Climate change: discount or not? future generations don't care that much.

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Abstract

This paper proposes a new way to model the cost of climate change, based on a vintage capital modeling. Climate change destroys capital, according to the difference between the current climate and the climate that prevailed when a given durable was built. This assumption is meant to account for the adaptation of economic agents to the changing climate. The main result is that the carbon tax is much less sensitive to the rate of time preference than in the Stern-Nordhaus controversy. Moreover, despite an estimate of the cost in line with Nordhaus' estimate for the 21st century, we find an optimal carbon tax much lower than his one.

Key words:
global warming, stock pollution, carbon tax, discount rate

Introduction

This paper aims at lowering the importance attached to the discount rate in the debate about climate change. We argue that the importance of discounting is overestimated, because the cost of global warming on the very long run is overestimated. In a numerical vintage capital model based on a modified version of Nordhaus' DICE model[2], we show that important changes in the discount rate have a small impact on the estimate of the carbon tax.

The Stern review[3] on climate change was given an important media coverage due to both its very pessimistic conclusions and the good scientific reputation of its author. According to him, the correction of the external effect of

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[1] The author is grateful to Peef Lesh'n for his helpful comments.
[2] Nordhaus (2007)
[3] Stern (2007)

greenhouse gazes requires an increasing Pigovian tax starting from a current level of \$350 per ton of carbon. However, since the publication of the Review, many authors have noticed that the result is very sensitive to the choice of a very low rate of time preference (ρ), coupled with a unitary elasticity of marginal utility of consumption (α)[4]. This debate has become a controversy since William Nordhaus published another study of the economics of climate change[5] with very different numerical results. He advocates a current carbon tax of \$32 per ton, ten times smaller than Stern's. Although Nordhaus' work rely on assessment studies that are less pessimistic than the ones used by Stern, the main reason for such different results is that Nordhaus uses a rate of time preference of 1.5 percent and an elasticity of 2. Nordhaus has a positive approach: he calibrates those parameters out of empirical consumption growth rates and interest rates using Ramsey equation. Stern has a normative approach, at least for the rate of time preference: he states that the only reason why a generation's welfare should be discounted is the risk of disappearance of the mankind. It follows that the estimate of the cost of climate change has become dominated by an ethical question: how much should present generations value the welfare of future ones?

However, there is a consensual point in this controversy: Stern and Nordhaus roughly agree on the economic model that should support the climate change debate. Their common model is inspired by stock-pollution-optimal-control models *à la* Plourde (1972) or Forster (1973). According to these models, a representative agent derives some utility from the use of a polluting good. The pollution accumulates into a stock that generates a cost or a disutility. There are few differences between the Stern-Nordhaus model and those textbook models. The main difference is that Stern and Nordhaus deal with a growing economy. In Nordhaus' DICE, the growing economy is represented by a Ramsey-like optimal saving model, like in Ploeg and Withagen (1991)[6]. The other difference is that the cost due to global warming is expressed in money equivalent. More precisely, both Stern and Nordhaus convert the state of the average temperature into an economic loss in terms of GDP percentage[7]. Since temperature is expected to be higher than the current level for several centuries whatever the scenario, and since GDP is expected to grow in the

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[4] see Weitzman (2007), Heal (2009) or Gollier (2006) among others.

[5] Nordhaus (2007)

[6] A big difference, from an analytical point of view, between Nordhaus' Dice and Ploeg and Withagen (1991) is that in the later, the resource scarcity is not accounted for, whereas fossil fuels are modeled as a non renewable resource in DICE. The closest theoretical models to Nordhaus' are Krautkraemer (1985) and Stollery (1998), but both models take pollution as irreversible. The presence of a capital stock, a resource stock and a pollution stock in the context of global warming generates intricate dynamics that impedes a deep analytic investigation.

[7] The stock of pollution does not directly decrease the utility.

same time[8], both authors predict a very high cost of global warming for the future generations. This cost is expected to be monotonically increasing over time. Under those assumptions, it is not surprising that the present-friendly parameters ρ and α have a strong impact on the evaluation of the cost of climate change.

This paper argues that there may not be a monotonic relationship between the age of a generation and the cost it suffers due to global warming. This result comes from a switch in the modeling of the cost of global warming: while current literature usually models it with a stock of pollution (temperature is modeled as a public bad), we argue that it is not the temperature by itself that is harmful but changes in temperature. Those changes are assumed to destroy a part of the human-made capital. This unusual modeling is meant to account for the adaptation of economic activities to the changing climate in the long run. The underlying assumption is that investment is climate-dependent. A changing climate will destroy a part of the durable goods that are not fit to the new temperature. But the new investments are performed according to this new temperature. It follows that the damage due to climate change, expressed in percent of GDP, reaches a peak when temperature change is the fastest, and then falls down when temperature stabilizes.

