33

■

Climate Change: Challenges for the World

Johan Eyckmans, Bert Willems and Jean-Pascal van Ypersele

October 2005

ENVIRONMENTAL
ECONOMICS & MANAGEMENT
MEMORANDUM

UCL
Université
catholique
de Louvain

Chair Lhoist Berghmans
in Environmental Economics
and Management

Center for Operations Research
and Econometrics (CORE)

Environmental Economics and Management Memorandum # 33

Climate Change: Challenges for the World

Johan Eyckmans
EHSAL and CES

Bert Willems
CES
Katholieke Universiteit Leuven

Jean-Pascal Van Ypersele
ASTR
Université catholique de Louvain

Reprint from

Economic Aspects of Climate Change Policy
A European and Belgian Perspective

A joint product of CES-K.U.Leuven and CORE-UCL
Edited by Bert Willems, Johan Eyckmans and Stef Proost

Published by ACCO
Brusselsestraat 153, 3000 Leuven (Belgium)

With the financial support of the Belgian Science Policy
Contract CP/10

2005

II. Climate Change: Challenges for the World

Johan Eyckmans, Bert Willems and Jean-Pascal van Ypersele

1 AIM OF TEXT

In this chapter we look at the climate change problem from a long-term and global perspective. The aim is to demonstrate how integrated assessment models, which combine stylized representations of the physics and economics of the problem, can be used to design long-term climate policy. The main questions we will address in this chapter are: (i) what is the optimal, global emission ceiling, (ii) what is the optimal timing of emission abatement efforts in order to achieve this global ceiling, and (iii) how does uncertainty affect the answers to these questions?

Designing optimal long-term climate policy is complicated because of the very nature of the problem. A first complication is that the climate change problem is characterized by major *irreversibilities*. Some of the greenhouse gasses which we emit today will remain in the atmosphere for several hundreds of years. Their natural decay rate is small, and once emitted, it is very costly to reduce their concentrations in the atmosphere in the future. Also with regard to the economics, irreversibility is an important issue. Committing resources today to developing new, low-carbon energy technologies implies that these resources cannot be used for other purposes. We will show that both irreversibilities play an important role in designing climate policy.

A second complication is that there are a lot of physical and economic *uncertainties* concerning key parameters of the climate change process and future economic development. On the physical side, climate sensitivity to changes in atmospheric greenhouse gas concentration and the regional distribution of climate change impacts are subject to considerable uncertainty. On the economic side, costs of emission abatement, and the damages for society of a changing climate, are only known within wide bounds.

A third issue is that uncertainty is not constant. As time passes, we will gain new insights into the physical processes of climate change; we will have better estimates of the costs of new technologies to reduce emissions, and of the cost of protecting ourselves against damages caused by a changing climate. Therefore, this *learning* process will have to be taken into account in an integrated assessment model.

This chapter will try to address these three issues in a systematic way, explaining how such aspects are introduced in an integrated assessment model. It does not intend to give an overview of emission abatement cost estimates, or the impact costs of changing climate. Neither will it give a detailed discussion of the physical processes involved. The reader can find an overview of all these aspects in the assessment reports by the Intergovernmental Panel on Climate Change (IPCC 2001a, 2001b, 2001c).

This chapter is organized as follows. In section two, we discuss some of the key physical aspects of climate change. We highlight the remaining uncertainties and irreversibility aspect of climate change, topics which are important for understanding the economic trade-offs later in the chapter. In the third section, we introduce the notions of emission benefits and global warming damages. In section four we discuss the main trade-offs: (i) how ambitious should we be in our climate target, and (ii) how should we share the burden over different generations to achieve this target? Section five looks at how uncertainty, learning and risk aversion affect the analysis. Finally, section six summarizes our main findings.

2 CLIMATE CHANGE: PHYSICS

In this section we discuss the key physical aspects of global warming that are particularly important for the economic analysis to come.

2.1 Greenhouse effect and natural variations

The atmosphere can be considered as a protective cap, which provides “thermal insulation” for life on Earth. The atmosphere allows most of the shortwave (visible) radiation energy from the Sun to reach the surface of the Earth. At the same time, it prevents part of the long-wave (infrared) radiation emitted by this surface to escape to space. Without this so-called greenhouse effect of the atmosphere, much less energy would be trapped near the surface, and temperatures on Earth would be about 30 degrees Celsius lower.

The Earth’s climate is very sensitive to the energy balance over time. Minor changes in the total amount or the geographical distribution of solar energy across the ages are enough to explain the large climate shifts observed between glacial and interglacial periods. At the height of the last Ice Age, 20,000 years ago, the average surface temperature was about 5°C colder than today, and large ice caps, about 2 km thick, covered most of Europe and North America. This cold climate is explained by small changes in the shape of the Earth’s orbit around the Sun, and of the tilt of its axis.

2.2 Human induced global warming and the Carbon Cycle

The rapid industrialization of the western world and its strong reliance on fossil fuels as an energy resource have added an extra element to the picture – human-induced global warming.

