperature is computed through successive iterations, or Lyssenko and Shiell (2008), who present an alternative method for considering non-cooperative N-agent games, our approach corresponds to the case in which a small country has to determine what is the best approach that it can taking as given the rest of the world's behavior.

The calibrated parameters for the three countries we will study are as follows (see Appendix 2 for the GAMS version of the model and the use of the parameters listed in this table):

[3] See Appendix 2 for a detailed description of how this model is programmed.

**Table 1. Calibrated Parameters for Countries Studied**

| Parameter | Brazil | USA | Chile |
|---|---|---|---|
| **Economy** | | | |
| Initial per capita stock of capital: $k_0$ (in LCU) | 22.023* | 121.257 ** | 10.460 *** |
| Initial per capita income: $y_0$ (in LCU) | 14.022* | 46.406 ** | 5.161 *** |
| I (TFP) | 2.301 | 5.762 | 1.211 |
| Share of capital remuneration: $\alpha$ | 0.5845 | 0.4348 | 0.61743 |
| Rate of growth of population: n | 0.0202 | 0.0087 | 0.0126 |
| Country pop/ROW pop (N/NW): np | 0.0287 | 0.0451 | 0.0025 |
| World population growth rate: nw | 0.0117 | 0.0117 | 0.0117 |
| World GDP growth rate: gw | 0.021 | 0.021 | 0.021 |
| **Environmental** | | | |
| Average temperature (Tm) | 14.45 | 14.45 | 14.45 |
| $CO_2$ per capita ($ER_{pc}$) | 1.94 | 18.50 | 4.21 |
| **Model** | | | |
| $\varphi$ (parameters of conversion of GHGs into temperature) | 0.002823 | 0.002823 | 0.002823 |
| Per capita emissions: $betp$ | 0.000013 | 0.000694 | 0.000001 |
| ROW per capita emissions: $betrow$ | 0.001011 | 0.003203 | 0.000316 |
| $H$ | 0.39149 | 0.02107 | 0.04834 |
| $B$ | 0.51524 | 0.05403 | 0.23728 |
| $P$ | 0.03505 | 0.11601 | 0.01290 |
| $Z$ | 0.00026 | 0.00026 | 0.00026 |

* In thousands of Brazilian reales. ** In thousands of US dollars. *** In millions of Chilean pesos.

### 4.2. Simulations

#### 4.2.1. Simulation 1: Baseline Scenario and Increase in TFP

The green lines in the graphs correspond to the baseline scenario, while the red lines reflect the simulation for a 50-year horizon. Simulations are run for the trajectories of the per capita stock of capital, income, consumption and investment, GDP growth and world GDP, the share of output that is lost (1/theta) (see Appendix 2) the mean temperature, and adaptation and mitigation expenditures in both nominal terms and in terms of GDP.

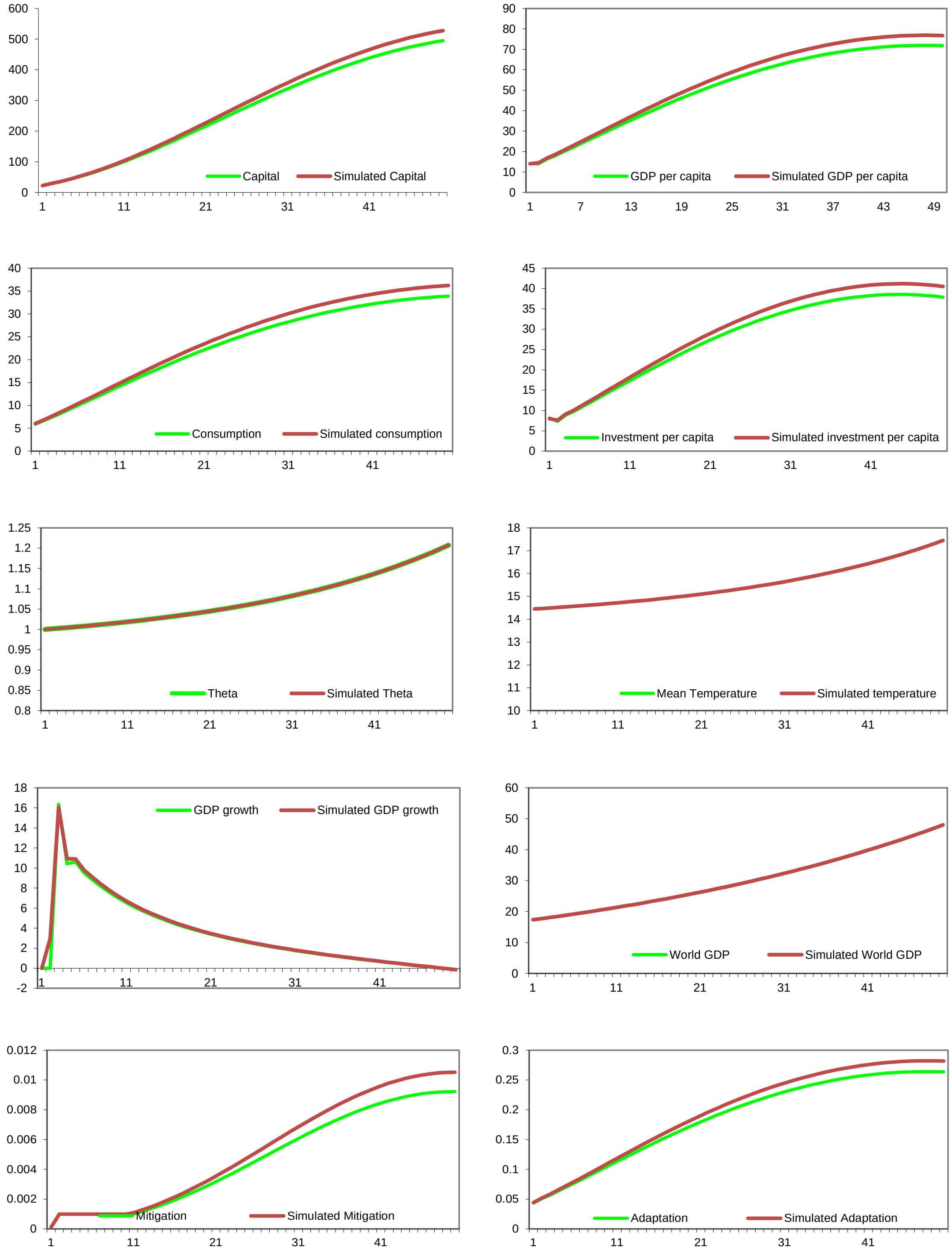
The first thing to note is that Chile does not spend on mitigation at any point in the entire time period under consideration, while Brazil begins to spend money on mitigation only after some years have passed, which illustrates that these economies are so small they do not take any advantage of any opportunities for mitigation. Brazil begins to spend on mitigation after about 10 years into the period under study (approximated to 2008) because its per capita income and population growth rates are such that its contribution to total emissions becomes more significant. However, these expenditures are very small as a percentage of GDP. In contrast, adaptation expenditures are positive for both countries for the entire time horizon.

The United States, on the other hand, spends on both mitigation and adaptation, as its economy is big enough to reap the benefits of the former. In fact, its mitigation expenditures as a percentage of GDP are higher than its adaptation expenditures as a percentage of GDP.

When we increase TFP by 1.5 percent for the United States and 3 percent for Chile and Brazil (so as to evaluate possible growth convergence), mitigation expenditures do not change for the first country, even though per capita GDP, consumption, investment and, thus, capital per capita all increase. For Brazil, there is an increase in expenditures on mitigation, although the amount is still very small in terms of GDP. The United States increases its mitigation expenditures more than its adaptation expenditures. In fact, expenditure on adaptation increases in all three countries, which shows that it is taken to be as a "normal good."

All this leaves the average temperature trajectory and theta almost unchanged for all countries because nothing is done to reduce emissions, all efforts concentrate on reducing their impact on production.

# Figure 1. Baseline Scenario and Simulation for Brazil



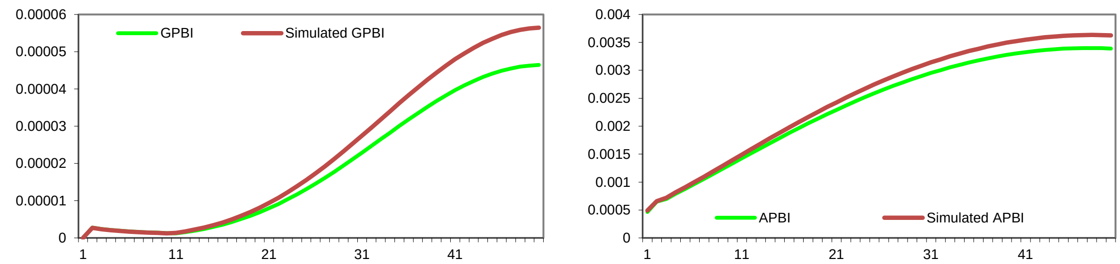
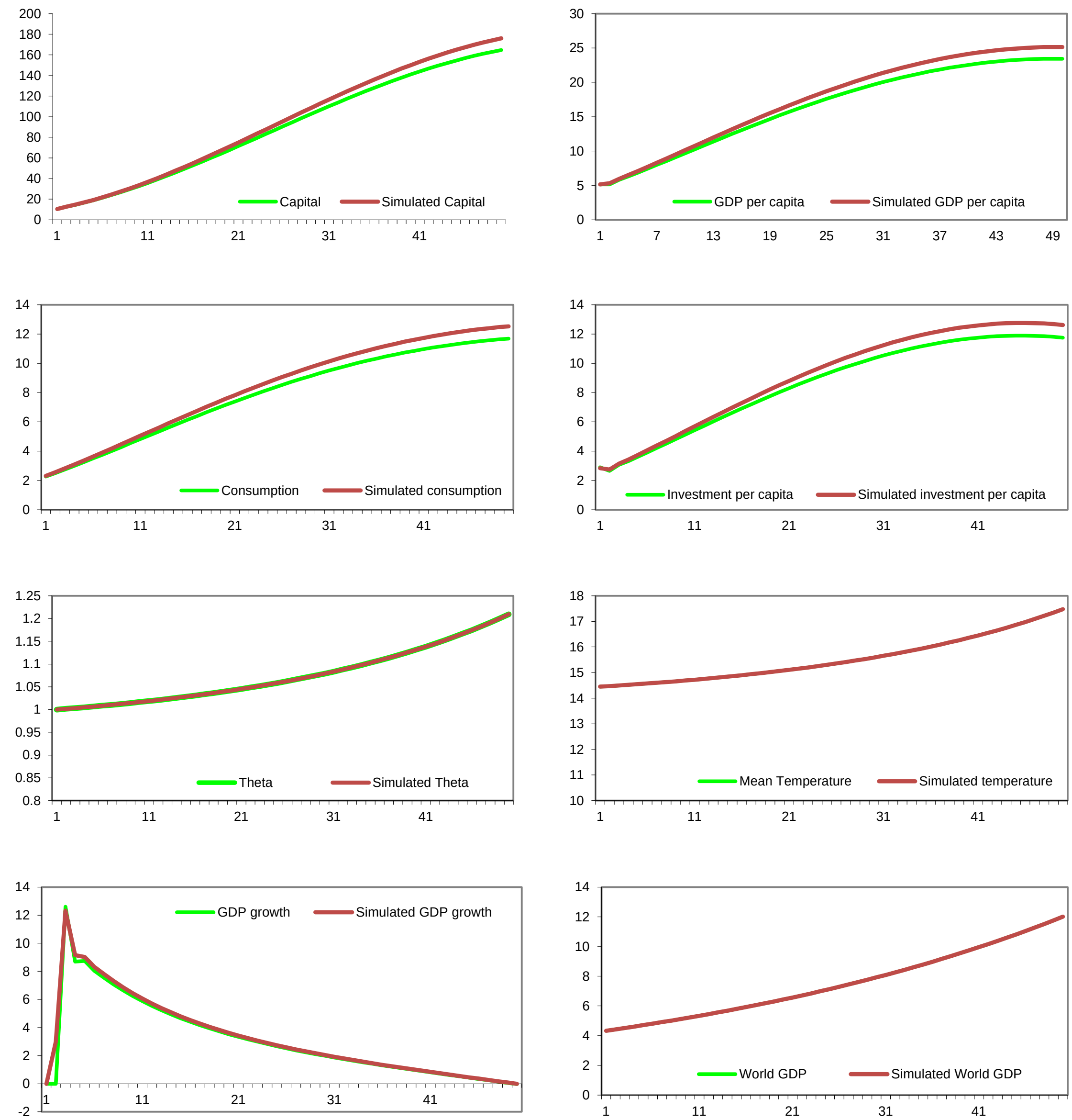



