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Climate and physical information needed for Economic and policy analysis.

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Introduction

Little progress has been made since 1992 on what constitutes a "*dangerous anthropogenic interference with the climate system*"[1]. The second Working Group of the IPCC-TAR(2001) has assembled new material on climate change impacts but in its Summary for Policy Makers it does not offer any economic assessment of these impacts. Together with the controversies about quantitative data, the response will be ultimately dictated by the very choice of decision-making frameworks[2]: bounded cost; minimax regret; maximin gain; minimax loss; cost-effectiveness, tolerable windows and safe landing approaches, cost-benefit analysis. This set of tools, each of them with its own technical specifics, merits and limitations, can be regarded as representative of the diversity of possible attitudes towards decision-making in a "sea of uncertainty" (Lave 1991).

The first objective of this paper is to show how optimal control models can encompass this large diversity of approaches. In doing so we shall put some rationale into the debate by disentangling the multiple sources of confusion which blur the real division lines and inhibit the emergence of sound compromises. These models force the analyst to a) identify the pathways through which climate change may impact on global welfare b) clarify the proxies that are used to capture the benefits of climate action, and against which the costs of this action are to be weighted (absolute or stochastic concentration ceilings, absolute or stochastic temperature targets, pure preference for the stability of climate, monetization of impacts) c) relate these proxies to the level of confidence on scientific information and to ethical choices such as intrinsic value of natural systems vs. utilitarian vision of environment, intergenerational solidarity or the precautionary principle.

The second objective of this paper is to carry out numerical experiments with typical decision-making attitudes and draw some lessons in terms of timing of climate mitigation policies. Since the accent is put on the influence of the decision-making framework and on the comparability of results, the paper will rely on simulations conducted on the basis on the same generic model. After having sketched this model in a first section we will demonstrate the main differences in results between i) cost-effectiveness analysis of deterministic vs. stochastic concentration or temperature ceiling objectives; ii) a cost-benefit analysis using a pure preference for current climate regime; iii) a cost-benefit approach using a monetized quantification of impacts. The underlying line of argument is that these seemingly purely technical options do represent various proxies of damages consistent with various attitudes towards climate change. We will not discuss the weaknesses and merits of each attitude, but we will demonstrate their implications and consequences.

The third objective is to come back to the very definition of the 'climate damages', to understand: i) how a climate impact is transformed into damages, i.e. welfare losses; ii) why the risks of "singularities" in damage curves (i.e. episodes with acceleration of damages) cannot be captured independently from assumptions about the inertia of economic systems and about the existence of direct or indirect compensation mechanisms; iii) the implications of this conceptual clarification for the "attribution" debate.

[1] UNFCCC, Article 2 (Objective).

[2] A comprehensive synthesis of literature can be found in IPCC/SAR/WGIII chap. 1&2 and IPPC/TAR/WGIII, chap. 10

The fourth objective is to make some proposals on tools, able to summarize the GCM outputs into simple functions and to be the input of the economic work. Two steps are necessary: the first one evaluates the climate response to an emission path through a low computational cost function; the second one creates a climate change indicator, to be used as an input into economic models. This indicator has not to be a precise measure of impacts or damages but to represent the major characteristics of the influence of climate change on ecosystem and human societies. The aim behind this preliminary work is to allow economic modellers to work on economic vulnerability by testing different damage function shapes, without needing any precise assessment of climate change damages, out of reach in our present knowledge.

Part 1: Elicitation of attitudes towards climate damages: Variation on a generic integrated economy-climate model

Our modelling framework is built on a Ramsey-like growth model (see box n°1) with the following features:

- the objective function to be maximized is the discounted sum of social welfare. The utility function *Ui(.)* of the representative individual of region 'i' has two arguments: the level of consumption (Ci_t) and the environmental quality (Ei_t). Intra-generational and inter-generational aggregation of welfares is made through the weights α_i and the coefficient ρ. They translate value judgments about income distribution and the pure time preference.