When fossil fuels are burned, CO_2, which is a non-toxic, odourless gas, is an inevitable by-product. Human-induced CO_2 emissions represent about 3% of total CO_2 emissions. Notwithstanding their small share, they create an important imbalance in the so-called carbon cycle. About half of these anthropogenic emissions remain and accumulate, causing an increase in the CO_2 concentration in the atmosphere. This increase in atmospheric CO_2 concentrations is very persistent because it takes several centuries for natural processes to absorb the extra carbon.

Measurements show that the CO_2 concentration in the atmosphere has increased by one third since the beginning of industrialization in the late 18^{th} century. Isotopic analysis of the atmospheric CO_2 has shown the anthropogenic nature of this increase.

A higher CO_2 concentration increases the greenhouse effect of the atmosphere: more of the heat radiation is reflected back to Earth, leading to higher temperatures. Evidence shows clearly and convincingly that the average temperature on Earth has increased by more than 0.6°C over the 20^{th} century. Climate model simulations have shown that most of the observed warming over the past 50 years is likely due to greenhouse gases from human activities (IPCC, 2001a).

Scientists are very confident that these higher CO_2 concentrations are leading to higher temperatures, but there is still some uncertainty on the size of the impact. It has been estimated by IPCC (2001a) that a doubling of the CO_2 concentration will lead to a temperature increase of approximately 1.5 to 4.5 degrees Celsius. Recent research, however, suggests that the upper bound of this estimate could reach 11°C.

2.3 Climate change, a complex process

Climate change is a complex physical process which requires the cooperation of different disciplines such as climatologists, astrophysicists, oceanographers, biochemists, and glaciologists. The interaction of the different physical, chemical and biological systems means that climate models are large, non-linear systems in which there are several positive and negative feedback mechanisms. These feedback mechanisms are second-order effects which reinforce or slow down global warming.

Another complication in modelling climate change is that the effects are not uniform. Some of the factors exert a forcing on the climate system which is higher in some regions than in others. For example, this is the case for sulphate air pollution, which tends to cool the climate regionally. These regionally different feedbacks explain why some regions might warm less than the average, or even cool down in some extreme cases, while the temperature in other regions will increase more than the average. The distribution of effects of climate change on precipitation and other hydrological variables is even less uniform than effects on temperature.

2.4 Climate change, a simplistic model

In the remainder of the text we will use a very simplistic physical model of climate change. It concentrates on CO_2 emissions, and on the CO_2 concentration in the atmosphere. It assumes that only a fraction $\delta(<1)$ of the CO_2 concentration in generation t remains in atmosphere in generation $t+1$. CO_2 emissions in generation t will contribute directly to the CO_2 concentration in generation $t+1$. Hence, the CO_2 concentration in generation $t+1$ can be described by:

$$c_{t+1} = c_t \delta + e_t \tag{1}$$

We also assume that the temperature increase in a period is directly related to the CO_2 concentration in that period:

$$T_t = \Gamma(c_t) \tag{2}$$

These two equations describe a simplistic climate model. Equation (1) describes how the stock of CO_2 evolves through time, while equation (2) describes the temperature-concentration relation.[1]

3 BENEFITS AND DAMAGES OF GREENHOUSE GAS EMISSIONS

In this section we will examine how humans interact with the climate system. We will distinguish between two types of interactions.

First, our current production processes depend heavily on fossil fuels which cause CO_2 emissions as a by-product when they are burned. Therefore emissions of CO_2, and other greenhouse gases can be said to generate *benefits* to mankind since they allow us to produce consumption goods and services. Without emissions, no consumption would be possible with current technologies.

Secondly, some economic sectors (e.g. agriculture and forestry) are likely to be negatively affected by climate changes resulting from an increase in atmospheric greenhouse gas concentrations. Moreover, climate change related natural catastrophes like extreme weather events will probably become more frequent and biodiversity might deteriorate. In this respect, greenhouse gasses are causing *damages*.

---

[1] Our physical model is a simplified version of the models which are used in most integrated assessment models, such as the RICE model of Nordhaus (Nordhaus and Boyer, 2000). We represent the physical process by a linear first-order differential equation. This allows us to explain the main economic intuition of an inter-temporal environmental problem. In practice, non-linear, higher-order differential equations are used.

We will discuss how economists weight benefits and damages of greenhouse gas emissions and define an "optimal" level for such emissions.

3.1 Benefits of GHG emissions or cost of GHG emissions reduction

We assume that the benefits of greenhouse gas emissions, in terms of the consumption goods and services they allow to be produced, can be represented by:

$$B_t(e_t) \tag{3}$$

Equation (3) specifies the value of the goods and services generation t can obtain while emitting e_t tons of GHG emissions. As emissions increase, a generation can produce more goods and services. However, at a high level, emissions no longer allow for the creation of extra services: the cost for transporting oil, and building cars, becomes higher than the benefit of the extra transport service. At the same time, it does not make sense to heat up a house to unbearably high temperatures. The level of emissions e_t^0, by which we can produce the largest value of goods and services, is called the business-as-usual level, or BAU in the sequel. A country without a climate change policy will emit up to this level.