**Figure 2. Baseline Scenario and Simulation for Chile**



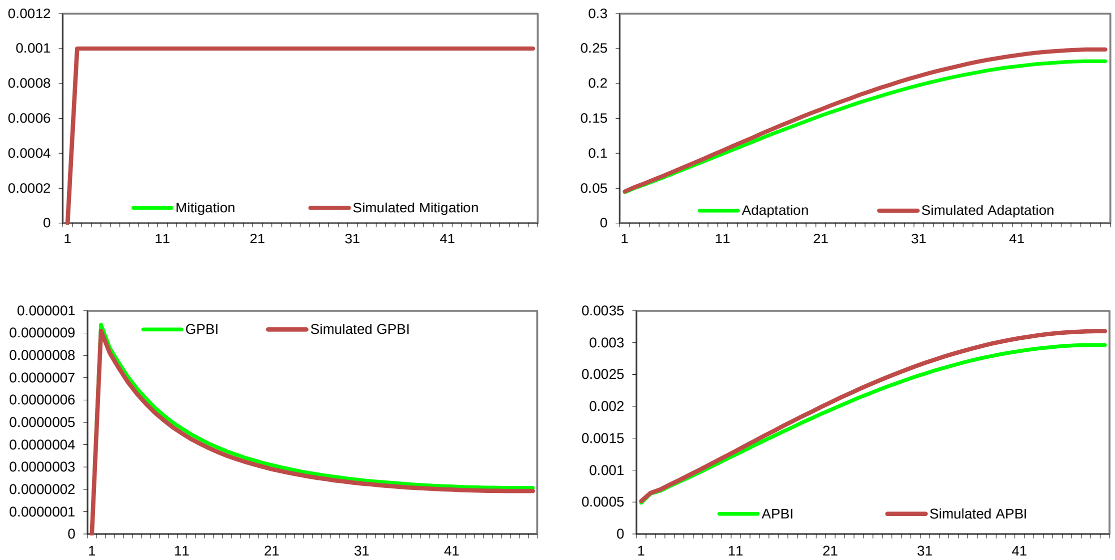
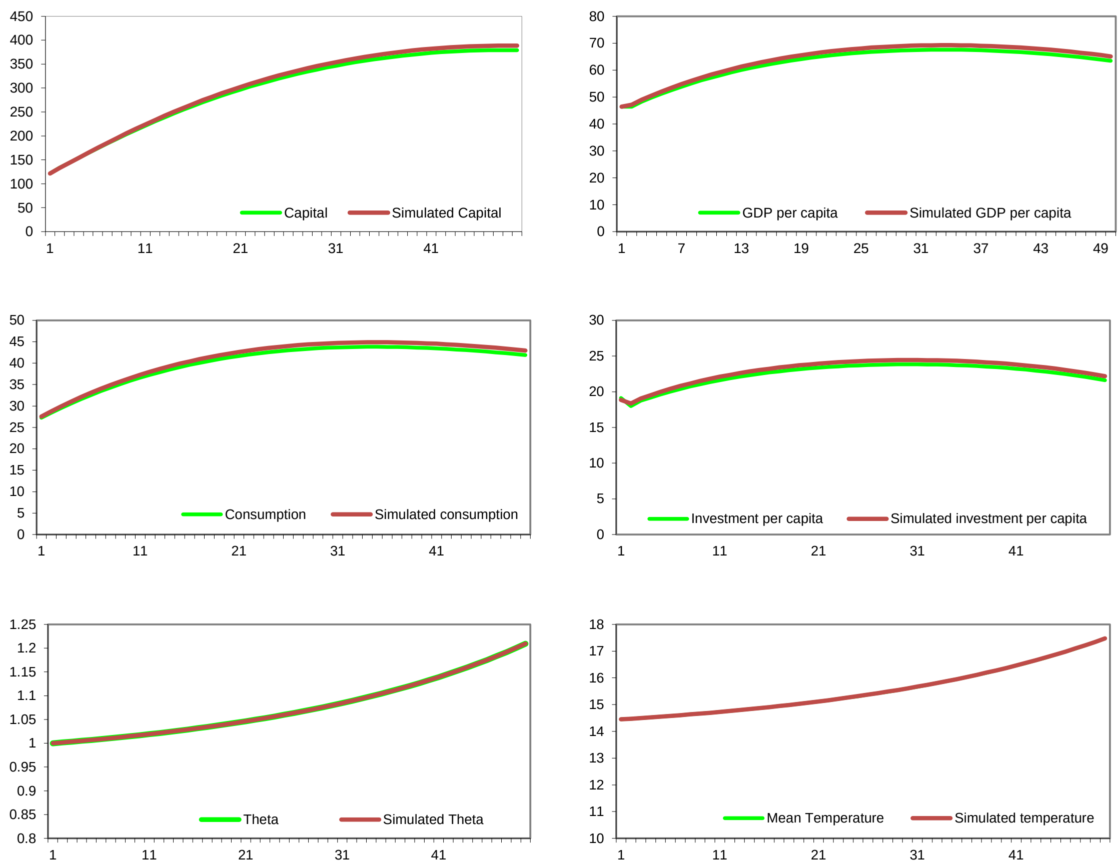
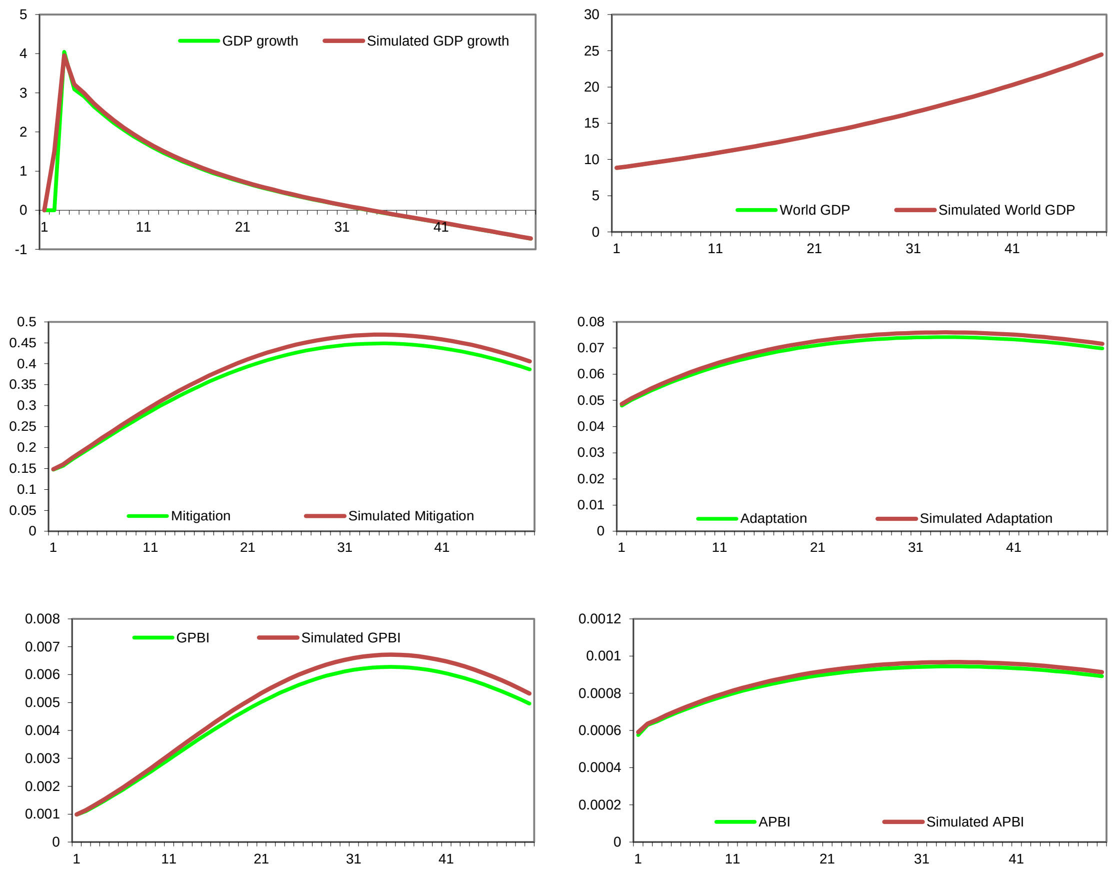



**Figure 3. Baseline Scenario and Simulation for the United States**



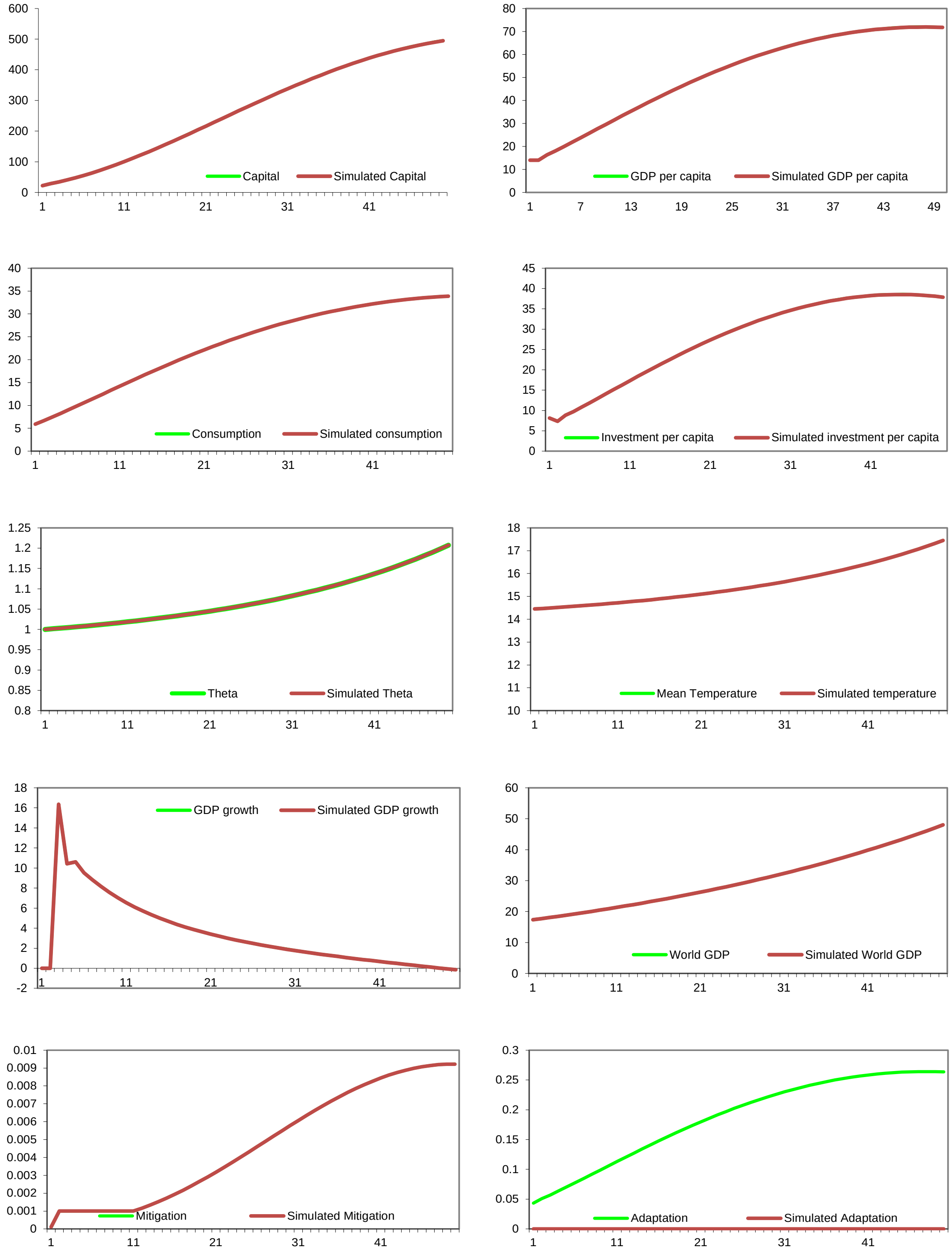


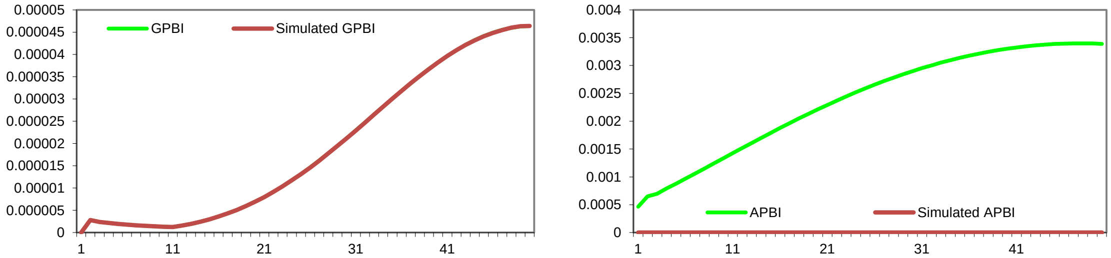

*4.2.2. Simulation 2: Adaptation Is No Longer Available (a=0)*

Now that countries cannot spend money on adaptation, the only control variable that they can use to lower the planet's temperature is mitigation. Thus, we are adding a restriction to the model.