The main consequence of this modeling is that a change in the discount rate have a smaller effect on the value of the current carbon tax than in the Stern-Nordhaus controversy. Our approach and the Stern-Nordhaus approach are not mutually exclusive, but can be considered as complements. Our aim is to establish a clear distinction between both, by presenting them as polar cases.

The rest of the paper is organized as follows: section 1 justifies in an informal way our approach of the cost of climate change, section 2 plugs our model into a modified version of Nordhaus' DICE model, section 3 presents the main results, and section 4 is a discussion section.

1 Our approach of the cost of climate change

In this section, we compare the Stern-Nordhaus modelling of the cost of climate change to ours. Stern and Nordhaus have different values for the carbon tax, but they share roughly the same model of the economics of global warming. This conceptual agreement was shown in Nordhaus (2007), who finds Stern's \$350 current carbon tax just by using Stern's ethical parameters in his DICE model, namely the almost-zero pure rate of time preference and the unitary elasticity of the marginal utility of consumption. Their model is a classical

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[8] Due to capital accumulation, population growth and technical progress.

stock-pollution model. The economic impact of temperature can be presented by the following equation:

$$COST_t = \omega\left(T_t\right) \times GDP_t$$

where T_t is the temperature at time t[9] and ω an increasing function $\mathbb{R} \rightarrow [0;1]$. Nordhaus' calibration is $COST_t = 0.0028388 T_t^2 \times GDP_t$. Assume that, from 2200 to infinity, the temperature stabilizes at 4 celcius degrees above the pre-industrial level. Then, the cost of global warming would be 4.54% of GDP forever, which is important. Stern's prediction are even more pessimistic: cost would be 13.8% of GDP from 2200 to infinity. With such a modeling, the impact of discounting is obvious. A *high* discount rate lowers this huge future cost, a very small one does not. This modeling of the climate damage is meant to aggregate a large amount of sectoral-regional studies. However, this aggregation is not neutral. Indeed, most assessment studies have an outcome that can be formulated as follows:

A x degree C increase in the average temperature (with respect to the pre-industrial level) would have a cost of \$ y in the sector of (...) for the country (...)

To be clear, most such studies actually account for adaptation in dynamical context. See, for instance, Tol (2002), for a discussion of the adaptation process and for related references. The point we make is that such studies *have* to be translated into the above-written sentence in order to be used by Stern and Nordhaus models.

Starting from this point, the y values are divided by the GDP of the country. For a given x, the aggregate cost is simply the sum of all sectoral and regional costs. Since studies are performed for different values of x, the modeler is endowed with a vector of temperatures and a vector of aggregate costs. Thus, he only has to specify a functional form for ω and use any relevant econometric tool to estimate the coefficients. However, even if the assessment studies are relevant (i.e. give good estimates of the damage), it does not follow that the ω function is relevant: such a deduction relies on the implicit assumption that the relation between the temperature and the cost is constant over time. Adaptation to the new climate makes a constant relation unlikely. Adaptation is a matter of time: if an abrupt climate change occurred at time t, then virtually no adaptation would be possible at $t+1$, a greater adaptation would be implemented at $t+10$. If the change is permanent, the adaptation would certainly be total at $t+700$. Our model aims at accounting for this adaptation process.

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[9] To be more precise, they take T_t as the temperature increase with respect to the pre-industrial level. But since the reference level is constant, the result is the same as if T_t was the temperature level.

Unlike Stern and Nordhaus, we argue that it is not the temperature by itself that is harmful but the changes in the temperature. Since Stern and Nordhaus implicitly assume that the cost of climate change is only due to the switch from a favorable climate to a less favorable one, we adopt the opposite extreme view that there is no favorable or unfavorable climate, but that the change is costly in itself (section 4 presents both approaches as polar cases). This change is assumed to destroy a part of the human made capital. The underlying ideas behind those assumptions are:

(1) Economic development involves capital accumulation
(2) Capital accumulation is partly climate-dependent

The first point is quite obvious, but it should be underscored that the concept of capital must be understood in a very general sense. A factory is a capital good, but so is a household's house, a railway, a healthy environment etc. All those goods are capital goods because they are assets that allow for future utility or benefit. Most often, they need to be built. Some goods such as a healthy environment are sometimes given by the nature, or sometimes humanly built when the eradication of a disease is needed.

The second point is fundamental. In virtually every country in the world, whatever the *per capita* income, both heavily populated areas and almost desert regions can be found. Both former forests that were converted into farmable lands and other ones that remain wild forests can be found. The choice of where to live or where to make agriculture is certainly not fully random. Cities are often built close to a river or to the sea, in flat places, away from hurricanes. Agriculture usually takes place where the soil is fertile, where the weather is shiny enough or rainy enough according to the crops. The optimal location of economic activities has to do with the climate. It follows that a climate change alters the optimal location of economic activities. On the short run, this sub-optimality results in a direct cost. On the long run, it results in the need for migration of economic activity toward the new optimal location. Since a large part of the capital is unmovable, or very costly to move, the migration will ultimately result in the destruction of a part of the capital. In the formal model described in section 2, we focus on this long run cost of climate change, namely, capital destruction.