Reducing GHG levels below the BAU-level, reduces the value of the goods and services which can be produced. The *cost of reducing GHG emissions* is given by the forgone benefits of restricting the emissions. In other words, the cost of limiting emission to a level $\overline{e}_t$ below the business-as-usual level e_t^0 is given by the difference in benefits: $B_t(e_t^0) - B_t(\overline{e}_t) > 0$.

3.2 Damages of climate change

Economists distinguish two broad categories of climate change damages: market and non-market damages.

Market damages of climate change involve direct damages, such as losses in agricultural or forestry production due to unfavourable climate conditions. In general, market damages are easy to measure since we can use market prices to express the losses in a common monetary measure. *Non-market* damages are related to goods and services for which no market exists, for instance, loss of biodiversity or disappearance of wetland ecosystems. Valuing these non-market effects is generally more difficult since we cannot use market prices in this case. However, economists have an extensive valuation toolkit at their disposal to deal with this problem. Several attempts have been made in the environmental economics literature to estimate, in monetary terms, the damages of climate change.

In order to estimate these damages, detailed studies need to be made which take into account the fact that different regions will experience different types of physical climate change, like sea level rise, loss of biodiversity, water provision problems and so on. Hence, damage estimates require coordinated efforts between climatologists and economists because impacts will not be uniform across the globe and economies differ with respect to their sensitivity to climate related processes. In addition, one should take into account that humans will adjust their behaviour to cope with the changing climate conditions. People might move to new locations, build higher dikes, or find crops which are more drought resistant. This reaction is called *adaptation*. Not taking into account human adaptation to the changing climate would seriously overestimate the damages of climate change. We refer the interested reader to Toll (2002a, b) for a recent meta-study of climate change damage estimates containing many references.

For the purpose of our exposition, we will assume that we can write climate change damages as an increasing function of greenhouse gases' concentration:[2]

$$D_t(c_t) \tag{4}$$

4 WEIGHTING BENEFITS VERSUS DAMAGES

In this section we show how a simple integrated physico-economic model can be used to derive "optimal" GHG emission trajectories. After discussing the characteristics of such optimal emission trajectories in the simplest possible model, we discuss alternative assumptions and extensions.

4.1 A three generations model

We consider three generations which will be indexed by 1, 2 and 3 respectively. Generation 1 is the current generation, or "we", while generation 2 is the generation of our children. The third generation stands for all future generations that are born after generation two. Using the notation introduced above, we can define the social surplus Z of generation *1* and *2* as:

$$Z_t(e_t, c_t) = B_t(e_t) - D_t(c_t) \tag{5}$$

The generation alive in period t enjoys the benefit of emitting e_t but incurs the climate change damages due to the GHG concentration c_t. The surplus of all future generations is assumed to be summarized by a function $Z_3(c_3)$ which is equal to the benefit of all future generations minus the damages associated with the inherited concentration level: $Z_3(c_3) = \overline{B} - D_3(c_3)$.

4.2 Optimal emission trajectories

In this subsection we look at an "optimal" emission trajectory through time. In economics, one formalizes "optimality" by introducing an omnipotent social

---

[2] The damage function is a simplified representation of how atmospheric CO_2 concentration, for instance, increases global temperature, changes precipitation and reduces diversity, and of the impact of these factors, measured in monetary terms, on mankind.

planner, who decides emission levels for the current and all future generations. For now, we will assume that the preferences of this social planner can be written as a weighted sum of the welfare level of our own generation and of our descendants:

$$Z_1(e_1, c_1) + \rho Z_2(e_2, c_2) + \rho^2 Z_3(c_3) \quad (6)$$

The discount factor ρ reflects the fact that money today is worth more than tomorrow. Indeed money today can be invested, and will give an extra return for the next generation. In section 4.3 we will discuss shortly what economics can tell about the discount-rate. We will split up the problem of the optimal emission trajectory into two questions. The first question deals with the optimal concentration level. The second question deals with the optimal timing:

- How ambitious should we be in setting the level of emissions?
- If we decide on a certain concentration target, should we reduce all emissions now, or should the next generation reduce emissions?

How ambitious should we be?

Given the objective function of the social planner, and given that emissions accumulate in the atmosphere according to equation (1), what condition characterizes the "optimal" emission levels? Leaving the computational details to the reader, it can be shown that the optimal emission level for the first generation should obey[3]:

$$B_1'(e_1^*) = \rho D_2'(c_2^*) + \delta \rho^2 D_3'(c_3^*) \quad (7)$$

We use asterisks to denote the optimal emission and concentration levels and primes for the first-order derivatives. Equation (7) shows the trade-off society needs to make between the benefits of emitting and the resulting damage of higher GHG concentrations. In words, the first generation should choose a GHG emission level e_1^* such that the benefit generated by an extra ton of emissions exactly equals the sum of all extra damages it creates for all future generations. One extra ton emitted in generation 1 increases CO_2 concentration in generation 2 with one ton, and damages with $D_2'(c_2^*)$. It increases CO_2 concentrations in generation 3 with δ ton and their damages with $\delta D_3'(c_3^*)$.

Hence, the fate of future generations should be taken into account, but their weight declines the more remote they are in the future–because of the discounting and because of the natural decay of atmospheric GHG concentrations.