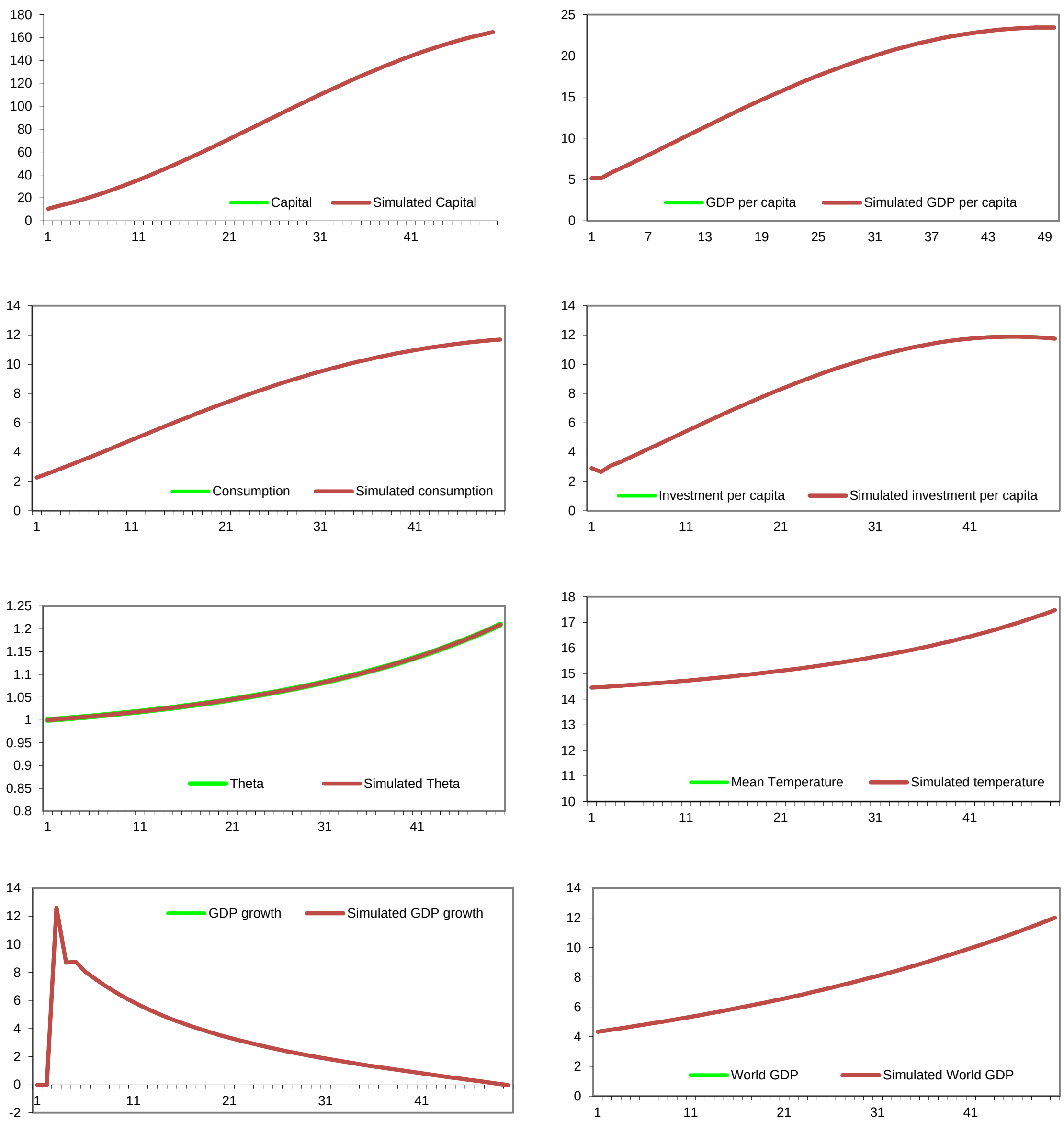
However, and quite surprisingly, this produces no effect whatsoever on the other variables. The economies do not replace adaptation with additional expenditures on mitigation. They instead show a preference for using their resources to increase consumption. (This is nevertheless difficult to observe in the graphics shown here since the effect on consumption is negligible.) Except for theta (which worsens slightly because the variable that compensates for its trajectory is eliminated), the values for all the variables are almost the same as in the baseline scenario.

# Figure 4. Baseline Scenario and Simulation 2 for Brazil






# Figure 5. Baseline Scenario and Simulation 2 for Chile



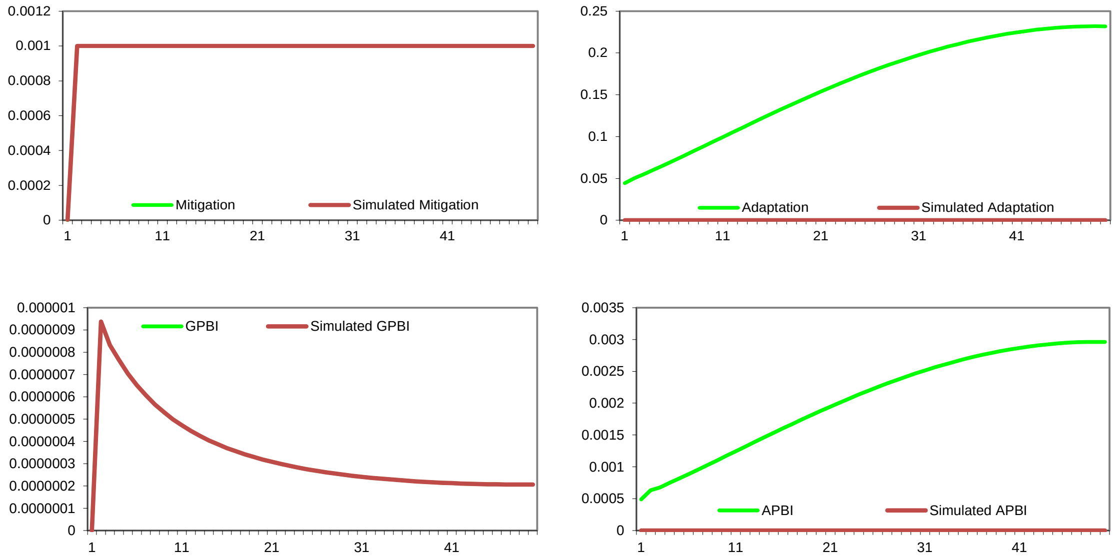
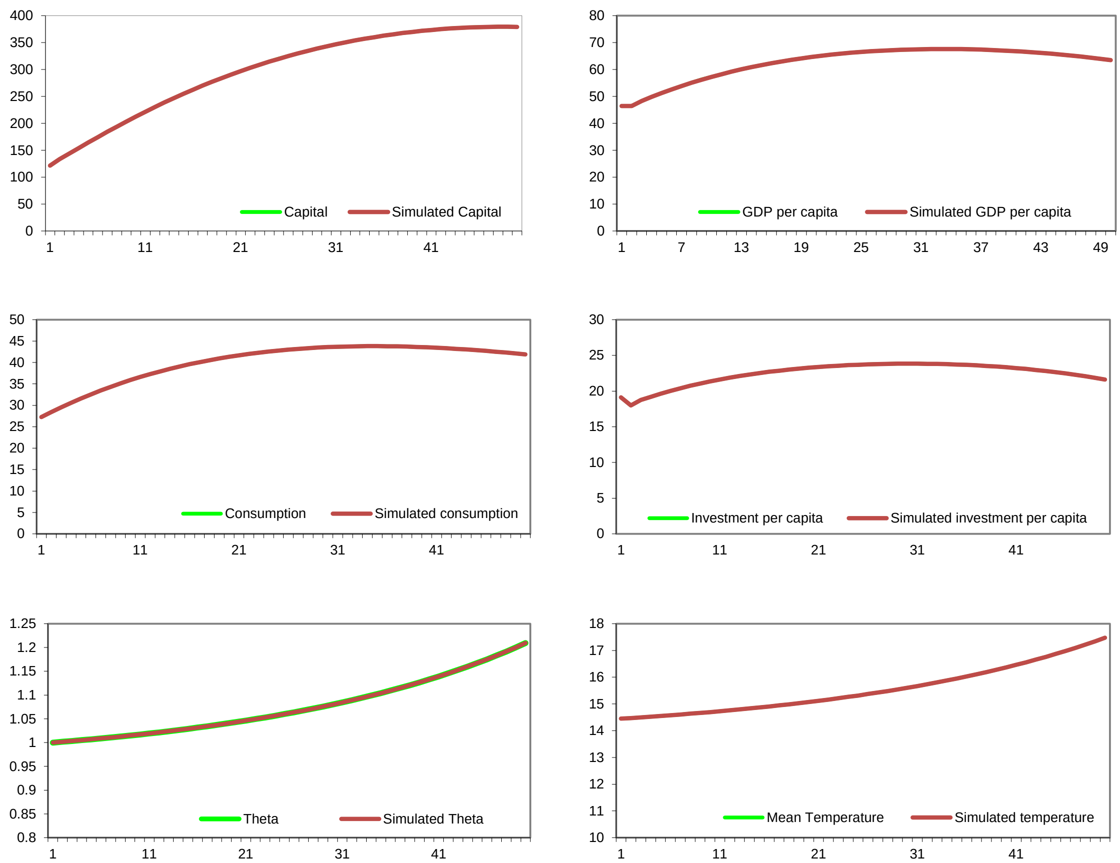
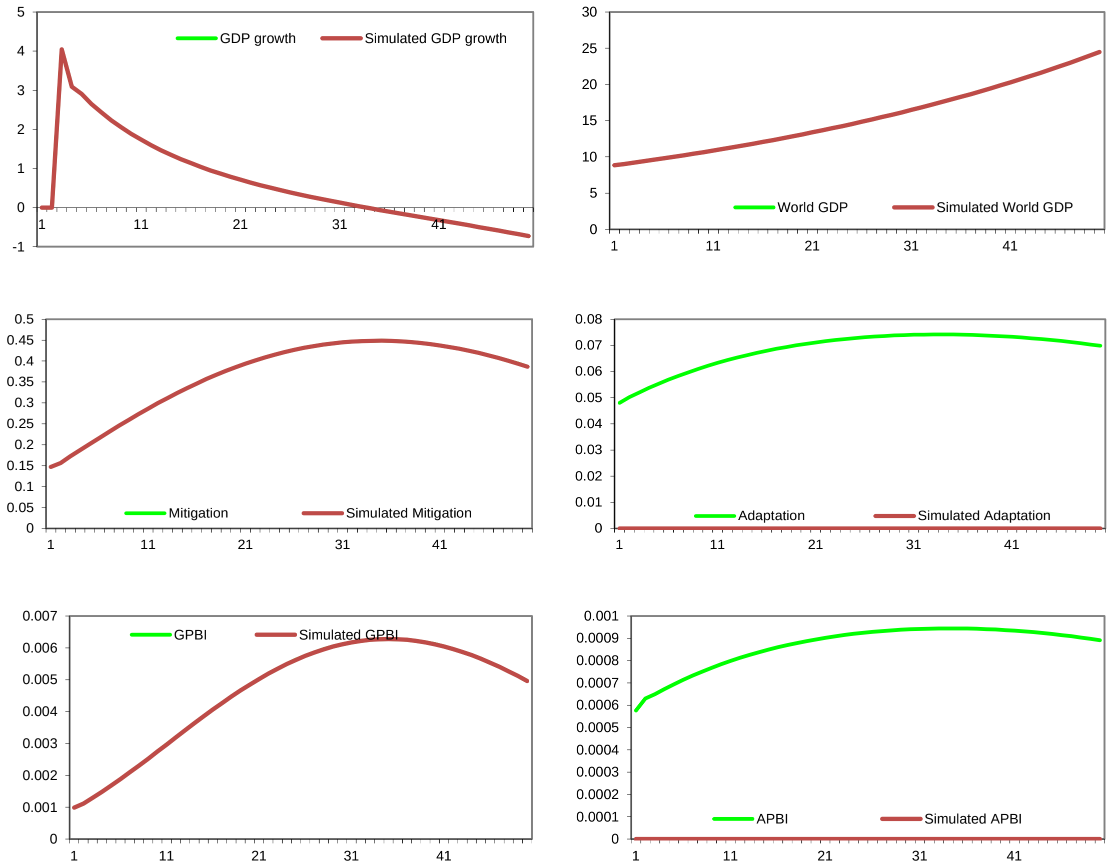