In the new optimal location, the new temperature has no cost. But starting from this new temperature, if climate keeps on changing, the same sort of migration will take place. To sum up, if temperature increases by 1 degree at time 1, and by another degree at time 2, the following happens: at time 1, a part of the capital will be destroyed, and the function that gives the quantity of destroyed capital will have "1" as variable. Then, the new capital goods built at time 1 are labeled with the new temperature. Then, at time 2, economy is endowed with two types of capital: durables built before time 1, and durables built at time 1. For the first category, the destruction suffered at time 2 is function of 2 (the rise in temperature since the durables were built). For the second category, the destruction is function of 1 (because temperature has only increased by 1 degree since they were built). Under those conditions, if temperature stabilizes for a long time, the cost tends toward zero, and all economic activities take place at an optimal location. Since climate change is due, for a large part, to the use of non-renewable resources, it is likely that, on the long run, temperature stabilizes[10] .

Now, let us illustrate the difference between Stern-Nordhaus approach and ours. The cost of global warming is expected to arise from phenomenons such as the rise in the sea level, the migration of the so-called climate refugees or the change in the agricultural yields due to drought. We argue that most of this cost is due to the gap between the climate that prevailed when investments were made and the current climate. Let us take three simple examples to illustrate this point.

It is well known that the huge coastal part of Bangladesh is very likely to be submerged if the ocean level rises. This would result in a very important and presumably very costly migration. A household who owns a \$50'000 house would bear a cost that would consist not only in the market value of the house. The willingness to pay for staying in her house would probably be much larger than its market value. Moreover, she would loose a part of her social capital, and need to build a new life after her migration. Overall, let us assume that the cost of the rising ocean would be for her \$200'000 when it happens. It means that, if the Bangladesh is submerged in 2055, the *instantaneous* cost of global warming for this household would be \$200'000. According to the classical stock-pollution modeling, if the climate stabilizes after 2055 and forever, this \$200'000 cost would be beard every period until infinity, which means that, at every period, the household would build a new house at the same submerged place as the first, and would have to migrate again. Moreover, since the cost, in these models, are expressed in terms of percentage of GDP, the cost would be higher at each period (the willingness to pay for staying at the submerged place and/or the market value of the house would increase proportionally with the GDP). On the contrary, in this paper, we assume that once she moved from the submerged area, the household stops building houses there. She is assumed to build her new house in a place that is safe given the current temperature.

Second example: the migrations due to drought. Obviously, if big areas become unfarmable because of drought, it will result in a huge cost. But it will also probably result in a desertification of the region, or, at least, an abandon of agriculture in this place. Once a region has become a desert, how could

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[10] see Sinclair (1992) and Grimaud and Rougé (2005) for the analysis of pollution caused by a non-renewable resource.

one assess the cost of climate change for this desert region? According to the classical stock-pollution modeling, again, if the climate stabilizes, the cost remains constant in terms of GDP percentage after the desertification. In this paper, we assume that after the desertification, no more economic activity take place in the region, and thus, climate change is no more costly for the region.

Third example: the possible expansion to the north of certain tropical diseases such as Malaria[11] . Malaria was present in Europe until the early 20th century, when it was eradicated. This eradication can be thought of as an investment: it consisted in expenditures (in DDT campaigns and changes in agricultural techniques) that resulted in a further health improvement, which obviously has an economic value. Thus, we can consider a malaria-free environment as a capital good. If climate change brings back malaria in Europe, then this capital good is destroyed. It will result in health consequences for the short run, and in the need to re-invest in an eradication program. Again, the classical stock-pollution modeling implicitly assumes an infinite persistence of the spread of malaria, whereas we assume that a new eradication campaign has a cost, but once it is done, there is no persistent cost.

Besides those speculative examples, a number of historical examples could be drawn where a big change in natural environment have a very high cost on the short-middle run, but virtually no effect on the very long run. Take, for instance, Pi-Ramsesses, once the capital city of the Egyptian Empire. Pi-Ramsesses was built in the northeastern region of the Nile Delta, but for millennia, scholars did not know the precise location. Discoveries by Austrian archaeologist Manfred Bietak[12] suggest that this location was the current Qantir, a very small town, that was irrigated by a branch of the Nile. According to Bietak, a fluctuation of this branch led the place to extreme drought, which made life unsustainable. Thus, the city was abandoned. There is no doubt that this environmental change led to an important economic loss. If Pi-Ramsesses' GDP was $x\%$ of Egyptian GDP, then the cost of this environmental change was probably not far from $x\%$ of Egyptian GDP, since a large part of the city's economic activity stopped. However, would anyone believe that a turning back of the branch of the Nile in its original position would *increase* Egyptian GDP by $x\%$? This would be an audacious belief. Nevertheless, this belief would be consistant with Stern-Nordhaus' modeling.