Likewise, it can be shown that generation 2 should choose an emission level satisfying:

[3] Eyckmans and Tulkens (2003) derive an optimality condition in the same spirit as condition (6) but using a more general model that distinguishes different global regions, a longer time horizon and a more realistic model of the world's climate system.

$$B_2'(e_2^*) = \rho D_3'(c_3^*) \tag{8}$$

Summarizing, economists recommend taking into account the discounted future damages of climate change, and balancing this with the present benefits of climate change.

Optimal timing

We now look at a slightly different question. The European Community recently agreed on a long-term climate target according to which global mean temperature change should not exceed 2 degrees Celsius. In our model this means that it has fixed an upper bound for the long-term concentration level c_3^* which is consistent with a 2°C warming. In this section we ask ourselves, given such a target, what is the optimal timing of emission abatement to reach it? How should generation 1 and 2 share the required emission abatement efforts?

The problem is therefore to find emission levels for generation 1 and 2, given that the concentration in generation 3 equals $c_3^* = \delta^2 c_1^* + \delta e_1 + e_2$.

Solving the problem of the social planner we obtain that:

$$B_1'(e_1^*) = \rho\left[B_2'(e_2^*)\delta + D_2'(c_2^*)\right] \tag{9}$$

The latter equation is the basic inter-temporal efficiency condition describing the optimal timing of emissions. It tells us how to distribute emissions between the current generation and their children. Consider for instance the consequences of emitting one ton more in the first period and making up for that by emitting δ tons less in the second. Since only a fraction δ of the ton extra emitted in the first period remains in the atmosphere in the second period, this operation is neutral for the concentration inherited by the third generation. The welfare implications of this change of timing of emissions are, first, an increase in the first generation's benefit by $B_1'(e_1)$: see the left-hand side of (9). Secondly, emitting δ less in the second generation reduces their benefit by $B_2'(e_2)\delta$, according to the first term of the right-hand side of (9). Thirdly, the second generation also incurs higher damages $D_2'(c_2)$, as the CO_2 concentration in period 2 will be higher: see the second term of the right-hand side of (9). The inter-temporal efficiency condition (9) says that under the optimal timing, it is impossible to increase overall welfare by reshuffling emissions from one generation to another. The potential gain for generation 1 of such a move exactly equals the accompanying loss (weighed by discount factor) for the second generation and hence, no overall welfare gain of such an experiment is possible.

4.3 Discounting

Above we introduced the objective of the social planner. One of the important parameters in the objective function was the discount factor ρ. In this section we will clarify why economists use such weights and how such weights could be chosen.

4.3.1 Classical Model

In the canonical economic growth model, economists argue that the discount parameter should be a reflection of the "time value of goods". The "time value" tells how much goods and services our generation should invest, in order to provide the next generation with 1€ worth goods and services. More particularly, by investing ρ € of goods and service this generation[4], society can create more capital and knowledge, which allows it to provide 1€ of goods and service in the next generation. The parameter ρ can be seen as a measure for comparing goods produced in different generations. Given the time value of goods we can write the total value of production of goods and services by all generations jointly as $Z_1 + \rho Z_2$.

Economists argue that we should maximize this total value of production of both generations, and then use transfers to shift the goods from one generation to the other. These transfers can be based on any philosophical intergenerational equity principle decided by society.

The reasoning behind classical discounting can be summarized in this statement:

> *one should maximize the size of the pie first, and only later decide how to share it.*

There is a long-standing debate on the appropriate way of measuring the "time value of goods": see, for instance, Portney and Weyant (1999) and all the contributions in this book. One approach is to use observed market interest rates (for instance the interest rate on long-term bonds) which reflect the return on private investments, i.e. how much one unit of consumption today can be converted to consumption tomorrow. Dasgupta, Mäler and Barrett (1999) show that, in the context of climate change, there are strong arguments to use discount rates which are smaller (and hence discount factors ρ's that are larger) than the ones based upon market rates of interest to evaluate the long-term consequences of current GHG emissions. Thus, they argue, we should value future generations more than implied by standard practices in cost-benefit analysis.

4.3.2 Critiques of the classical model

The first critique of the classical model is that it assumes the possibility of reallocating consumption between generations in a lump-sum way, i.e. in a way that does not affect the emission behaviour of the generations. In the real world, financial intergenerational transfers are difficult to imagine. Rather, these transfers take the form of technology and capital (physical, natural and human) transfers. Kneese and Schulze (1985) discuss the implications for optimal inter-temporal decision making for environmental problems when lump-sum transfers are not available. They show that in such cases, the optimal policy prescription strongly depends on the underlying normative world-views. This critique could be summarized as follows:

---

[4] Investing means that society will not consume everything that it produces, but will use some of its productive capacity to build new knowledge, new tools, and the like.

the way one cuts the pie will change the size of the pie.

Secondly, the classical model assumes implicitly that physical capital can substitute for natural capital. But this assumption is challenged by many ecological economists who have argued variously for the possibility of “strong,” “weak” and “no” substitutability: see Pearce and Turner (1990). It should be clear that deviating from the “strong” substitutability assumption renders inappropriate the use of a discounted sum of future consumption as a societal objective function. This critique can be summarized as follows:

there is not one pie, but two pies – an environmental and a physical capital pie; and generations like to eat both pies.