- the economic system is described by a production function of the composite good (equation 2) from 2 factors, capital and labor, an instantaneous equilibrium constraint (equation 3) where consumption, investment, abatement *f(.)* and adaptation *g(.)* expenditures are equal to production, and a "law of motion" (equation 4) of the economic system driven by capital accumulation. Note that abatement and adaptation expenditures depend both on the level of current action (Ab_t and resp. Ad_t) and on its rate ($\dot{Ab}_t$ and $\dot{Ad}_t$).

- parameters Φ and Ψ are introduced to capture the influence of climate change (and its rate) on the economic system, given adaptation expenditures. Climate change is driven by: the greenhouse gases (GHGs) emissions (equation 5), the atmospheric concentration level governed by emissions and the carbon cycle (equation 6) and the sensitivity of climate system to the GHGs concentration level (equation 7). Note that (6) and (7) are specified to represent the path dependency of climate dynamics.

<u>Box n°1:</u> The Generic Model.

Objective function:

$$\underset{Ci_t, Ii_t, Abi_t, Adi_t}{Max} \sum_t \sum_i \alpha_i \cdot \frac{U(Ci_t, Ei_t)}{(1+\rho)^t} \quad (1)$$

Production function:

$$Qi_t = F_i(Ki_t, Li_t, t) \cdot \Phi_i\left(\theta i_t, \dot{\theta i}_t, Adi_t, \dot{Adi}_t, t\right) \quad (2)$$

Income-expenditure identity:

$$Qi_t = Ci_t + Ii_t + f_i(Abi_t, \dot{Abi}_t) + g_i(Adi_t, \dot{Adi}_t) \quad (3)$$

Capital dynamics:

$$Ki_{t+1} = (1-\delta i)Ki_t + Ii_t + \Psi_i\left(\theta i_t, \dot{\theta i}_t, Adi_t, \dot{Adi}_t, t\right) \cdot Ki_t \quad (4)$$

GHG emissions:

$$em_t = \sum_i G_i(Qi_t, Abi_t, t) \quad (5)$$

Concentration dynamics:

$$M_{t+1} = h(M, em_1, em_2, ..., em_t) \quad (6)$$

Climatic change:

$$\theta i_{t+1} = L_i(\theta i_t, M_1, M_2, ..., M_t, t) \quad (7)$$

Environmental quality:

$$Ei_{t+1} = J(Ei_t, \theta i_t, \dot{\theta} i_t, Adi_t) \quad (8)$$

The dot denotes time derivative and i is the regional index.

Variables

Abi_t: abatement stock
Adi_t: adaptation stock
Ci_t: consumption
Ei_t: environmental quality
em_t: GHG emissions
Ii_t: investment
Ki_t: capital
M_t: GHGs concentration
Qi_t: production
θi_t: climate change indicator

Parameters

α_i : the aggregation utilities weights
δi: capital stock depreciation rate
ρ: discount rate

Functions

F_i: production function
$f_i(Abi_t, \dot{A}bi_t, t)$ abatement cost
$g_i(Abi_t, \dot{A}bi_t, t)$ adaptation cost
Φ_i: climate impact on production
Ψ_i: additional capital depreciation due to climate impacts
U(Ci,Ei): welfare derived from consumption and environmental quality

Used as a generic tool this model is helpful to understand why the relationship between climate impacts (defined as a physical transformation of natural and man-made environments) and climate damages (defined as welfare losses resulting from these impacts) is much more complex than it is suggested by a simple additive conversion. This relationship encompasses several pathways from impact to damages:

- direct impact on utility: the variable E_t, of which the variation is determined by (8), captures the impacts of climate change irrespective of their influence on the productive system. It translates precautionary ethics leading to prefer current climate regime or psychological motivations about endangered habitats, the amenity or bequest value of landscapes. Depending on the specification of the utility function, E appears (or not) as a superior goods (to which agents dedicate a growing share of their revenue as income increases).