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[11] Notice that a scientific consensus does not exist about the likelihood of a spread of tropical diseases due to global warming.

[12] Bietak (1996).

2 Modeling the cost of climate change

In this section, we describe the way we modify Nordhaus DICE model in order to integrate our modeling of the cost of climate change. Let $K_{t,t'}$ be the stock of t'^{th} generation of physical capital at time t. The only difference between two generations of capital is that each one is fit to the state of the climate at the time it is built. Capital depreciation has two components: a constant, linear one, $\delta K_{t,t'}$ ($\delta \in]0;1[$), and another one that depends on the gap between the current climate, proxied by the temperature T_t, and the climate at the date when the stock was built $T_{t'}$: $\phi\left(|T_t - T_{t'}|\right)$. We assume $\phi' > 0$, $\phi(0) = 0$ and $\phi \in]0; 1-\delta[$. The dynamics of each generation of capital is given by:

$$K_{t+1,t'} = \begin{cases} Q_t - C_t, \ if \ \ t = t' \\ \left[1 - \delta - \phi\left(|T_t - T_{t'}|\right)\right] K_{t,t'}, \ if \ \ t > t' \\ 0, \ if \ \ t < t' \end{cases} \tag{1}$$

Where Q_t is the aggregate income and C_t the consumption. The aggregate stock of capital is given by:

$$K_t = \sum_{t'=0}^{t} K_{t,t'}$$

The evolution of the aggregate capital stock is given by:

$$K_{t+1} - K_t = Q_t - C - \delta \sum_{t'=0}^{t} K_{t,t'} - \sum_{t'=0}^{t} \phi\left(|T_t - T_{t'}|\right) K_{t,t'}$$

which would reduce to $K_{t+1} - K_t = Y_t - C - \delta \sum_{t'=0}^{t} K_{t,t'}$ without climate change. Clearly, the instantaneous cost of climate change is given by $\sum_{t'=0}^{t} \phi\left(|T_t - T_{t'}|\right) K_{t,t'}$.

The remaining of the model is the classic DICE model. A representative household maximizes:

$$\sum_{t=0}^{\infty} L_t \frac{c_t^{1-\alpha}}{1-\alpha} \left(1+\rho\right)^{-t}$$

with $\alpha > 0$ and $c_t \equiv C_t/L_t$, subject to the law of motion for each stock of capital (equation 1) and to an initial value K_0 given. It is assumed that all the stocks aggregated in K_0 were built at the same (preindustrial) temperature. Resource extraction is constrained by the limits in the fossil fuel resources:

$$\sum_{t=0}^{\infty} E_t \leq S$$

where S is the initial value of the (non-renewable) resource stock. The emission level is a function of gross production (Y_t) and abatement efforts ($\mu_t \in [0,1]$):

$$E_t = \sigma_t \left(1 - \mu_t\right) Y_t$$

Where $\sigma_t > 0$ is an exogenously decreasing factor. Abatement efforts lower the GDP, so the aggregate income net of the abatement cost is:

$$Q_t = \left(1 - \theta_{1,t}\mu_t^{\theta_2}\right) Y_t$$

where $\theta_{1,t} > 0$ and $\theta_2 > 0$ are parameters. Gross production is a Cobb-Douglas function of aggregate capital, labor (L_t) and an exogenously increasing TFP factor (A_t):

$$Y_t = A_t K_t^{\gamma} L_t^{1-\gamma}$$

($\gamma \in]0,1[$) We specify ϕ function, for simplicity, as:

$$\phi\left(|T_t - T_{t'}|\right) = \psi_1 |T_t - T_{t'}| + \psi_2 |T_t - T_{t'}|^2$$

($\psi_1 > 0; \psi_2 > 0$) and we verify, when we perform the simulations, that the condition $\phi \in]0; 1-\delta[$ is always respected.

The remaining is the complex[13] climatic module of the DICE, which we present in appendix A. This module establishes the dynamic link between the (industrial) emissions E_t and the atmospheric average temperature T_t.

Solving this program gives the optimal consumption-emission path, for a given value of (ρ, α). Following Nordhaus (2007), we also compute a *business as usual* (BAU) path, which is done in two stages: first, we compute a *Hotelling* path by setting $\phi = 0$. This gives the consumption-emission path that would be optimal[14] in the absence of climate change. From this run, we save the rates of emission control. Then, we implement a new run that integrates the ϕ function, and we force the emission control rates to be the same as in the

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[13] From an economist's point of view...

[14] This optimum would also be a decentralised equilibrium if ρ and α are the same for the households and for the *central planner*.