4.3.3 A positive analysis

Condition (7), characterizing the optimal emission level for generation 1, depends on the atmospheric concentration of GHG in periods two and three (through marginal damages). It shows that when setting the emission level of our generation, our government should take into account the climate change damage to *all* future generations.

However, it has often been argued that in practice governments are not forward looking and prefer to solve only those problems that are relevant within their own legislature.[5] An optimal climate change policy would require them to evaluate their actions over a time-span of several centuries. Phelps and Pollak (1968) have studied the effects of having such short-sighted governments. They show that society will not follow the optimal trajectory, and that the non-coordination of subsequent governments leads to wasteful decisions.

5 UNCERTAINTY

As we have mentioned above, there are large uncertainties with respect to the different physical and economic aspects of climate change. In this section, we look at how uncertainty affects the conclusions reached above, and in particular the optimal emission trajectories and timing.

5.1 Two states: high and low climate change intensity

The simplest approach to deal with uncertainty is to take the “best guess” of the damage functions and physical parameters, and look for the optimal emission path with respect to this expected damage function. This is the approach taken by most integrated assessment models.

Uncertainty can easily be introduced into our model by assuming that the climate change problem can take only two forms: with probability p_H the climate

---

[5] In Belgium, a former prime minister declared in a boutade that he would only solve problems once they had been posed. Another former budget minister declared that the budget deficit came by itself and will therefore disappear by itself.

change damages are large, and with probability p_L the damages are small[6]. In the best guess approach, the Pareto efficient emission trajectory maximizes the expected surplus:

$$\max_{e_1,e_2} \quad p_H \left\{Z_1^H(e_1,c_1) + \rho Z_2^H(e_2,c_2) + \rho^2 Z_3^H(c_3)\right\} + p_L \left\{Z_1^L(e_1,c_1) + \rho Z_2^L(e_2,c_2) + \rho^2 Z_3^L(c_3)\right\} \tag{10}$$

where $Z_\bullet^H(\bullet)$ and $Z_\bullet^L(\bullet)$ represent the surplus functions when the climate problem is large and small, respectively. It can be shown that the optimal emission trajectory under the best guess approach should satisfy:

$$B_1'(e_1^*) = \rho ED_2'(c_2^*) + \delta\rho^2 ED_3'(c_3^*) \tag{11}$$

in which $ED_2'(c_2^*) = p_L D_2^{L\prime}(c_2^*) + p_H D_2^{H\prime}(c_2^*)$ stands for the expected damage in generation 2 and in a similar way $ED_3'(c_3^*)$ denotes expected damages in all future generations. So, expression (11) defining the optimal emissions for generation 1 under uncertainty and the best-guess approach is very similar to the corresponding expression (8) under certainty. The only difference is that we have replaced the certain marginal damages by probability weighted expected marginal damages. Whether generation 1 should limit its emission more under uncertainty than under certainty depends on the difference between "certain" damages $D_t(\bullet)$ and "expected" damages $ED_t(\bullet)$, and on the slope of the benefit and damage functions.

There are two problems with this best-guess approach, however. The first problem is that it does not take into account that people are risk averse, and are willing to pay for reducing risk. The second problem is that it does not take into account that, as time passes, generations will learn more about the possible adverse effects of climate change, and can adjust their emissions based upon this new information. In the remainder of the chapter we will discuss how the optimal emission path should be adjusted when uncertainty is fully taken into account and more particularly, whether the first generation should emit more or less compared to the certainty case. The following subsections discuss risk aversion and learning respectively.

5.2 Uncertainty and risk aversion

Most people dislike risk. They tend to prefer a payment of 1000€ with certainty over a lottery ticket with a 50% chance of winning 4000€ and a 50% chance of losing 2000€ – even though this lottery has the same expected payoff of 1000€. People who prefer a certain amount over a risky amount with the same expected

---

[6] Since there are only two possible states, it follows that $p_L + p_H = 1$.

value, are said to be *risk averse*. Risk averse people will try to reduce the risk they face by buying insurance.

One should take this fact into account when calculating optimal emission trajectories,. In an integrated assessment model, risk aversion can be modeled by giving states of the world in which climate damages are high (and hence, expected consumption lower), a higher weight in the societal objective function. In the analytical model the weighting of the different outcomes can be represented by adding weights λ_H and λ_L to the payoffs, such that $\lambda_H > \lambda_L$.

$$\max_{e_1,e_2} \; p_H\lambda_H\left(Z_1^H(e_1,c_1)+\rho Z_2^H(e_2,c_2)+\rho^2 Z_3^H(c_3)\right) + p_L\lambda_L\left(Z_1^L(e_1,c_1)+\rho Z_2^L(e_2,c_2)+\rho^2 Z_3^L(c_3)\right) \quad (12)$$

Introducing risk aversion will lead to more emission reduction effort in the current generation, as we want to prevent catastrophic events in the future. We get a similar expected optimality rule as in (11), but here the perceived damages are higher since risk averse people will give relatively more weight to the worst outcome than risk neutral people:

$$B_1'(e_1^*) = \rho E^* D_2'(c_2^*) + \delta\rho^2 E^* D_3'(c_3^*) \quad (13)$$

in which $E^* D_2'(c_2^*) = \pi_L D_2^{L\prime}(c_2^*) + \pi_H D_2^{H\prime}(c_2^*)$ (with $\pi_k = p_k\lambda_k / [p_L\lambda_L + p_H\lambda_H]$ for k = L and H respectively) stands for the risk adjusted expected damage in generation 2 and in a similar way $E^* D_3'(c_3^*)$ denotes risk adjusted expected damages in all future generations.