**Figure 6. Baseline Scenario and Simulation 2 for the United States**





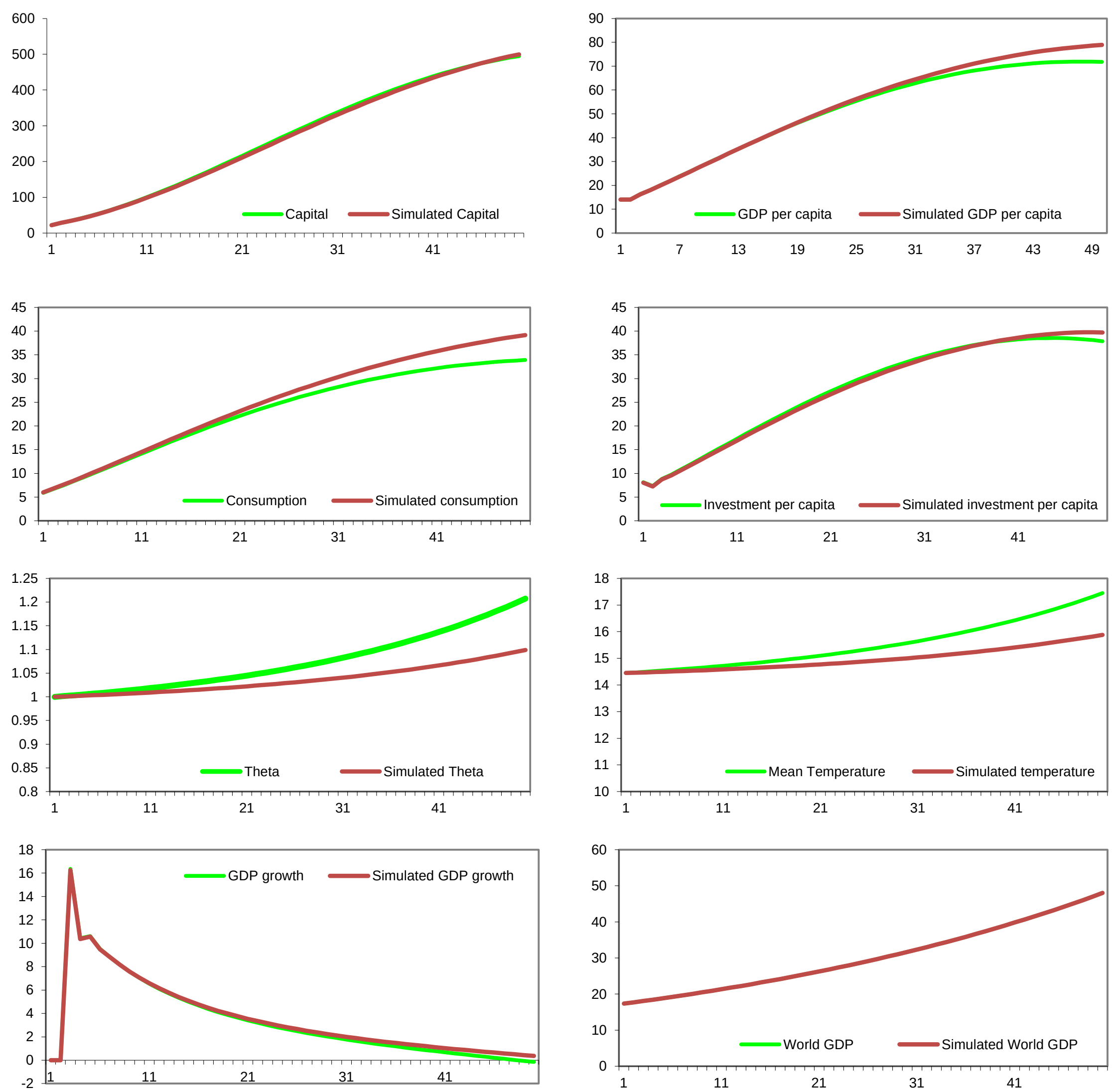

*4.2.3. Simulation 3: Lower Levels of Pollution Generated by the Rest of the World.*

We now reduce the emissions coming from the rest of the world by half. This could be the result of a tight constraint on emissions or of technological progress that makes production cleaner, for example. This, in turn, generates a smaller increase in the average temperature (implicit in the trajectory of 1/theta), which leads to an increase in productivity and, with it, per capita GDP. The results differ dramatically across countries.

In Chile, only adaptation expenditures increase, even in terms of GDP, despite the expansion of per capita income. This once again illustrates Chile's status as an "environmentally small economy," which implies that it has no incentives to devote resources to mitigation.

In Brazil, there is a disproportionate increase in mitigation expenditures relative to adaptation expenditures, but only in the final years of the simulation (presumably because of the prior growth in income). However, mitigation expenditure remains below adaptation expenditure as a percentage of GDP. Per capita consumption increases, but investment rises slightly only in the last 10 years, and then only after a slight decrease. Finally, the United States raises its adaptation expenditures but postpones spending on mitigation, meaning that, for now, the impact of climate change has also been pushed forward in time. This is a worrying result, as environmentally large economies could have incentives to postpone their mitigation efforts when the rest of the world has made a commitment to reduce its emissions. Also, this increase is smaller than it is in Brazil, presumably because rest-of-world emissions for the former account for three-fourths of total emissions, while for the latter they represent around 98 percent of total emissions.

**Figure 7. Baseline Scenario and Simulation 3 for Brazil**



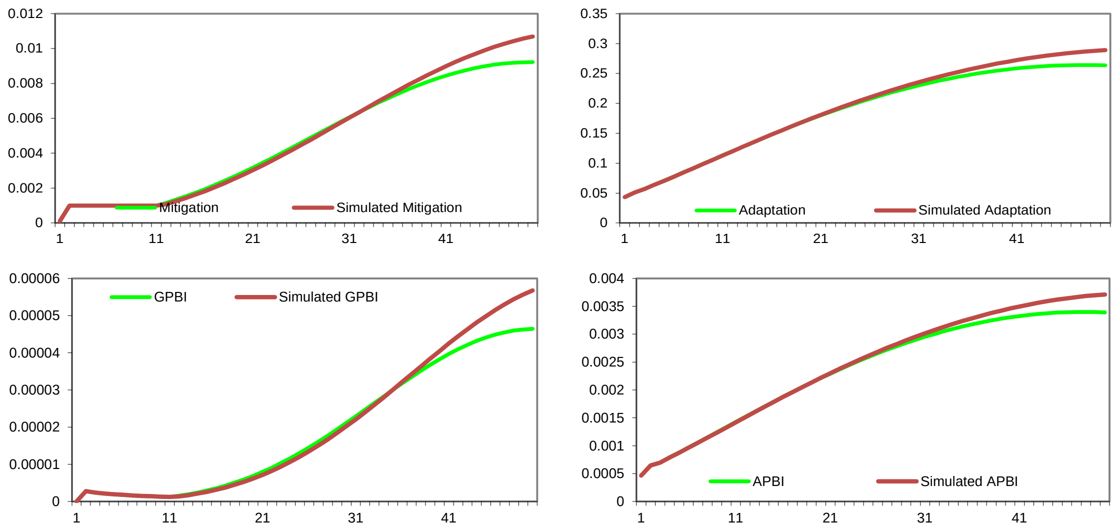
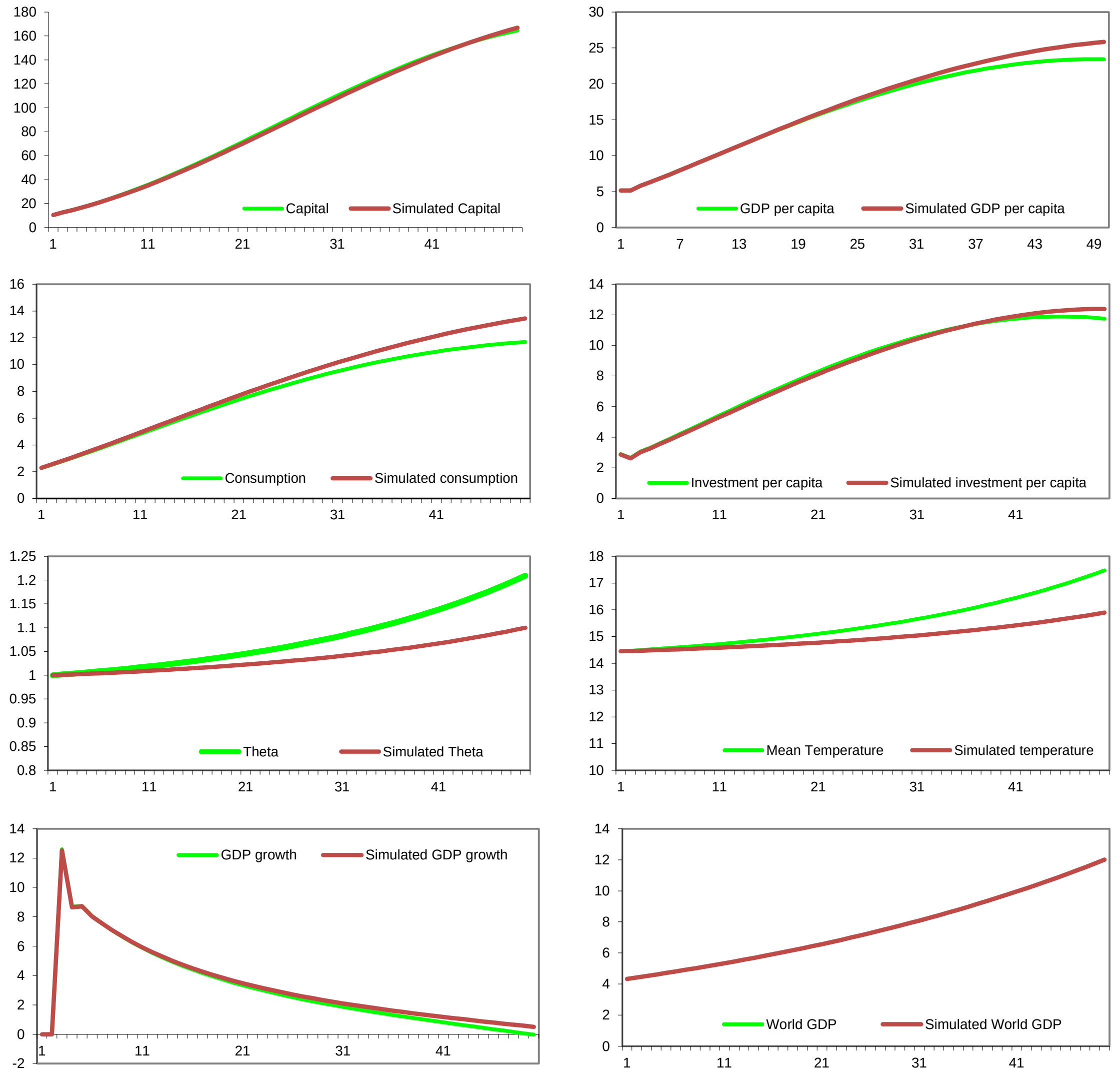
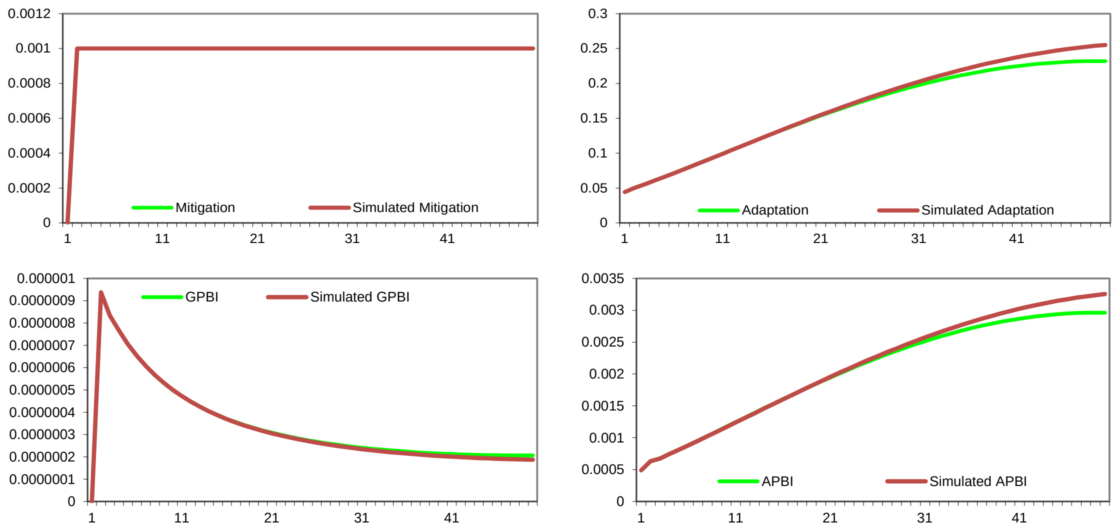
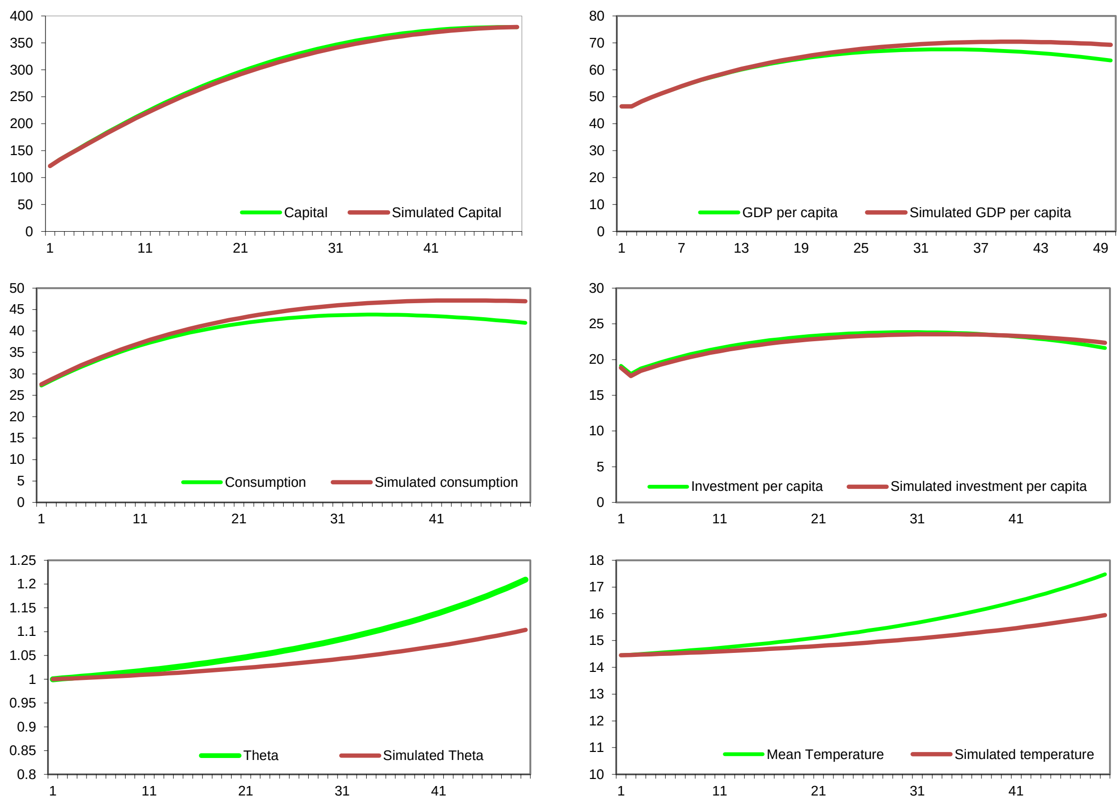