Hotelling path.

3 Results

We now present the results of the simulations with the original DICE (o-DICE) and our modified version (m-DICE). With each model, we compute the BAU outcome, the optimal outcome with Nordhaus' 1.5% rate of time preference (1.5%-opt) and the optimal outcome with Stern's 0.1% rate of time preference (0.1%-opt). Notice that, in every case, we take Nordhaus' elasticity of marginal utility of consumption ($\alpha = 2$)[15]. For all the other parameters, we use the same as Nordhaus (2007) and we set $\psi_1 = 0.03$ and $\psi_1 = 0.02$, which makes the cost of climate change *in line* with Nordhaus' estimate for the twenty first century in the BAU run. More precisely, this calibration makes the cost higher than Nordhaus' before 2060, and lower after this date. This calibration is based on the assumption that the assessment studies used by Nordhaus provide a good forecast for the next fifty years.

3.1 The carbon tax is always lower than with the original DICE model

As can be seen in figure B.2, the modified DICE model advocates a \$11.9 (\$12.1) carbon tax[16] in 2015 for a 1.5% (0.1%) discount rate. These levels are much lower than what results from the original DICE model (respectively \$41.8 and \$90.1). This comes from the difference in the long run damage between both versions. Indeed, between 2015 and approximately 2060 for the $\rho = 1.5\%$ optimal run[17], the damage of climate change is higher in the modified version than in the original one. This is shown in figure B.3. Thus, it can not be stated that the modified version underestimates the cost of climate change for the next five decades, at least compared to the DICE model. On the other hand, starting from the end of the twenty first century, the damage becomes much higher with the original version than with the modified one, as one can see in figure B.4 (mind the logarithmic scale!). The local minimum attained at the end of the twenty third century corresponds to the beginning

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[15] We don't present the results of the simulations with an unitary elasticity, because they don't add any significant analytical insight. Basically, as for the rate of time preference, switching from Nordhaus' $\alpha = 2$ to Stern's $\alpha = 1$ has an important effect with the original DICE and a small one with the modified version.

[16] In both models, following Nordhaus (2007), the carbon tax is given by the opposite of the multiplier of the emission constraint $E_t - \sigma_t (1 - \mu_t) Y_t = 0$ divided by the discounted marginal utility of consumption (i.e. the shadow price of the capital stock).

[17] and approximately 2080 for the $\rho = 0.1\%$ optimal run.

of a slight global cooling. Notice that cooling, in our model, has the same effect as warning, since the change in temperature is measured in absolute value: a one degree warming has the same cost than a one degree cooling. At the same period, with the original Dice model, one can observe a slight lowering in the slope of the instantaneous cost. Of course, the original Dice model takes a cooling as a beneficial phenomenon.

3.2 Changes in discount rate have a small effect on the first periods optimal tax

In the original DICE model, the cost of climate change increases dramatically over time for two reasons: first, because the temperature is higher in the future than in the present and the cost depends on temperature; second because the cost is a percentage of GDP and GDP is higher in the future than in the present. It follows that, in this original version, climate change is wildly a matter for the future generations. Thus, a change in the discount rate has a very high impact on the carbon tax in the first period. The less you care for the future (the higher ρ), the smallest the carbon tax.

In the modified version, the cost of climate change depends in the change in temperature, which does not depend monotonically of time. However, this cost is expressed as a percentage of the capital, and the capital increases over time. Thus, in the modified version, future generations tend to suffer more than present one from climate change. But the increase in the damage is much less dramatic than in the original DICE model.

The consequence is that a change in the discount rate has a limited impact on the carbon tax in the first period. It follows that the debate on the discount rate should have less importance than it has since the Stern-Nordhaus controversy.

4 Discussion

The numerical results of this paper are likely to be controversial, since they result in a low carbon tax, compared to the results of the existing literature. However, the main purpose of this paper is not to advocate such a low carbon tax, but to underscore the possibility that the usual modeling of the cost of climate change might not be the only possible modeling. Nordhaus' main argument against Stern's review is the following:

How do damages, which average around 1 percent of output over the next *century, become a 14.4 percent reduction in consumption now and forever? The answer is that, with near-zero discounting, the low damages in the next two centuries get overwhelmed by the long-term average over the many centuries that follow. In fact, using the [Stern] Review's methodology, more than half of the estimated damages "now and forever" occur after the year 2800. The damage puzzle is resolved. The large damages from global warming reflect large and speculative damages in the far-distant future magnified into a large current value by a near-zero time discount rate.*

Nordhaus believes the far-distant damages are *speculative*. If this is a way to refer to the scientific uncertainty about the impact of climate change in the very long run, then it cannot by itself be taken as a justification for disregarding it. Gollier (2006) shows, on the contrary, that uncertainty on environmental damage should lead to a decrease in the discount rate. In fact, one can infer that Nordhaus can hardly figure out that after several centuries of temperature stabilization, very-distant future generations could suffer from the fact that the average temperature is hotter than nowadays. However, this is consistent with his own modeling of the temperature as a public bad. The alternative modeling we propose in this paper may fit to what Nordhaus has in mind when he calls *speculative* the far-distant damages. It focuses on the change in the temperature and not on the level of the temperature as a factor of damage. Of course, this modeling also has its challenges. Life on earth would certainly be impossible for very low or very high temperatures. Thus, if economic welfare can be represented as a function of the temperature, the curve would probably be a *reverted U-shaped* one, whereas our modeling implicitly assumes it is flat.