5.3 Learning and Irreversibility

So far we have assumed that uncertainty concerning climate change damages remains the same over time. However, it is likely that scientific advances will give mankind more insight into the causes and potential impacts of climate change. In other words, humankind will learn more about the climate change problem; this will, in all likelihood, reduce future uncertainty. Learning implies that one can adjust the level of CO_2 emissions on the basis of all the information available at a particular moment in time. In the analytical model, learning can be represented by assuming that one makes a decision under uncertainty in the first generation, and has perfect information in the second generation. Hence, we have to decide upon an emission level e_1 in generation 1, and can decide upon a different emission level e_2^H, e_2^L in generation 2, depending on whether the climate problem is recognized to be large or small.

$$\max_{e_1, e_2^H, e_2^L} \quad p_H \left\{ Z_1^H(e_1, c_1) + \rho Z_2^H(e_2^H, c_2) + \rho^2 Z_3^H(c_3^H) \right\} + p_L \left\{ Z_1^L(e_1, c_1) + \rho Z_2^L(e_2^L, c_2) + \rho^2 Z_3^L(c_3^L) \right\} \tag{14}$$

In the “best-guess” calculations, we did not allow future generations to adjust their behaviour based upon new information. However, not taking into account that future generations will adjust their behaviour based upon new information will overestimate the expected total cost of climate change. When we allow them to adjust their behaviour depending upon the realization of climate change damages, it is evident that total social surplus can only increase relative to the best-guess solution.

The fact that learning exists – that future generations are able to adjust their emissions levels, based upon new information – will also change the decisions we should take today. The intuitive idea is that the current generation should take decisions which do *not restrict the freedom of future generations*. If current generations can choose between an irreversible action and a reversible action, it should give a premium to the reversible action. The extra value of choosing a reversible action and keeping the options open for future generations is called the *quasi-option value* of a reversible investment: see Arrow and Fisher (1974).

Emission reduction effort is only partially reversible. If we spend a lot on emission reduction in the first generation, and it turns out in the second period that we did too much, then one can relax abatement efforts in the future, but one can never regain the excessive efforts of the first period. The same is true in the case of spending too little on emission abatement in the first stage. Doing too little in the first stage, and realizing later that the climate change problem is bigger than expected, will oblige one to do more in the second generation, at a higher cost. The relative size of these two irreversibilities will determine whether generation 1 should give more or less effort than under the best-guess approach. Theoretically, it could go either way. However, according to Ingham and Ulph (2003), most numerical models predict that with learning one might emit more today than in the “best-guess” approach. However, this result needs to be qualified, as the results depend on the precise parameterization of the problem.[7] Figure 1 illustrates the emission path under the best-guess approach (solid line) and under learning (dotted line).

[7] Kolstad (1996) shows that partial irreversibility will not change the optimal level for the current generation, but he does so under a very restrictive assumption. In our simplistic model, the assumption boils down to assuming that the damage for future generations is linear in concentration.

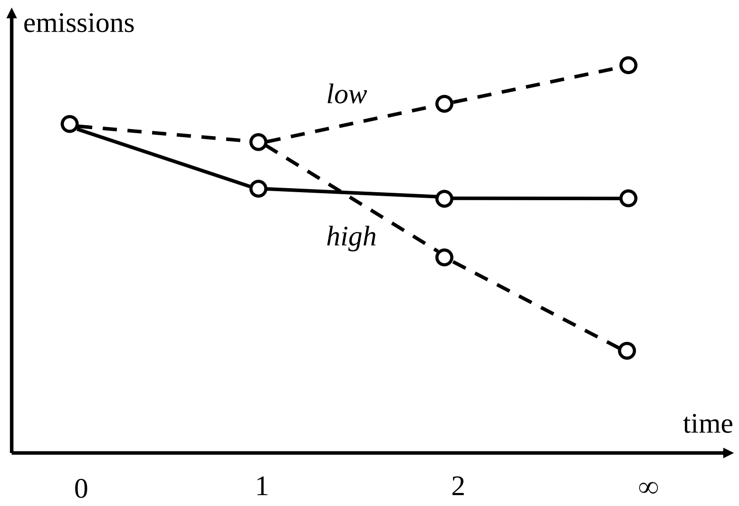

Figure 1: The effect of learning on the optimal emission trajectory

Compared to the best-guess approach, the learning case allows for more flexibility. Generation 2 can choose an emission level conditional on the realization of climate change damages (high or low). According to Figure 1, the fact that all uncertainty will be resolved in period two allows generation 1 to emit more. The irreversibility related to emission abatement investment is, apparently, dominating the irreversibility related to climate change damages.