- climate change impacts on production: these impacts operate through three main channels: a) some changes in productivity in sensitive sectors like agriculture (parameter Φ), b) the acceleration of the turnover of productive capital and infrastructures because of extreme events or because of adaptation measures (parameter Ψ), c) the slowing down of productivity growth due to the redirection, imposed by the supply-demand equilibrium, of investments from the composite good sector to protection, adaptation or mitigation.

- Joint effect of uncertainty and of the increase of climate variability: strong noise affects long term climate signals and may exert a multiplier effect on adaptation and mitigation costs by increasing the risks of misplaced sunk costs. Combined with an increased frequency of unexpected local shocks which are difficult to compensate and to insure, this may result in a higher risk premium on investment and a slowing down of technical progress.

Controversies arise when, instead of using this framework as a heuristic tool, it is used to perform numerical experiments that aim at providing useful information to decision-makers. A first, and misplaced, criticism is that the approach relies on utilitarian ethics and on narrow *homo oeconomicus* anthropology. In fact, interpreted in the engineer's economist tradition [30], this framework can account for diverse value judgments and altruistic attitudes. The planner's program aggregates indeed the utility of agents with various degrees of concerns regarding climate change (substitution elasticity between C and E), various judgments about equity (α_i) and solidarity with future generations (ρ). The real obstacle to an operational use of this model is the cascade of uncertainty that remains for a) the link between economic growth and GHGs emissions, b) the behaviour of the carbon cycle (including the pace of deforestation), c) the response of climate to a given GHG concentration level, d) the impacts of a given climate change (sea level rise, responses of ecosystems, water cycles), e) the economic and social costs of these impacts, including adaptation costs.

This cascade of uncertainties explains and legitimates the huge diversity of attitudes regarding the benefits of climate mitigation, which can be regrouped in four broad categories:

a) A first attitude considers that the uncertainty about climate impacts and damages is so high that neither E nor Φ or Ψ can be assigned any numerical value; environmental benefits are thus set in the form of ceilings on GHGs concentration, on temperature or on any other multidimensional indicator. Approaches such as a safe corridor, a safe landing or a viability path belong to this cost-efficiency framework and their outcome depends obviously on whether the constraints are set by a *convinced ecologist* or by a *skeptical ecologist* (*à la* Lomborg).

b) Sharing the same distrust about predictions of climate impacts, the convinced and the skeptical ecologist may search for a *reasoned compromise* views, and agree on a sequential decision-making process in which an initial trajectory can be adapted in the light of new information. This common willingness to consider several conceivable futures and to keep open alternative options leads to substitute a stochastic to a deterministic cost-efficiency model.

c) Another attitude builds on a higher degree of confidence about the predictions of climate change while being skeptic about damages predictions. The argument E can thus be inserted in the utility function to express a *pure preference for current climate regime (PCCR)*. The main difference with the previous attitudes is that the optimistic (low concern) and the pessimistic (high concern) views are aggregated in a cost-benefit analysis which employs a climate change indicator as a proxy of an itemized assessment of damages.

d) The last attitude requires such an itemized monetary assessment of impacts. This assessment cannot be totally free from value judgments and implies more or less controversial methods. But many take this risk, for lack of anything better, to put some rationale into questions posed by the society, including governments wanting to convince public opinion to accept unpopular measures or to resist disproportionate demands from environmentalists.

To explore these attitudes through harmonized numerical experiments we build upon the generic framework we have just expounded. However, to focus on parameters (and their related uncertainty) that are critical to discuss damages, these experiments will be conducted for a single baseline growth scenario[3]. For clarity sake we then chose not to use an explicit growth model and to carry out sensitivity analysis about discount rates resulting from this scenario and various pure time preference coefficients. The analytical disadvantage of resorting to implicit growth models is the impossibility of capturing a) the differences between a given impact being channelled through Φ (production function) or Ψ (capital turnover) b) the optimal trade-off between consumption and abatement for funding mitigation and adaptation expenditures. These are serious issues but which cannot be treated, given space constraints, in the same article that issues we will concentrate upon hereafter. Note that, unless indicated, identical specifications apply to economic growth, GHGs emissions, abatement costs, carbon cycle, climate module and at last damage functions.