Figure B.5 pictures what should probably look like the impact of climate change on economic welfare. This impact is twofold: first, the change would be harmful by itself because of the adjustment costs, second it would lead the economy to a different temperature, that would be more of less welfare enhancing. In this case, Stern-Nordhaus' approach and ours would only be two polar cases, and discounting would have a bigger impact than what we find here. Thus, the big issue is to determine which of the slopes is the greatest. If $W(T, \Delta T)$ is the welfare as a function of the temperature and of the change in temperature, then the big issue is to compare $\left|\frac{\partial W}{\partial T}\right|$ and $\left|\frac{\partial W}{\partial \Delta T}\right|$.

Given the numerical importance of this issue, empirical assessment of the cost of global warning should distinguish what part of the cost is due to the new temperature and what part is due to the change in temperature. Actually, some studies explicitly take the temperature level as a argument of the aggregate production function, such as Choiniere and Horowitz (2000) or Van Kooten (2004). However, those studies can hardly account for the major expected economic impacts of climate change, such as disease spreading, the increase in the sea level, the climate refugees, since those phenomenons are not accounted for in the per-capita GDP measure.

The assessment study by Mendelsohn et al. (1994) for the agriculture also links the agricultural yields with the climate. The authors account for the adaptation of the farmers to the changes in climate, but only in terms of the choice of crops. The more fundamental choice of what land to make farmable is exogenous. This assumption is relevant for a few decades, but probably not for several centuries. Indeed, in the very long run, farmers should be allowed to choose the lands to be exploited, and not only the type of use of a given land.

In a recent study, Dell et al. (2009) discriminate between the short-run impact of an unexpected change in temperature and the long-run economic impact of climate, after adaptation is enforced. The long-run cost, i.e. the after-adaptation cost, relies on the differences within a given country in gdp and temperature. However, the location choice is not explained in this paper, and one can guess that the productive activities take place in temperate regions.

Both aforementioned studies are confronted with the difficulty of defining the long term, i.e. the term after which adaptation is expected to take place. In virtually every economic context, 'short run' means several months, while 'long run' means no more than several years. In the context of climate change, even several decades might not be long enough a term for full adaptation, because of the radical changes that can be induced by climatic events, such as big population migrations. We hope the model presented in this paper can help thinking more smoothly this adaptation process.

Conclusion

Climate change is often viewed as one of the major global issues of the twenty first century. Most assessment studies show, indeed, that substantial costs are likely to be suffered because of the increase in the average temperature. The mainstream interpretation is that climate change is about to move the global economy from a favorable climate to a less favorable one. This paper suggests another interpretation of this cost. We argue that the cost is due to the need of adaptation to the new climate. This is captured by a vintage capital model in which each generation of durable good is labeled by the temperature that prevails when it is built. With this model, if the temperature stabilizes on the long run, the cost is asymptotically nil, whereas, with the usual modeling, it tends to be a constant percent of GDP. This model is consistent with the fact that few contemporary Egyptians are interested by the irrigation of Pi-Ramsesses. The main result of this model is that the optimal carbon tax is much less sensitive to the discount rate than in the Stern-Nordhaus controversy. The second is that this tax is lower than it is in previous studies.

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A DICE's climate module

Dice's climate module is given by the following set of equations:

$$
\begin{aligned}
&M_{at}(t) = E(t) + E_{land}(t) + \kappa_{11} M_{at}(t-1) + \kappa_{21} M_{up}(t-1)\\
&M_{up}(t) = \kappa_{12} M_{at}(t-1) + \kappa_{22} M_{up}(t-1) + \kappa_{32} M_{lo}(t-1)\\
&M_{lo}(t) = \kappa_{23} M_{up}(t-1) + \kappa_{33} M_{lo}(t-1)\\
&F(t) = \eta \left\{\log_2 \left[M_{at}(t)/M_{at}(1750)\right]\right\} + F_{ex}(t)\\
&T(t) = T(t-1) + \xi_1 \left\{F(t) - \xi_2 T(t-1) - \xi_3 \left[T(t-1) - T_{lo}(t-1)\right]\right\}\\
&T_{lo}(t) = T_{lo}(t-1) + \xi_4 \left[T(t-1) - T_{lo}(t-1)\right]
\end{aligned}
$$

where: $M_{at}(t)$, $M_{up}(t)$ and $M_{lo}(t)$ are the carbon concentrations at time t in the atmosphere, the upper oceans and the lower oceans. $E_{land}(t)$ is the exogenous emission level due to the changes in land use. $F(t)$ is the total radiative forcing, and F_{ex} the exogenous forcing. $T(t)$ and $T_{lo}(t)$ are the temperature levels in the atmosphere and in upper oceans, expressed in difference with the pre-industrial level. $\kappa_{i,j}$ and ξ_k are parameters.