6 CONCLUSION

In this chapter we have learned how global optimal inter-temporal climate policies can be determined using an integrated assessment model that combines the key physical and economic aspects of the problem. Along the optimal GHG emission trajectory, every generation's emissions should take into account the climate change damages they will inflict upon future generations. However, damages more remote in the future are weighted less because of discounting and natural decay of atmospheric GHG concentrations. We have discussed which physical and economic parameters affect the overall ceiling and timing of emission abatement efforts. We have also shown that the independent decisions of successive generations will lead to an excessively high level of climate change in the future. Finally, we have shown that uncertainty affects the solution in two ways. First, because people are risk averse, more ambitious reduction targets should be set today in order to prevent catastrophic events in the future. Secondly, the design of current climate policies should take into account that future generations will have learned about the crucial parameters and will therefore be able to make decisions with less uncertainty than current generations. According to numerical simulations, this learning effect allows generation 1 to emit more compared to a best-guess approach without learning.

7 REFERENCES

Arrow, K.J. and Fisher, A.C. (1974). *Environmental Preservation, Uncertainty, and Irreversibility*. Quarterly Journal of Economics 88, 312-19.

Dasgupta, P., Mäler, K.-G. and Barrett, S. (1999). *Intergenerational Equity, Social Discount Rates, and Global Warming*. In P.R. Portney and J.P. Weyant (eds), *Discounting and Intergenerational Equity* (pp. 51-77). Washington D.C.: Resources for the Future.

Eyckmans, J., and Tulkens, H. (2003). *Simulating Coalitionally Stable Burden Sharing Agreements for the Climate Change Problem*. Resource and Energy Economics 25, 299-327.

Ingham, A. and Ulph, A. (2003). *Uncertainty, Irreversibility, Precaution and the Social Cost of Carbon*. Tyndall Centre Working Paper No. 37. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK.

IPCC (2001a). *Third Assessment Report – Climate Change 2001. The Science of Climate Change*. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

IPCC (2001a). *Third Assessment Report – Climate Change 2001, Impacts, Vulnerability and Adaptation*. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

IPCC (2001a). *Third Assessment Report – Climate Change 2001, Mitigation*. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Kneese, A.V. and Schulze, W.D. (1985). *Ethics and Environmental Economics*. In A.V. Kneese and J.L. Sweeney (eds), *Handbook of Natural Resource and Energy Economics – Volume I* (pp. 191-220). Amsterdam: Elsevier-North.

Kolstad, C. (1996). *Learning and Stock Effects in Environmental Regulation*: *The Case of Greenhouse Gas Emissions*. Journal of Environmental Economics and Management 31, 1-18.

Nordhaus, W.D. and Boyer, J. (2000). *Warming the world: Economic Models of Global Warming. Cambridge, Mass.:* MIT University Press.

Pearce, D.W. and Turner, R.K. (1990). *Economics of Natural Resources and the Environment*. Hertfordshire, U.K.: Harvester Wheatsheaf.

Phelps E.S. and Pollak, R.A. (1968). *On Second-best National Saving and Game-equilibrium Growth.* The Review of Economic Studies 35, 185-99.

Portney, P.R. and Weyant, J.P. (eds). (1999). *Discounting andIntergenerational Equity*. Washington D.C.: Resources for the Future.

Tol, R.S.J. (2002a). *New Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates*. Environmental and Resource Economics 21, 47-73.

Tol, R.S.J. (2002b). *New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates*. Environmental and Resource Economics 21, 135-60.

Environmental Economics & Management Memoranda

38. Paul-Marie BOULANGER and Thierry BRECHET. Models for policy-making in sustainable development: The state of the art and perspectives for research. November 2005.

37. Johan EYCKMANS an Henry TULKENS. Optimal and Stable International Climate Agreements. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

36. Thierry BRECHET and Benoît LUSSIS. The Clean Development Mechanism in Belgian Climate Policy. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

35. Vincent VAN STEENBERGHE. The impact of banki!ng on permits prices and compliance costs. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

34. Johan EYCKMANS, Denise VAN REGEMORTER and Vincent VAN STENBERGHE. Kyoto-permit prices and compliajce gosts: an analysis with MacGEM. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

33. Johan EYCKMANS, Bert WILLEMS and Jean-Pascal VAN YPERSELE. Climate Change: Challenges for the World. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

32. Marc GERMAIN, Stef PROOST and Bert SAVEYN. The Belgian Burden Sharing. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

31. Ingmar SCHUMACHER. Reviewing Social Discounting within Intergenerational Moral Intuition. June 2005.

30. Stephane LAMBRECHT. The effects of a demographic shock in an OLG economy with pay-as-you-go pensions and property rights on the environment: the case of selfish households. January 2005.

29. Stephane LAMBRECHT. Maintaining environmental quality for overlapping generations: Some Reflections on the US Sky Trust Initiative. May 2005.

28. Thierry BRECHET, Benoît LUSSIS. The contribution of the Clean Development Mechanism to national climate policies. April 2005.

27. Thierry BRECHET, Stéphane LAMBRECHT, Fabien PRIEUR. Intergenerational transfers of pollution rights and growth. May 2005.