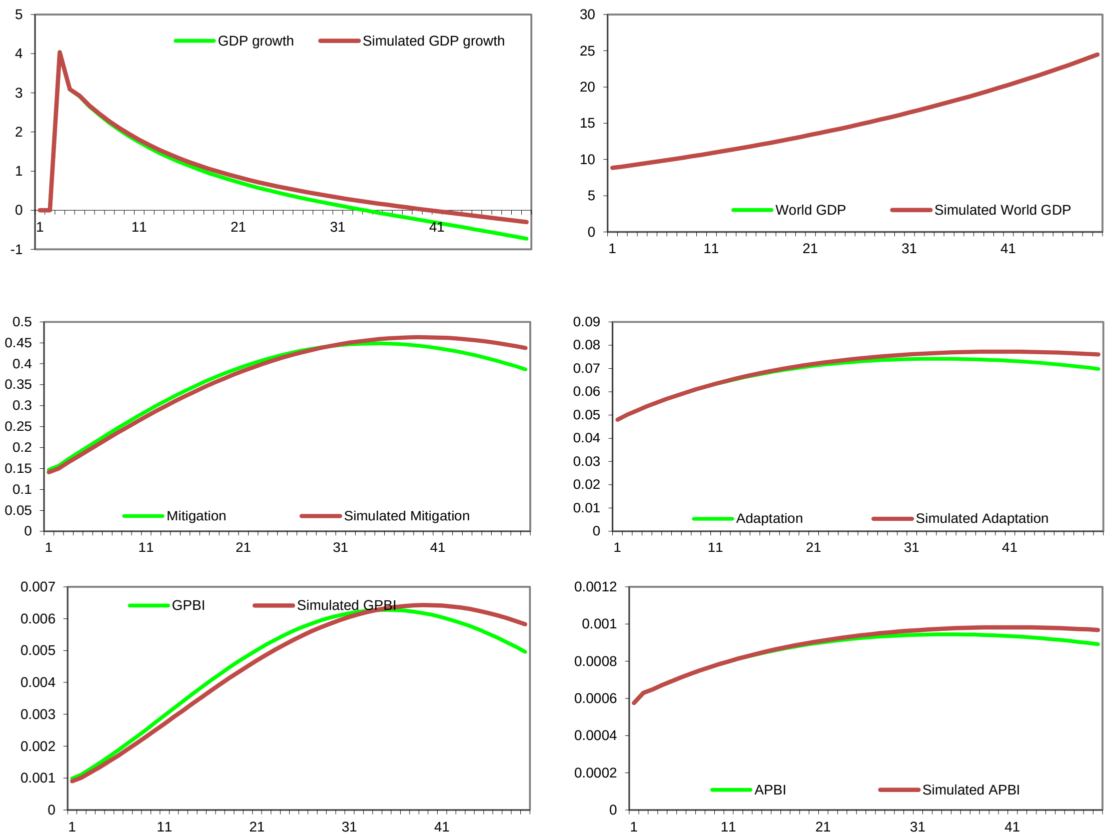

**Figure 8. Baseline Scenario and Simulation 3 for Chile**






# Figure 9. Baseline Scenario and Simulation 3 for the United States



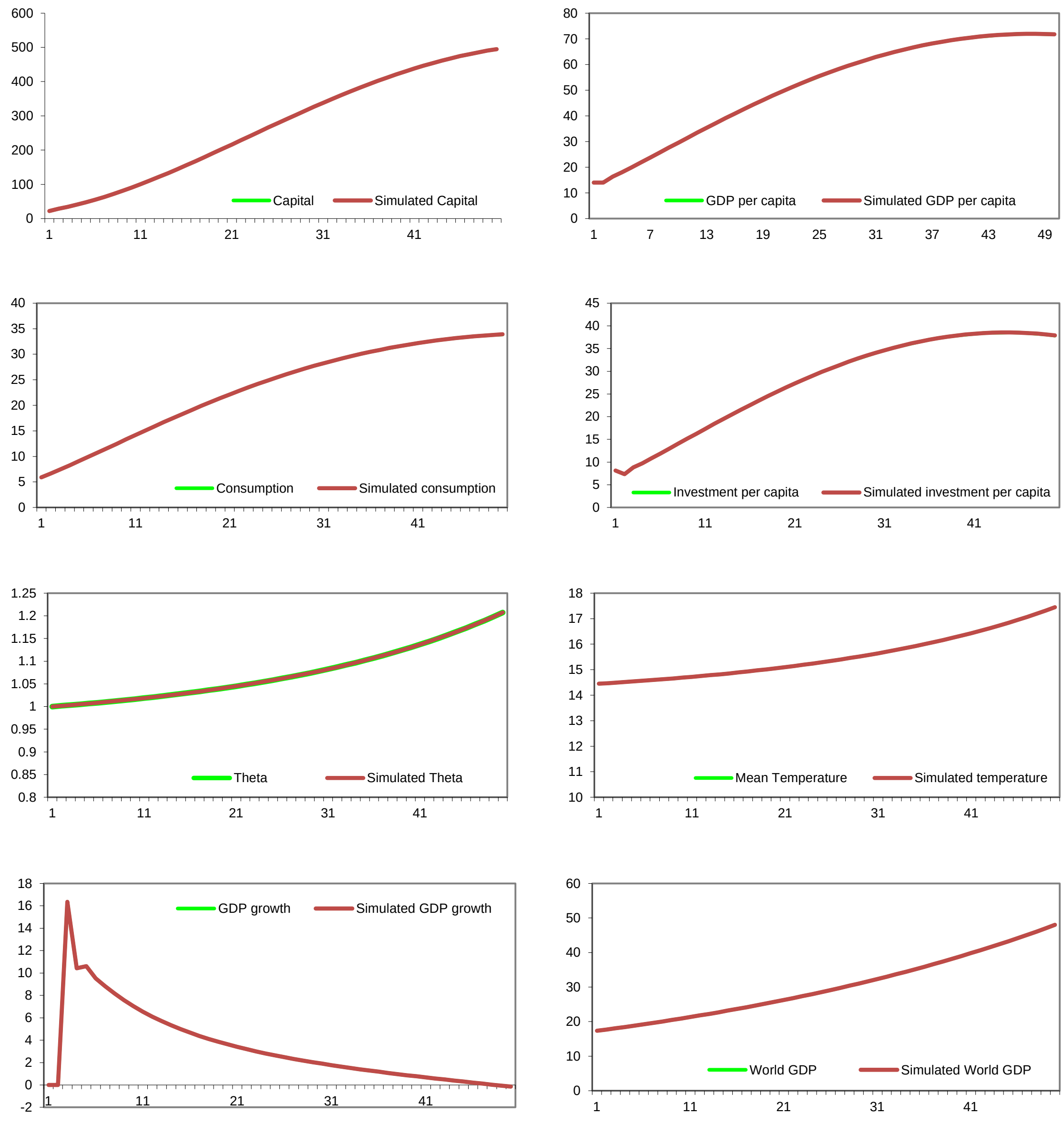



*4.2.4. Simulation 4: Mitigation and Adaptation Costs Decrease by 50 Percent.*

Under this scenario, the parameters that reflect the cost of mitigation ($\eta$) and adaptation ($\rho$) are halved. This generates significant changes in the variables under study. There is no change in the mitigation expenditures of Chile, which remain null, but in Brazil and the United States, there is a remarkable increase in mitigation expenditures, which shows just how sensitive the decisions made by large economies are to cost/effectiveness ratios. There is also a considerable increase in adaptation expenditures in all three countries and in mitigation expenditure in the United States, even when measured as a share of GDP.

A comparison of the cases of Chile and the United States based on this simulation indicates that the problem with mitigation expenditures in environmentally small economies goes beyond cost. Indeed, it is a cost-benefit problem: the effectiveness of mitigation instruments is so low for them (since they would be mitigating a negligible fraction of the emissions that affect them) that any positive cost deters these economies from spending money on mitigation. Brazil seems to be a threshold case which suggests that fast-growing economies that account for a more significant percentage of total emissions may adopt more mitigation measures if the cost of cleaner technologies is reduced.

**Figure 10. Baseline Scenario and Simulation 4 for Brazil**



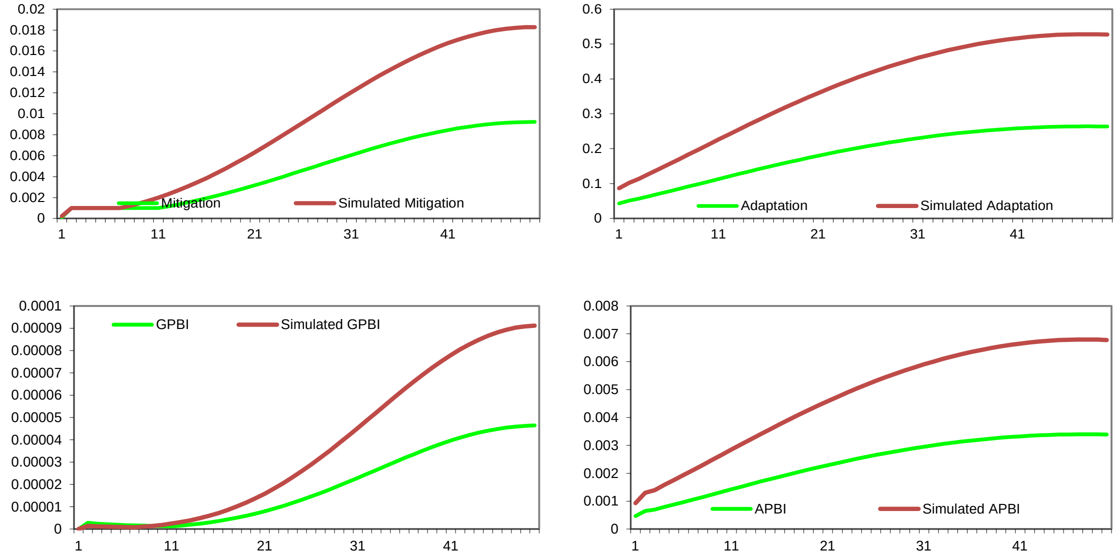
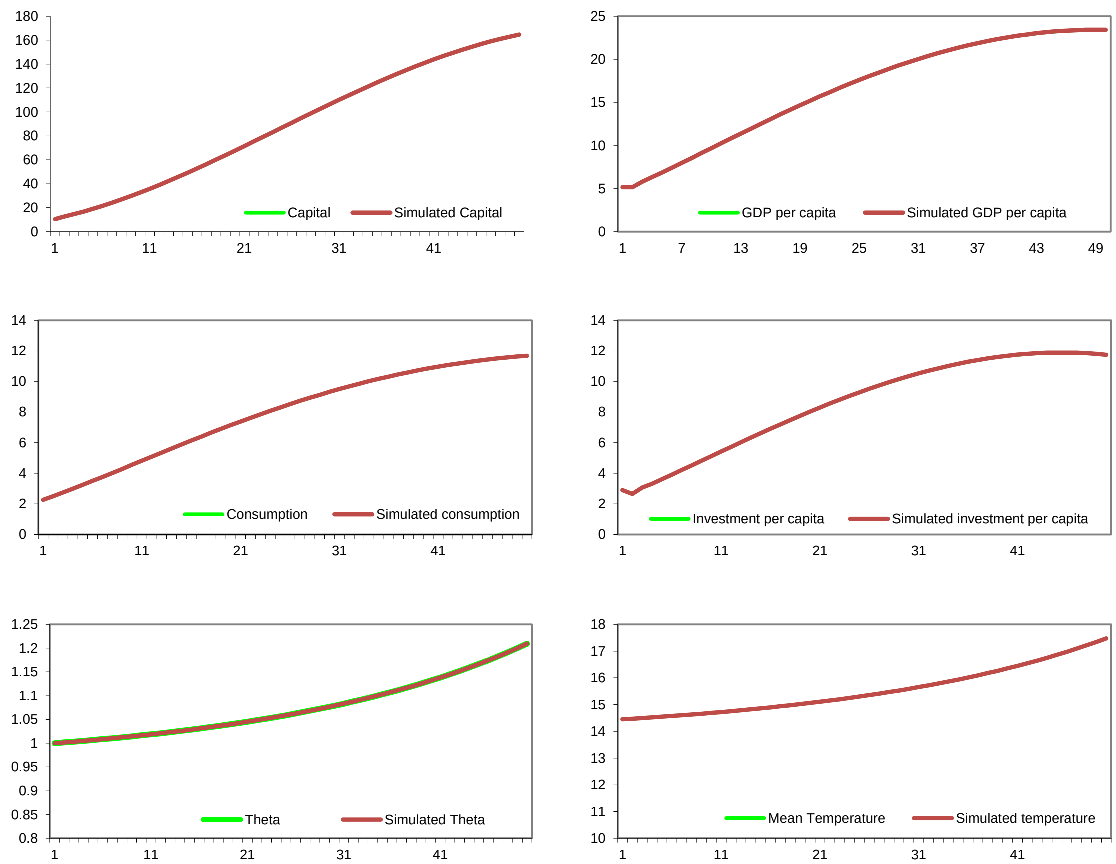