Figure B.1 illustrates those relations.

B figures

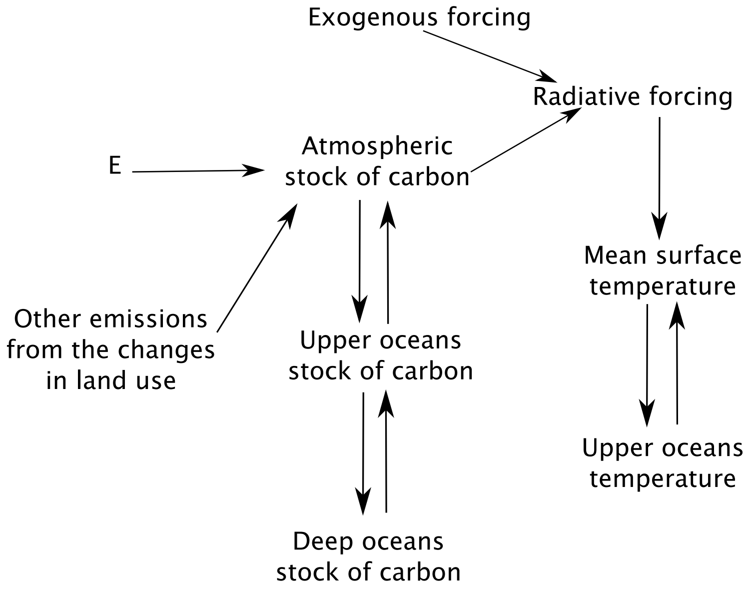

Fig. B.1. DICE's climate module

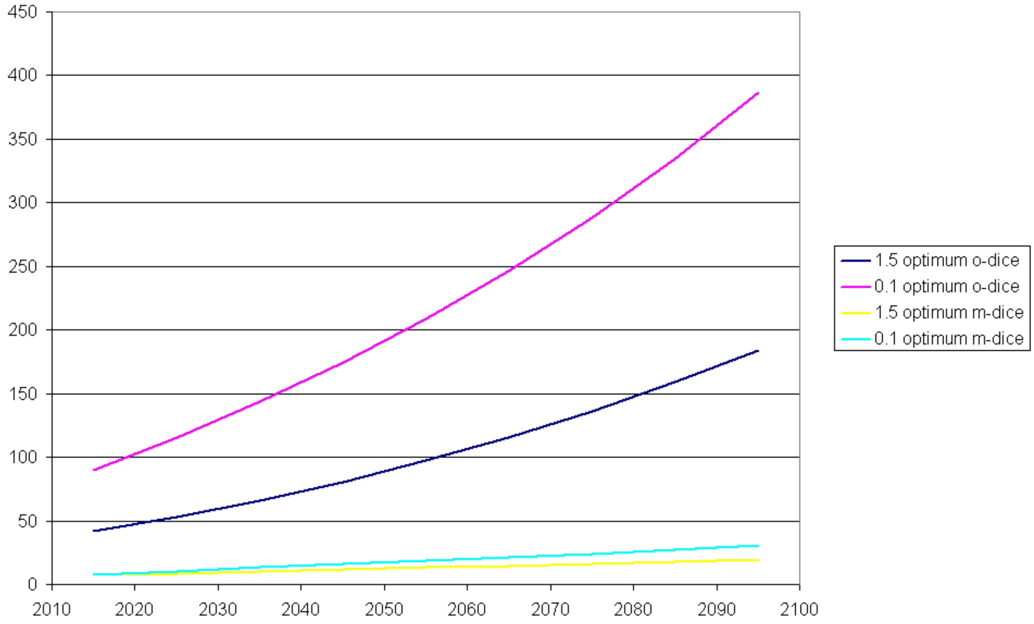

Fig. B.2. Time paths of the carbon tax

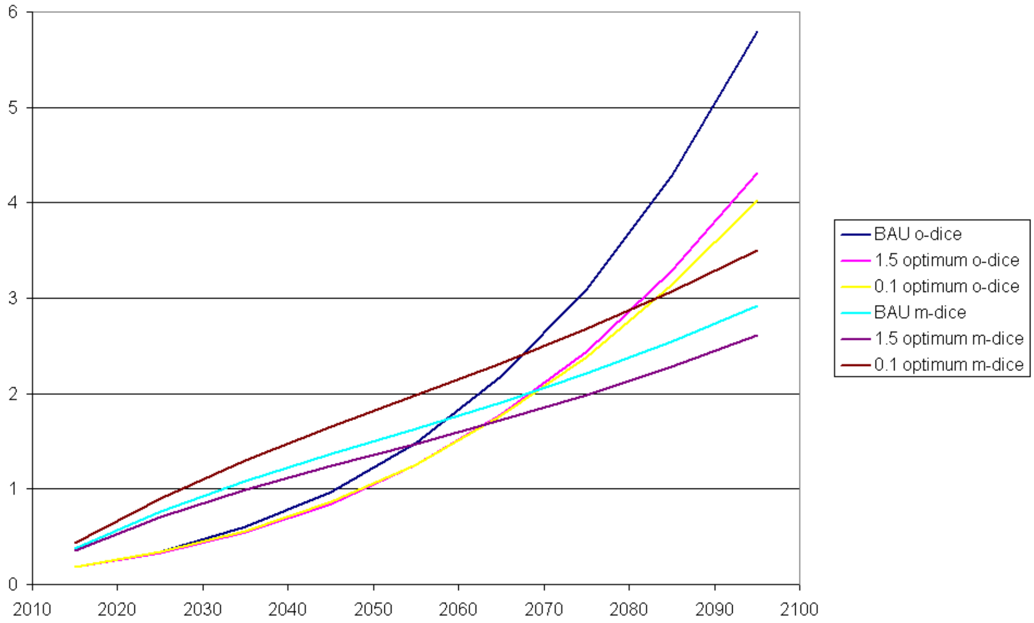