26. Maryse LABRIET, Richard LOULOU. From non-cooperative CO_2 abatement strategies to the optimal world cooperation: Results from the integrated MARKAL model. April 2005.

25. Marc GERMAIN, Vincent VAN STEENBERGHE, Alphonse MAGNUS. Optimal Policy with Tradable and Bankable Pollution Permits : Taking the Market Microstructure into Account.*Journal of Public Economy Theory*, 6(5), 2004, 737-757.

24. Marc GERMAIN, Stefano LOVO, Vincent VAN STEENBEGHE. De l'impact de la microstructure d'un marché de permis de polluer sur la politique environnementale. *Annales d'Economie et de Statistique*, n° 74 – 2004, 177-208..

23. Marc GERMAIN, Alphonse MAGNUS, Vincent VAN STEENBERGHE. Should developing countries participate in the Clean Development Mechanism under the Kyoto Protocol ? The low-hanging fruits and baseline issues. December 2004.

22. Thierry BRECHET et Paul-Marie BOULANGER. Le Mécanisme pour un Développement Propre, ou comment faire d'une pierre deux coups. *Regards Economiques*, Ires n° 27, janvier 2005.

21. Sergio CURRARINI & Henry TULKENS. Stable international agreements on transfrontier pollution with ratification constraints. In C. Carraro and V. Fragnelli (eds.), *Game Practice and the Environment*. Cheltenham, Edward Elgar Publishing, 2004, 9-36. (also available as CORE Reprint 1715).

20. Agustin PEREZ-BARAHONA & Benteng ZOU. A comparative study of energy saving technical progress in a vintage capital model. December 2004.

19. Agustin PEREZ-BARAHONA & Benteng ZOU. Energy saving technological progress in a vintage capital model. December 2004.

18. Matthieu GLACHANT. Voluntary agreements under endogenous legislative threats and imperfect enforcement. November 2004.

17. Thierry BRECHET, Stéphane LAMBRECHT. Puzzling over sustainability: an equilibrium analysis. November 2004.

16. Vincent VAN STEENBERGHE. Core-stable and equitable allocations of greenhouse gas emission permits.. October 2004. (also available as CORE DP 2004/75)

15. Pierre-André JOUVET Philippe MICHEL, Pierre PESTIEAU. Public and private environmental spending. A political economy approach. September 2004. (also available as CORE DP 2004/68.)

14. Thierry BRECHET, Marc GERMAIN, Vincent VAN STEENBERGHE. The clean development mechanism under the Kyoto protocol and the 'low-hanging fruits' issue. July 2004. (also available as CORE DP 2004/81).

13. Thierry BRECHET, Philippe MICHEL. Environmental performance and equilibrium. July 2004. (also available as CORE DP 2004/72).

12. Luisito BERTINELLI, Eric STROBL. The Environmental Kuznets Curve semi-parametrically revisited. July 2004. (also available as CORE DP 2004/51).

11. Axel GOSSERIES, Vincent VAN STEENBERGHE. Pourquoi des marchés de permis de polluer ? Les enjeux économiques et éthiques de Kyoto. April 2004. (also available as IRES discussion paper n° 2004-21).

10. Vincent VAN STEENBERGHE. CO_2 Abatement costs and permits price : Exploring the impact of banking and the role of future commitments. December 2003. (also available as CORE DP 2003/98).

9. Katheline SCHUBERT. Eléments sur l'actualisation et l'environnement. March 2004.

8. Marc GERMAIN. Modélisations de marchés de permis de pollution. July 2003.

7. Marc GERMAIN. Le Mécanisme de Développement Propre : Impacts du principe d'additionalité et du choix de la baseline. January 2003.

6. Thierry BRECHET et Marc GERMAIN. Les affres de la modélisation. May 2002.

5. Marc GERMAIN and Vincent VAN STEENBERGHE. Constraining equitable allocations of tradable CO_2 emission quotas by acceptability, *Environmental and Resource Economics*, (26) 3, 2003.

4. Marc GERMAIN, Philippe TOINT, Henry TULKENS and Aart DE ZEEUW. Transfers to sustain dynamic core-theoretic cooperation in international stock pollutant control, *Journal of Economic Dynamics & Control*, (28) 1, 2003.

3. Thierry BRECHET, Marc GERMAIN et Philippe MONTFORT. Spécialisation internationale et partage de la charge en matière de réduction de la pollution. (also available as IRES discussion paper n°2003-19).

2. Olivier GODARD. Le risque climatique planétaire et la question de l'équité internationale dans l'attribution de quotas d'émission échangeable. May 2003.

1. Thierry BRECHET. Entreprise et environnement : des défis complémentaires ? March 2002.

Environmental Economics & Management Memorandum

Chair Lhoist Berghmans in Environmental Economics and Management
Center for Operations Research & Econometrics (CORE)
Université catholique de Louvain (UCL)
Voie du Roman Pays 34
B-1348 Louvain-la-Neuve, Belgium

Hard copies are available upon request : env@core.ucl.ac.be
Papers are available in pdf format on line : www.core.ucl.ac.be/chlhoist