**Figure 11. Baseline Scenario and Simulation 4 for Chile**



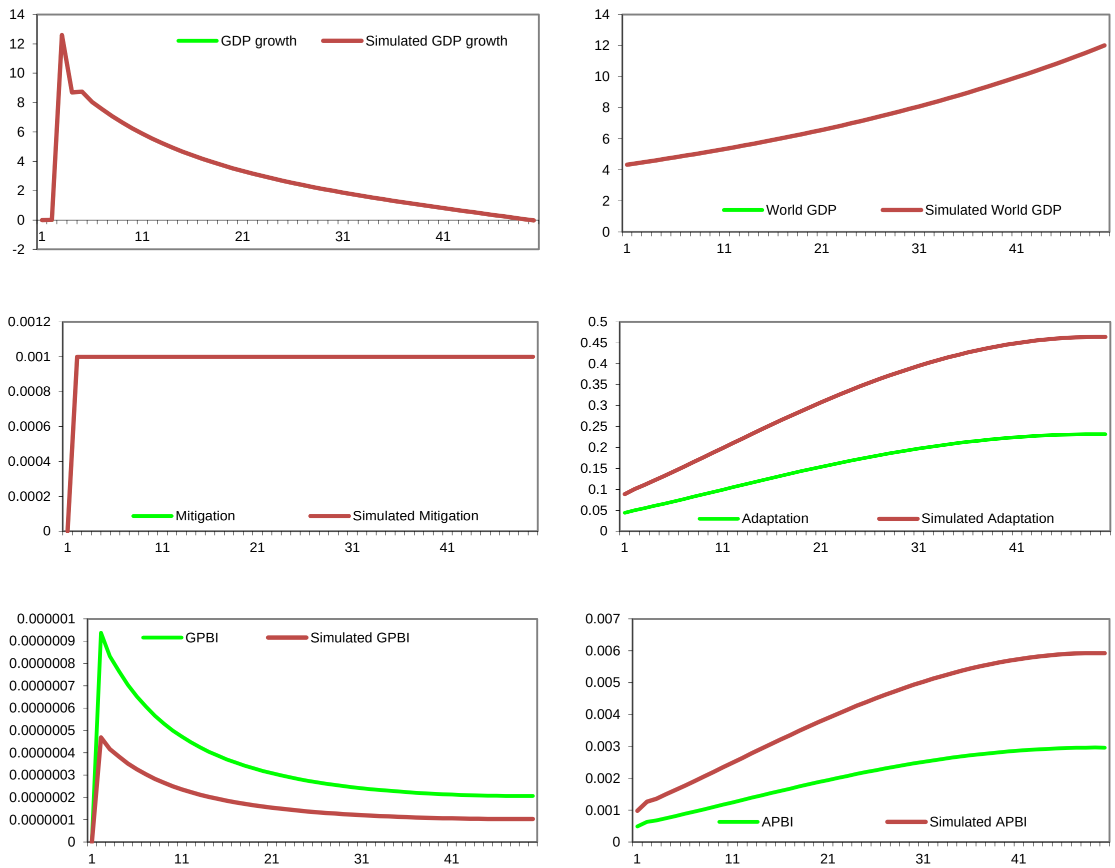
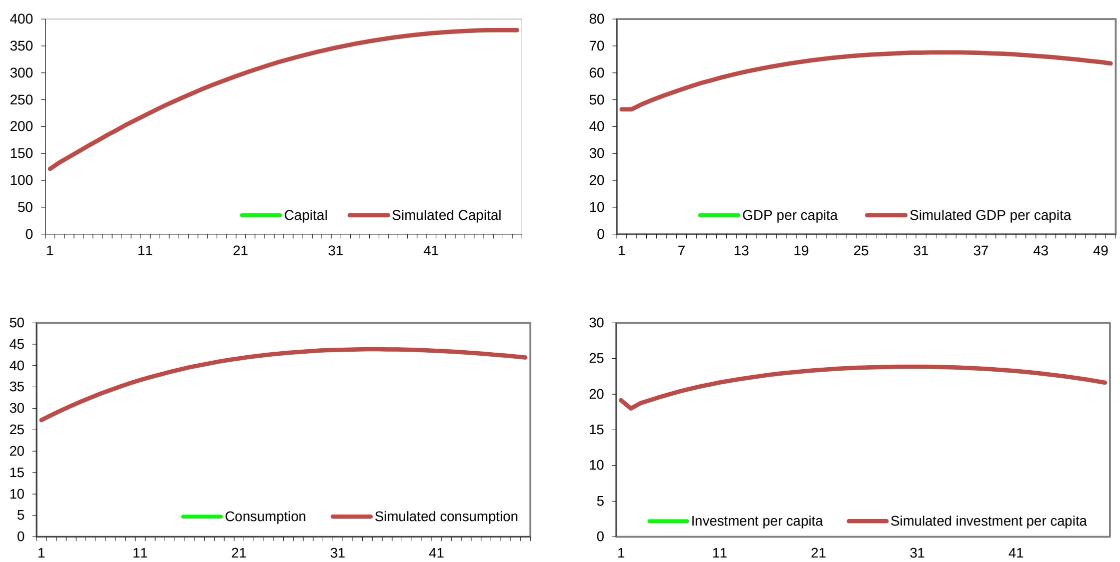
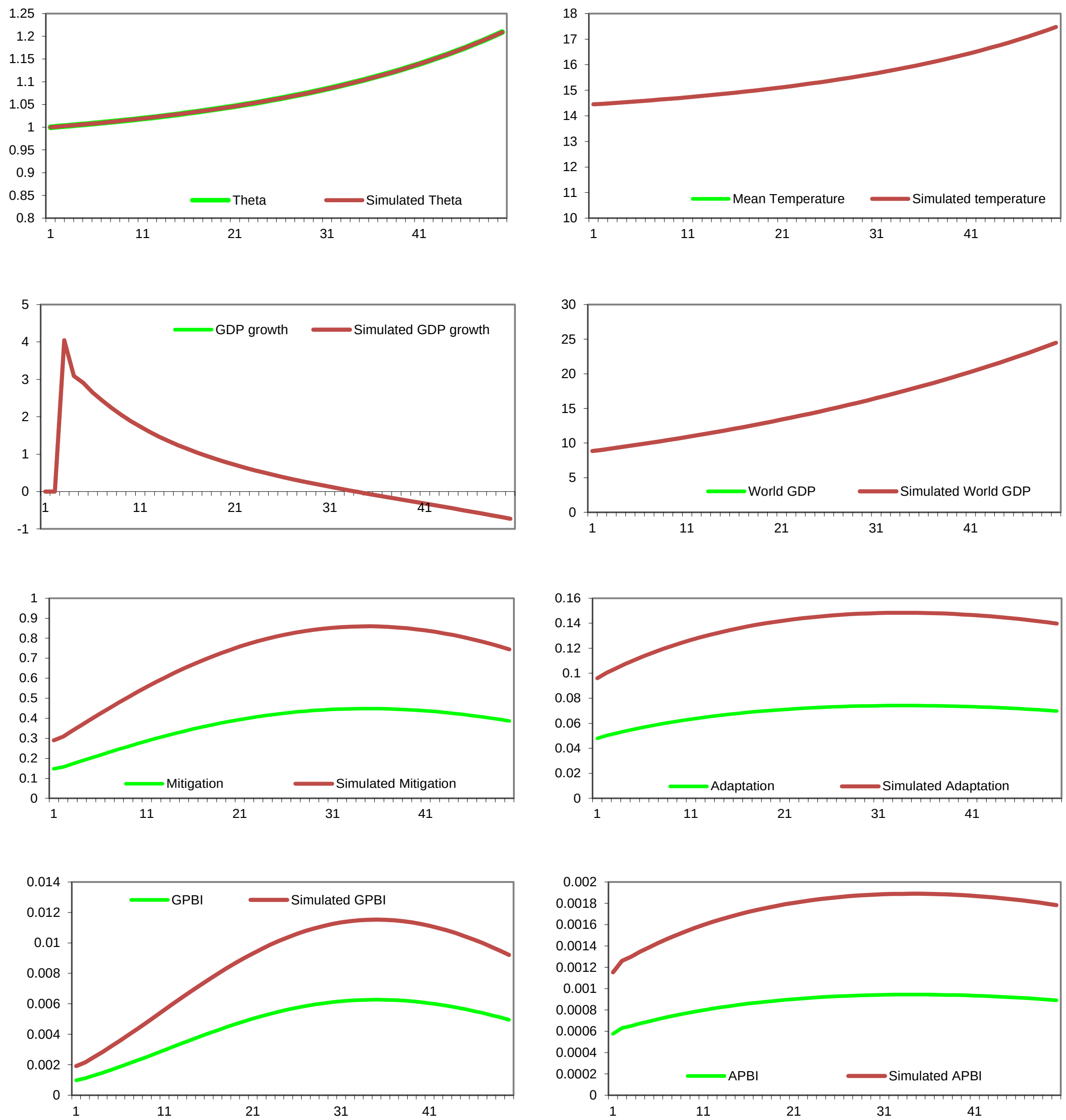



**Figure 12. Baseline Scenario and Simulation 4 for the United States**





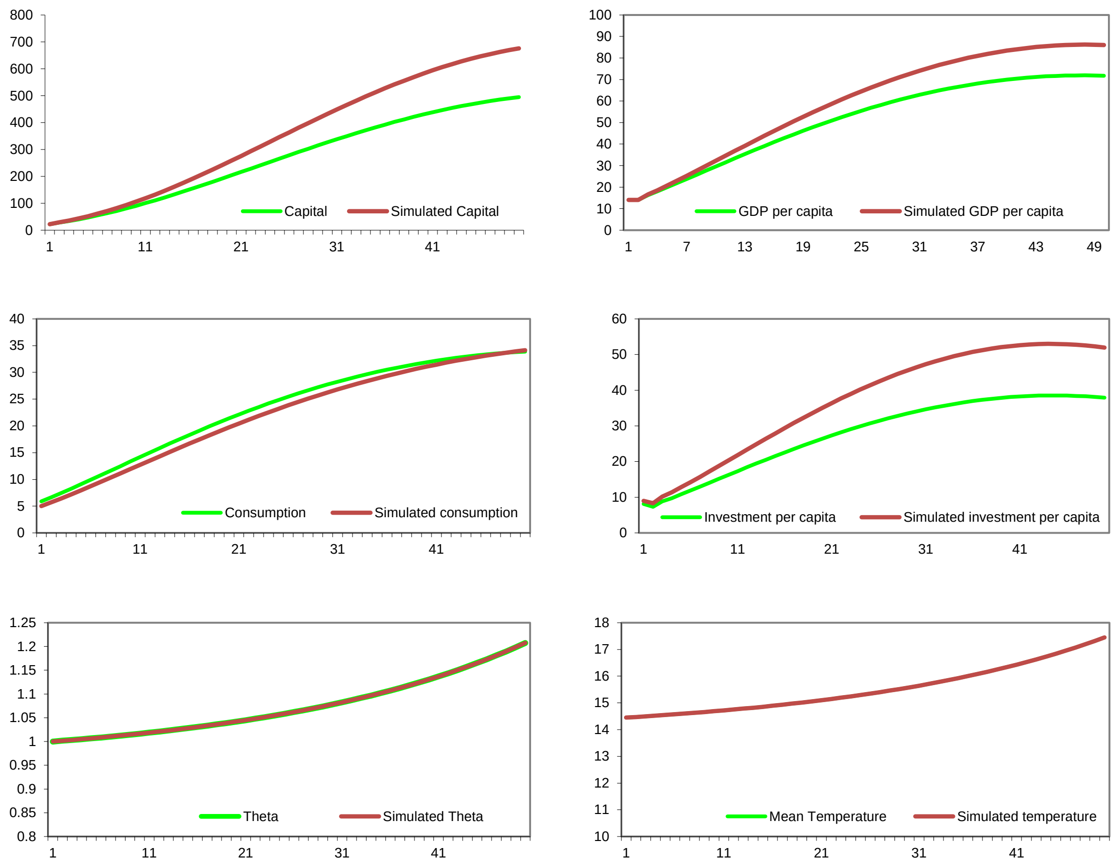

### *4.2.5. Simulation 5: Reduction of the Discount Rate from 3 Percent to 1.5 Percent*

When the discount factor is reduced, future consumption carries greater weight in the intertemporal utility function. This means that investment is enhanced (as well as capital per capita) and, with it, GDP growth. It has been argued that this kind of analysis should be done in the evaluation of investment projects related to climate change because it would demonstrate that a larger number of environmentally friendly projects are worth carrying out. The simulations address a generalized reduction in the discount rate, and they show that all three economies would grow faster.