Fig. B.3. Time paths of the instantaneous cost in the short run

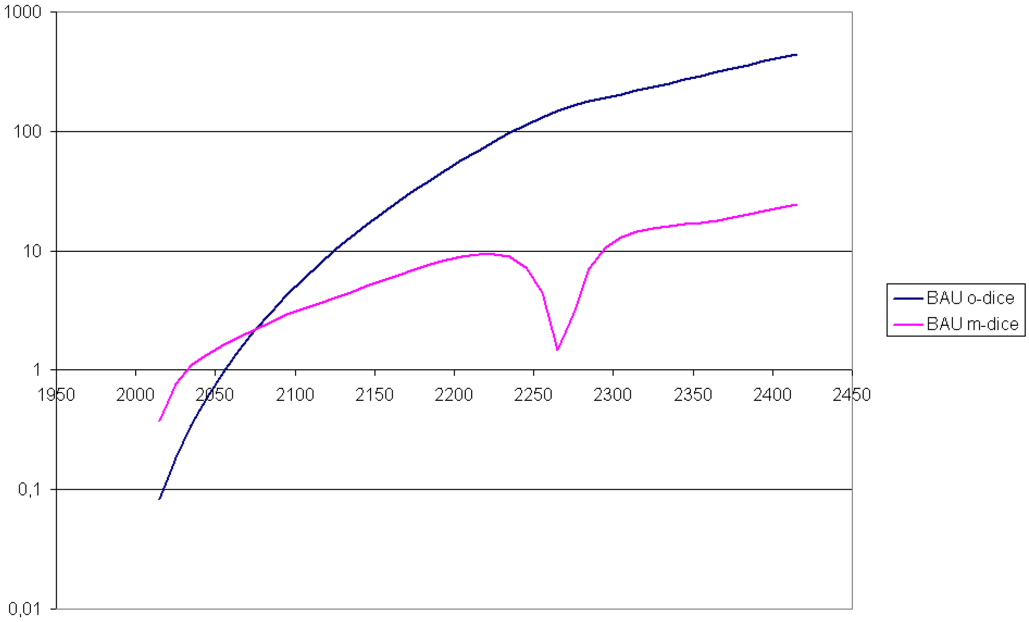

Fig. B.4. Time paths of the instantaneous cost in the long run (logarithmic scale)

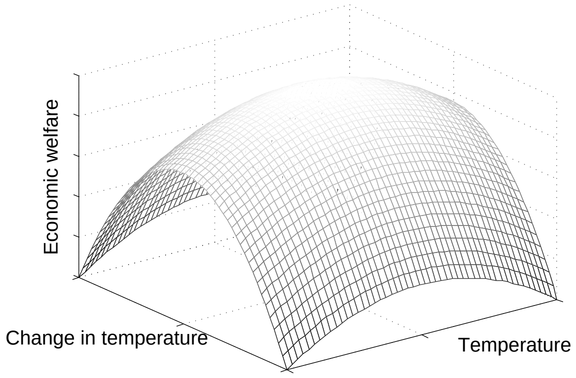

Fig. B.5. Welfare impact of T and ΔT