[3] Namely, the marker of A1 SRES family scenario (see appendix A for additional details).

Part 2: Insights from numerical experiments

I. Lessons from a cost-efficiency analysis framework

1.1. The intrinsic impasse of a one shot cost-efficiency analysis

The simple model described in section 1 can be easily restated in a cost-efficiency framework by suppressing parameters Φ and Ψ and by dropping E from the utility function, thereby maximizing the utility of consumption only (see box n°2): in the resulting program, the planner finds the least-cost emission pathway guaranteeing a given concentration target. Such a program was used by Wigley *et al.* (1996) to demonstrate that early decoupling from current emissions trends is not an optimal strategy and that the bulk of abatements should be postponed in order to avoid costs of accelerating the turnover of capital stock, to benefit from innovations on carbon saving technologies and to account for the fact that welfare losses of a given expenditure will be lower for future and richer generations.

In this framing, the optimal timing of action depends entirely on the selected target: using the Wigley et al. assumptions, Ha-Duong *et al* (1997) find a 3 % only departure from current emissions trends in 2020 for a 550 ppm target and a 20 % departure for a 450 ppm target. But, since this one shot analysis does not consider the acquisition of future information, it provides no clue for choosing between the tenants of each target.

One way out is to use a cost-efficiency analysis within a sequential decision framework "*balancing the economic risks of rapid abatement now (that premature capital stock retirement will later be proven unnecessary), against the corresponding risk of delay (that more rapid reduction will then be required, necessitating premature retirement of future capital)*" (IPCC/SAR/WG III, SPM). This economic rationale has the advantage of allowing for a compromise between stakeholders interpreting scientific knowledge in very different ways and sharing various degrees of risk aversion.

1.2. Stochastic cost-efficiency analysis: in search of revisable compromises

A stochastic cost-efficiency analysis was used by Ha-Duong *et al* (1997) to respond the WRE paper in *Nature (*Wigley *et al,* 1996). Without coming back to the details of the DIAM model[4], it matters to remind that its main feature is to treat in a systematic way the interplay between uncertainty about the ultimate target and the inertia of technical and environmental systems. Without inertia indeed, the transition costs for switching from one emission path to another would be null, and uncertainty would not matter; in fact, inertia raises both the costs of premature abatement and the costs of accelerating abatement if stronger action is called later.

Having expressed the cost of abatement as a function of both its scale and the rate at which it is being achieved, Ha-Duong *et al* reproduced WRE results for a 550 ppm target in a certainty case and explored which optimal abatement strategy minimizes the cost of meeting the same target set as the expected value of three ceilings 450 ppm, 550 ppm and 650 ppm, with equal probabilities and a resolution of uncertainty in 2020 or in 2035. They find that the first period abatements should be higher than when the 550ppm ceiling is known ex-ante. This is explained by the fact

[4] See Ha-Duong et al. 1997

that, if the WRE emissions path is followed, the transition costs towards the 450ppm-path, if this ceiling is proven to be necessary, are higher than the sunk costs entailed if the final ceiling is finally at 650ppm. This is typically due to the inertia of the economic systems that increase abatement costs in case of accelerated action.