The results do not provide as much of a basis for optimism as expected. The generalized reduction of the discount rate could have increased the long-run stock of capital even more than the average temperature. This means that the reduction of discount rates should be limited to those projects that make a real reduction in emissions. Although the United States is making additional expenditures on mitigation, it can be seen that the mean temperature increase remains constant and that the economy makes the necessary efforts to avert an increase in emissions beyond the initial pattern—but no more than that. Brazil also engages in more mitigation, but Chile does not.

Adaptation rises in all three countries. This is due to the greater affluence of their economies, which allows them to devote more resources to protecting production. The fact that any given percentage reduction in total production will be more significant in absolute terms under the new scenario is an additional factor.

**Figure 13. Baseline Scenario and Simulation 5 for Brazil**



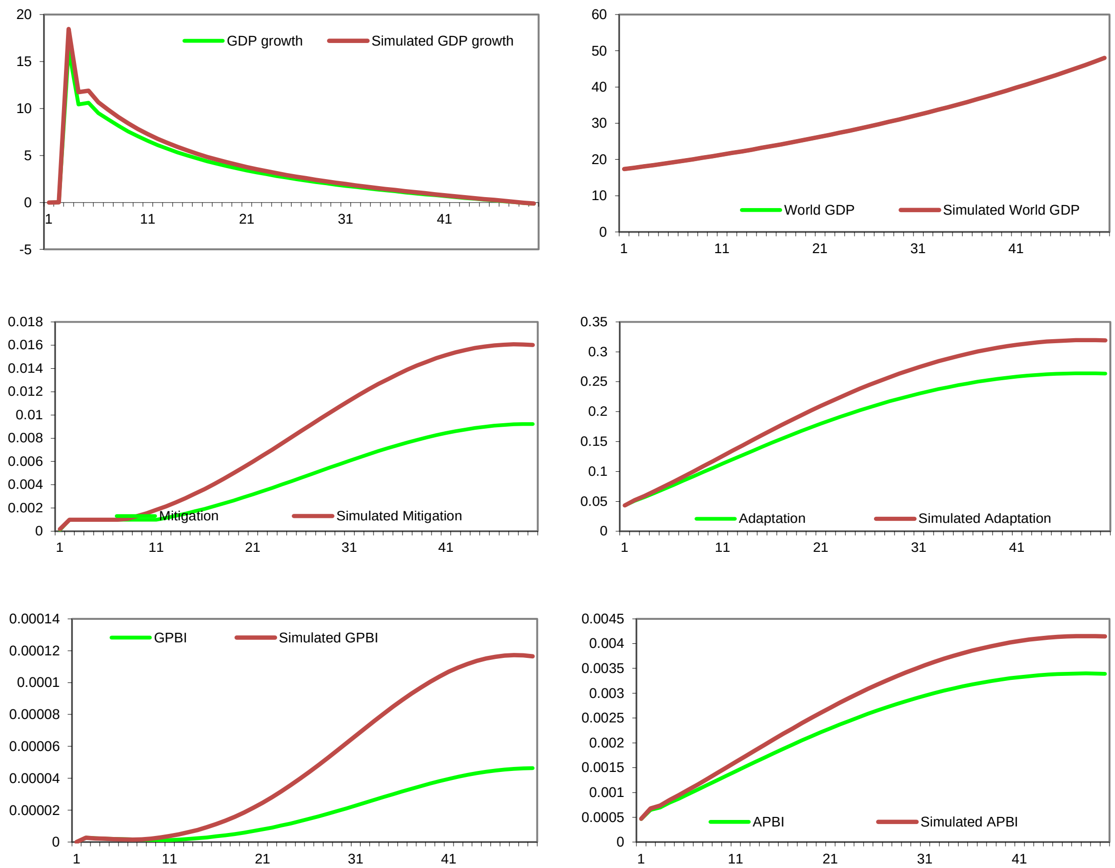
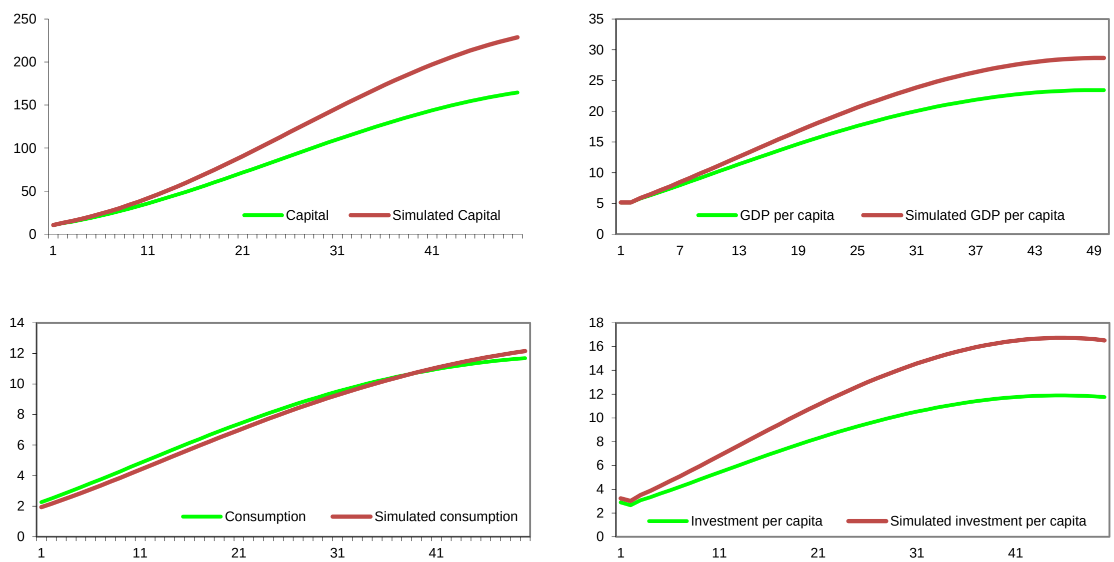



**Figure 14. Baseline Scenario and Simulation 5 for Chile**



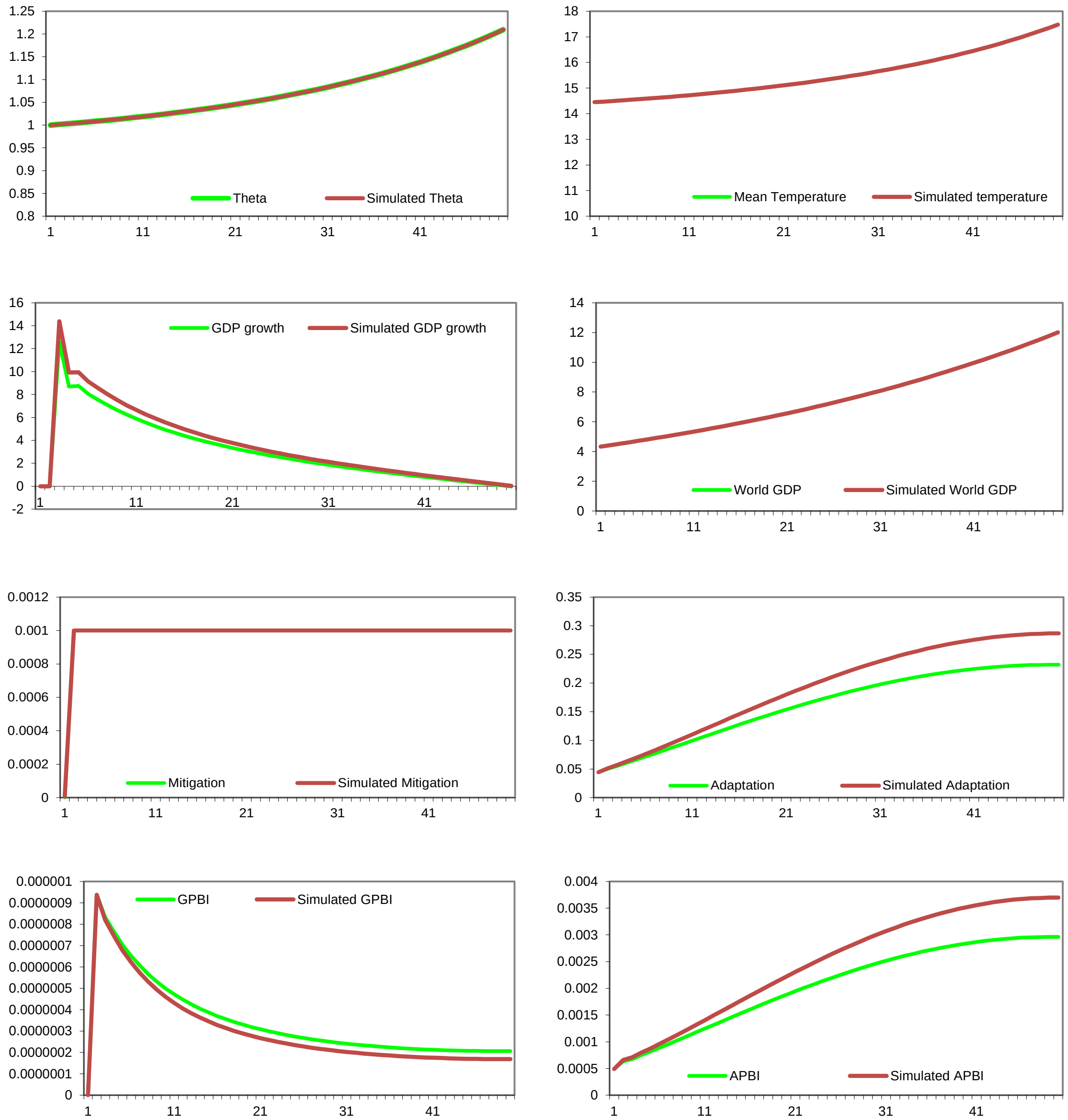
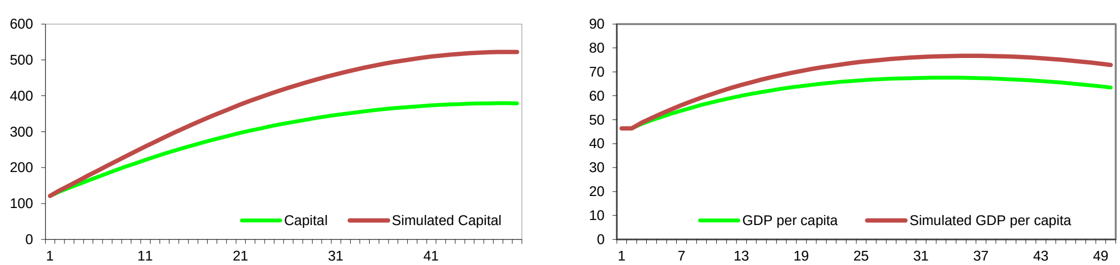
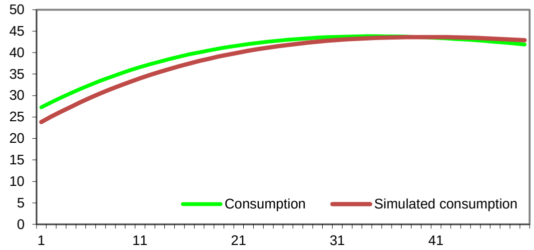
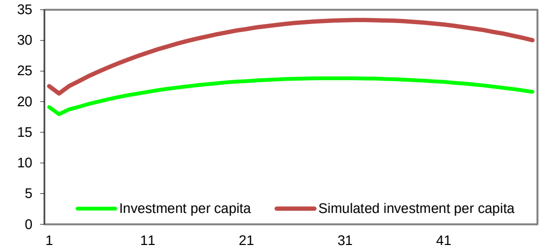
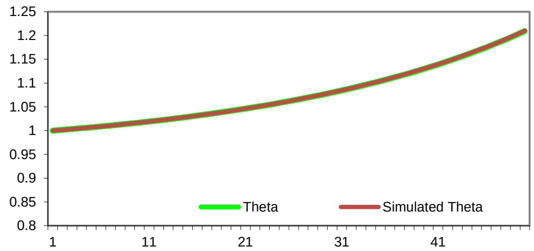