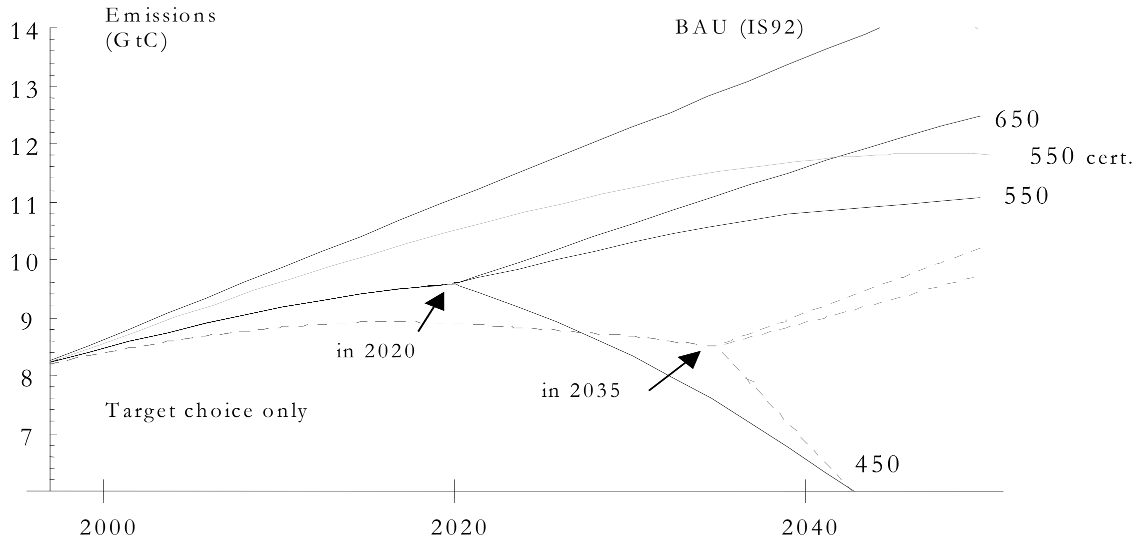

Figure 1 : Optimal mitigation paths with prior knowledge of the final ceiling (grey continuous lines) and with uncertainty (black continuous and dashed lines) with a resolution of uncertainty in 2020 and in 2035.

The key lessons of the sensitivity tests carried out with this model (Ha-Duong, 1997)[5] is that the level of the discount rate matter less than :

a) the set of probabilities placed on the targets, and, more specifically the weight given to the tightest one (this set can be interpreted either in terms of subjective probabilities or as a representation of a compromise between stakeholders with different expectations),

b) the date of resolution of uncertainty: If uncertainty is to be resolved in 2035 only, the policy preserving the option of staying below the 450 limit is a far earlier emissions reduction.

These two results stay valid, ceteris paribus, in any of the alternative models presented hereafter. A cost-efficiency analysis of concentration ceilings is relevant because it follows the very language of the UNFCCC through which Parties convey *de facto* their views about climate change damages. However, concentration ceilings are a poor proxy of these damages. This is why it is attractive to repeat the same exercise with a temperature ceiling.

This adds another layer of uncertainty to the model, related to climate sensitivity. Climate sensitivity is the global mean surface temperature increase at equilibrium when the CO_2 concentration is kept constant, at the doubling of the pre-industrial level. Literature sets this parameter between +1.5 °C and +4.5°C (IPCC/TAR/WGI, chp IX).

To assess its influence we developed the cost-efficiency model described Box 2. This model minimizes the discounted sum of abatement costs (a surrogate of a utility-maximisation model). The constraint is set so that temperature cannot go beyond a given difference with respect to its 1990 value. Abatement costs function captures socio-economic inertia and incorporates an

[5] We will not cover in this paper the role of the reduced forms of carbon cycles whose selection impacts greatly the allowed carbon budget available for a given target (Gitz, 2002).

autonomous technological change (see Appendix A). C-cycle sub-model (equation 6) is taken from Nordhaus *et al.* (1999); its parameters (transfer coefficients and initial conditions) are given in Appendix A.

Variations in global mean temperature (equation 7) derive from a two-box climate model (Appendix A). Since the main issue is the timing of abatement over the short run, we calibrated this model in such a way that it gives a better description of warming over forthcoming decades[6]. To account for uncertainty on climate sensitivity, we calibrated the model for three values of this parameter: 2.5°C, 3.5°C and 4.5°C.

Box 2: Cost-efficiency framework model (certainty case) The model may be run alternatively for three values of climate sensitivity: 2.5°C, 3.5°C and 4.5°C.

Objective function: $$\underset{Ab_t}{Min} \sum_{t=1990}^{2300} \frac{f(Ab_t, \dot{Ab}_t, t)}{(1+\rho)^{(t-1990)}} \qquad (1)$$

$$w.r.t. \quad (\theta_t - \theta_{1990}) \leq \theta_{MAX}$$

GHG emissions (em_t): exogenous baseline, based on A1-m scenario (5)

Concentration dynamics: $$M_{t+1} = H\left(M_t, em_t(1 - Ab_t)\right)$$ Nordhaus *et al.* (1999) (6)

Climatic change: (see appendix A) $$\theta_{t+1} = L(\theta_t, M_t)$$ 3 values for climate sensitivity (7)

ρ: discount rate (5%.year^{-1})
Model time step is decadal.
See appendix A for specification and calibration of functions *f(.), H (.), L(.)*, and data (em_t).

This model can be run on a perfect information mode and on an uncertainty mode (see Box 3). In the second option, uncertainty on climate sensitivity is discrete (three possible values) and information arrives at a fixed time in the future (t_{info}). The program has to solve a set of three parallel problems, each corresponding to the model using one of the three climate sensitivity parameters. This means that there are three equations 6 and 7 representing three alternative 'states of the world'. The objective function (equation 1a) is specified as the minimisation of expected costs of abatement paths given a probability distribution over these states of the world. Additional constraints (equation 1b) are added to impose that, before the disclosure of information, decision variables be the same across all states of the world. Technically the model solution corresponds to perfect information when t_{info} =1990, imperfect information with learning when (1990<t_{info} <2300), absolute uncertainty when t_{info} =2300.

[6] This implies to prioritise the description of the interaction between atmosphere and superficial ocean neglecting interactions with deep ocean.

<u>Box 3:</u> Sequential decision framework with uncertainty on climate dynamics. There are three states of the world (s): climate sensitivity (T_{2x}) may be {2.5°C,3.5°C,4.5°C} with the corresponding e*x ante* subjective probability (p_s) {1/6;2/3;1/6}. Therefore climate dynamics is dependent upon the state of the world (note that L(.) is indexed by s).

Objective function: $$\underset{Ab_t^s}{Min} \sum_s p_s \sum_{t=1990}^{2300} \frac{f(Ab_t^s, \dot{Ab}_t^s, t)}{(1+\rho)^{(t-1990)}} \quad (1a)$$

$$w.r.t. \quad \left(\theta_t^s - \theta_{1990}\right) \leq \theta_{MAX}$$

$$\forall t \leq t_{info}, \ \forall (s,s') \in S, \ Ab_t^s = Ab_t^{s'} \quad (1b)$$

GHG emissions (em_t): exogenous baseline, based on A1-m scenario (5)

Concentration dynamics: $M_{t+1}^s = H(M_t^s, em_t(1 - Ab_t^s))$ Nordhaus *et al.* (1999) (6)

Climatic change: $\theta_{t+1}^s = L^s(\theta_t^s, M_t^s)$ 3 values for climate sensitivity (7)
(see appendix A)

t_{info}: date of arrival of information on climate sensitivity, 1990to2100 & 2300. Before disclosure of information, commande variable (Ab_t) are equal whatever state of the world occurs *expost* (equation 1b).
ρ: discount rate (5%.year^{-1})

Model time step is decadal.
See appendix A for specification and calibration of functions *f(.), H (.), L(.)*, and data (*em_t*).

Let us start from a +2°C target[7] with respect to 1990 which corresponds to an expected value of 500ppm for GHGs concentration. In fact this concentration ceiling passes from a very stringent 440 ppm value when climate sensitivity is set to its upper value to a very lax 590 ppm value is set to its low value. A +1°C and +3°C target would respectively lead to a 379-448 ppm range (expected value: 408ppm) and to a 515-780 ppm range (expected value: 617ppm) for concentration ceiling.