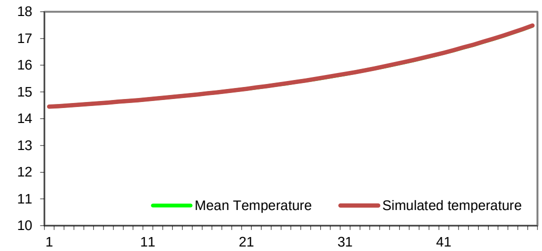

**Figure 15. Baseline Scenario and Simulation 5 for the United States**

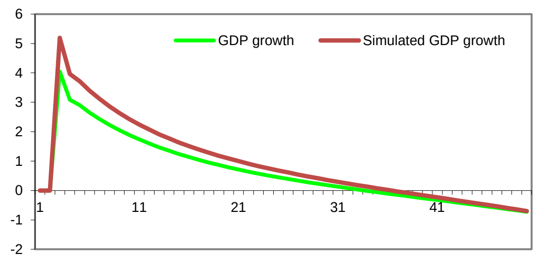


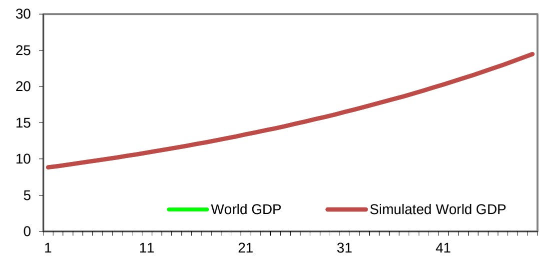

Consumption
Simulated consumption
50 45 40 35 30 25 20 15 10 5 0
1 11 21 31 41

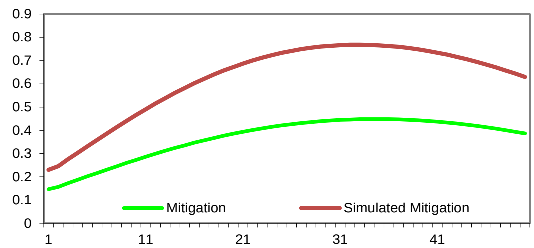

Investment per capita
Simulated investment per capita
35 30 25 20 15 10 5 0
1 11 21 31 41

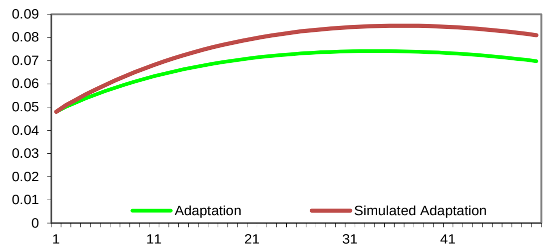

Theta
Simulated Theta
1.25 1.2 1.15 1.1 1.05 1 0.95 0.9 0.85 0.8
1 11 21 31 41

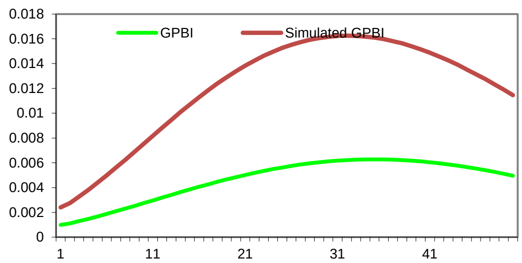

Mean Temperature
Simulated temperature
18 17 16 15 14 13 12 11 10
1 11 21 31 41

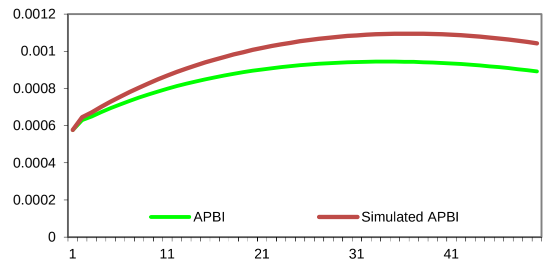

GDP growth
Simulated GDP growth
6 5 4 3 2 1 0 -1 -2
1 11 21 31 41


World GDP
Simulated World GDP
30 25 20 15 10 5 0
1 11 21 31 41


Mitigation
Simulated Mitigation
0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
1 11 21 31 41


Adaptation
Simulated Adaptation
0.09 0.08 0.07 0.06 0.05 0.04 0.03 0.02 0.01 0
1 11 21 31 41


GPBI
Simulated GPBI
0.018 0.016 0.014 0.012 0.01 0.008 0.006 0.004 0.002 0
1 11 21 31 41


APBI
Simulated APBI
0.0012 0.001 0.0008 0.0006 0.0004 0.0002 0
1 11 21 31 41

## 5. Conclusions

In this paper we have done two things. First, we have developed an optimal growth model with climate change which draws its inspiration from the DICE model but that allows for the existence of a steady state. The idea was to explore the impact of climate change on the properties of that steady state and to get an insight of the incentives to mitigation and adaptation. Thus this model allows for the use of mitigation as well as adaptation measures in order to reduce the effect of climate change. Although this is already an improvement on most past studies, which include only mitigation policies, we go further by allowing for the possibility that the effects of these (mostly mitigation) policies will differ from country to country depending on the size of each country's contribution to total emissions relative to that of the rest of the world.

Second, we conducted several dynamic comparative exercises to obtain an intuition of the possible reactions of economies in terms of adaptation and mitigation to different parameters when the steady state does not necessarily exist. To see the relevance of those exercises, consider for example the case of absence of technical progress in climate change mitigation; then even if per capita consumption were constant, total emissions would grow because of the growth in total population, and what matters for climate change are total emissions and not per capita emissions.

The simulations confirm the findings from the analytical model, which looks at structural features of the countries for the reasons underlying their attitude with respect to mitigation and adaptation. Based on the model, we expected economies that do not account for a significant percentage of total emissions to spend much less than those that play a more influential role in generating pollution. This is the case of Chile and Brazil, as compared to the United States. The case of Brazil is particularly interesting, however, because it is an economy in transition which, after a number of years, becomes a more significant source of pollution and begins to undertake some mitigation expenditures.

Reducing mitigation costs or the discount factor—or even boosting growth—has no significant effect on mitigation expenditures for environmentally small economies, which is a signal that the problem does not lie on the cost side of the equation, but rather on the effectiveness side. Pollution generates externalities that affect other countries, and environmentally small economies—for which most of the problems related to climate change stem from emissions produced in the rest of the world and must thus be taken as a given—

cannot do much to reduce total emissions and so are obliged to concentrate their efforts on adaptation.

Three main conclusions emerge from our study. First of all, while most countries incur adaptation expenses because they need to reduce the negative impact of emissions-driven climate change, mitigation expenses are incurred only when the economy is responsible for a significant share of total GHG emissions. This is not necessarily a consequence of its cost, but is rather a cost-effectiveness issue: economies that account for a small fraction of total emissions can do little to reduce them, so their expenditures would be futile.

The second conclusion relates to the first: when adaptation is not possible, small economies will not spend more, but rather less, on mitigation. This is because they are unable to reduce the impact of the existing stock of GHG and are thus doomed to slower growth. This should be seen as sufficient reason to subsidize adaptation expenditures in the least developed economies.

It is also apparent that the only way to ensure that countries will spend on mitigation measures is through credible (i.e., enforceable) international agreements under which countries make joint commitments to reduce emissions. However, one of our simulations shows that, if the rest of world were to reduce emissions unilaterally, all three of the economies studied here would have an incentive to reduce mitigation expenditures.

The model also shows that economies in transition that are growing fast and that account for a somewhat significant percentage of total emissions may engage in mitigation activities if their cost is affordable. Richer countries can provide incentives for developing economies to increase their mitigation expenditures. However, the equilibrium effort levels for each country will have to be determined on the basis of further research.

## Appendix 1. Sources of Parameter Values

$k_0$ was obtained based on the ratio of total capital to total output. Data were drawn from Daude and Fernández Arias (2010).

$y_0$ was obtained from the World Bank for 2007. Since we had data for nominal per capita GDP in US dollars and nominal GDP in both dollars and local currency units, we estimated an implicit exchange rate (E):

$$GDP_{pc}(LCU) = GDP_{pc}(US\$)\frac{GDP(LCU)}{GDP(US\$)} = GDP_{pc}(US\$)E\left(\frac{LCU}{US\$}\right)$$

$gw$ and $nw$ were obtained from the World Bank database and correspond to the period 2004-2008.

The per capita production function is:

$$y = Ik^{\alpha}$$

$\alpha$ was obtained as the average share of capital remuneration between 2004 and 2008 from IBGE (Brazil), Chile's Central Bank and NBER.

$I$ is calibrated from the initial production data $(\alpha;\ Y_0;\ K_0)$

Per capita tons of $CO_2$ for each country (*betp*) were obtained by calculating the ratio of each country's total emissions for 2007 to its population, based on data from the World Bank.

Calibration of the mitigation cost function was based on the assumption that it is quadratic:

$$ExpM_{pc} = \eta M^2$$

Thus, marginal expenditure on mitigation is:

$$MgExpM_{pc} = 2\eta M$$

Total per capita emissions $ET_{pc}$ were obtained based on the assumption that 2.5 percent of realized emissions were prevented:

$$ET_{pc} = \frac{ER_{pc}}{1 - ET_{ev}}$$

Thus, per capita mitigated emissions in tons of $CO_2$ are then:

$$M_0 = ET_{ev}ET_{pc} = ET_{pc} - ER_{pc}$$

Marginal costs in local currency units are the result of the estimated marginal cost in US dollars times the implicit exchange rate:

$$MgC(LCU) = MgC(US\$)E$$

The marginal cost of US$ 20 is an average of estimations from different sources. Aldy et al. (2010) place the figure at US$ 10 per ton of carbon dioxide to limit emissions to 3°C and at between US$ 25 and US$ 70 to hold the rise in temperature to just 2°C. The estimated market price per ton of $\mathrm{CO_2}$ has been around US$ 20, as can be deduced from the European Environment Agency (EEA) report (2010a). However, since this value could correspond only to private costs, without including social ones, we took into account the McKinsey report (2009), where total costs are approximated to US$ 20 with the production technologies available today. This allows us to obtain $\eta$ from the marginal expenditure function.

The $b$ parameter that reflects the effectiveness of mitigation was obtained from the following formula:

$$b = \left(\frac{1}{1 - ET_{ev}} - 1\right)\frac{1}{M_0}$$

In turn, per capita adaptation expenditures are modeled as: $ExpA_{pc} = \rho A^2$ and it follows that marginal per capita expenditure is: $MgExpA_{pc} = 2\rho A$

Since the $A$ parameter is an index, say $A_0 = 1$, we can calibrate $\rho$ using the results provided by the EEA report (2010b) and the Stern Review (2007), which indicate that additional adaptation expenditures could amount to 0.5 percent of GDP. In other words, since those papers characterize those estimates as being additional, we interpret them as marginal; this interpretation allows us to err on side of pessimism. Thus, we adopt the upper bound of the interval suggested in the literature. This means that we are adopting a pessimistic stance in terms of the total cost of adaptation. We include an exercise that reduces adaptation costs in order to observe the degree of sensitivity:

$$\rho = \frac{MgExpA_{pc}}{2} = \frac{0.005Y_0}{2}$$

Most projections indicate that the increase in the average temperature over the next 50 years will be 3°C. Using a geometric progression, the annual average temperature increase ($\Delta T$) is therefore 0.0037 degrees.

Using this figure, we calculate the adaptation effectiveness parameter $z$ as:

$$z = \frac{\Delta T + Tm}{Tm} - 1$$

## Appendix 2. Equations Used in the Simulations in GAMS

(1) VAUT.. *VA=E=sum(t,(1/rt(t))*N(t)*(C(t)**(1-sigma)-1)/(1-sigma)))*;

where *sigma* is the elasticity of marginal utility of the CRRA utility function, which along with the discount rate $r$ (which is taken here as constant, but could also vary across time), plays a crucial role in the determination of future consumption relative to present consumption. The current population is denoted as $N(t)$.

(2) K(t+1).. *K(t+1) =E=Y(t) - C(t)+((1- δ)/(1+n))*K(t) - η*m(t)**2 – ρ*a(t)*2*;

This is the law of motion for capital, which is expressed as the difference between output and consumption and mitigation and adaptation expenditures, plus the actual stock of capital, while accounting for depreciation and population growth.

(3) YY(t+1).. *Y(t+1) =E= (I*(1+tfp)*(K(t)**alpha))/ theta(t)*;

Per capita output is the result of the production function, divided by *theta* (which means that $\Theta(S - za) = 1/theta\,(t)$), the function that reflects the damage that climate change causes in the economy. In fact, theta is a function of average temperature:

(4) TH(t+1).. *theta(t)=E=(Tem(t)/(tm*(1+z*a(t)))*

We add the restriction that 1/*theta(t)=Θ(S −z a) ≤ 1* to rule out cases in which adaptation expenditure allows shocks to increase production rather than reduce it. In turn, the planet's average temperature follows the law of motion as indicated below:

(5) TT(t+1).. *Tem(t+1)-Tem(t)=E= φ *Tem(t)*(betrow*(YW(t)*Nw*nwt(t))+ betp*(Y(t)*N*nt(t)*1/(1+b*m(t))))*;

In turn, population in each country and in the rest of the world grows according to:

*nt(t)=(1+n)**(ord(t)-1);*
*nwt(t) = (1+nw)**(ord(t)-1).*

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