For +2°C target, and assuming that information on the value of climate sensitivity arrives in 2020, the first period optimal emissions path is very close to the one consistent with the most pessimistic hypothesis about this value (see Fig. 2). The reinforcement of the dominance of the worst case is due to the fact that pessimistic assumptions on climate sensitivity give a tighter

[7] This figure is circulated in many studies such as the Global Fast Track Assessment (Parry *et al.*, 2001) where the additional number of people at risk of water shortage increases sharply once global mean temperature rise gets close to +2°C. Simonnett (1989) also suggests that a +2°C temperature increase dramatically reduces suitable areas for Robusta coffee in Uganda. The World Bank (2002) estimates that in 2050 Tarawa atoll (Kiribati archipelago) could face climate change costs equivalent to 13 to 27% of the whole archipelago GDP. Note that this target is less binding than are former EU long-term climate goals (EU, 1996), amounting to a maximum +2°C global mean temperature rise *wrt preindustrial level*.

constraint than 450 ppm concentration: the concentration ceiling is 440 ppm and the + 2° temperature ceiling is reached as early as 2050 in the baseline case, which forces to a strong acceleration of abatements in case of delayed response.

This very high environmental irreversibility is captured by the value of information on climate sensitivity. The Expected Value of Perfect Information (EVPI) is classically the difference between the expected value in the Learn then Act hypothesis (climate sensitivity known from the outset and policy adopted consequently) and the Act then Learn hypothesis (a policy must be adopted before we know the value of this parameter). Logically, the later is the date of resolution of uncertainty the higher is this value. Before 2040 (figure 3), it increases linearly until 13% of its final value and increases sharply between 2040 and 2070 to reach 83% of this value. To give a comparative benchmark, expected value of discounted abatement costs over the three states of the world in the LTA hypothesis would amount almost to 52 units in the same metrics. This high opportunity cost to know climate sensitivity before 2040 indicates the risk of postponing too much a serious hedging strategies in case of pessimistic prospect about progress in knowledge.

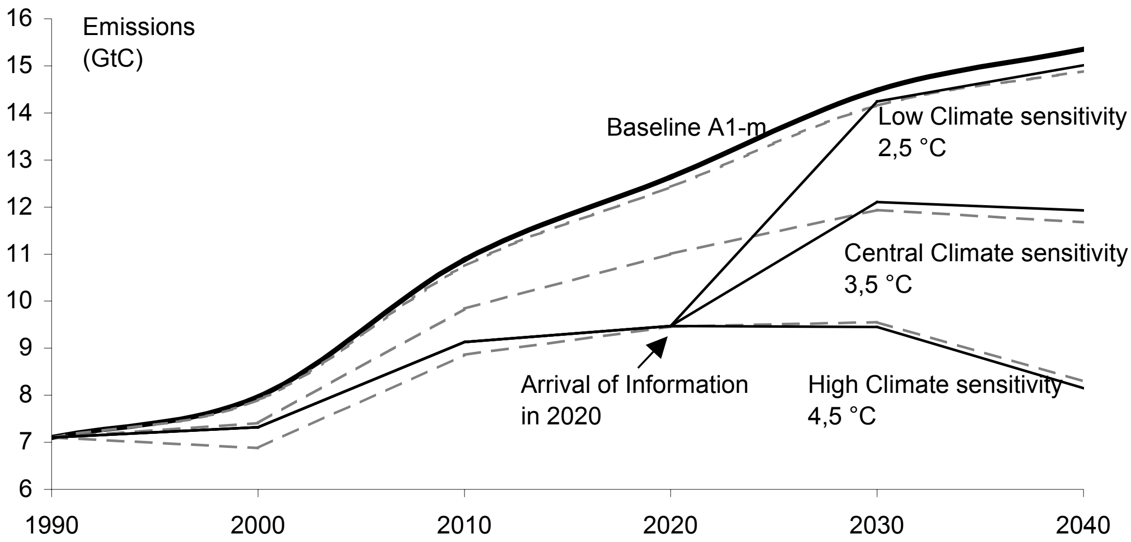

Figure 2: Hedging strategies for a given +2°C temperature ceiling : with perfect information (grey dashed line) and with uncertainties (black continue line).

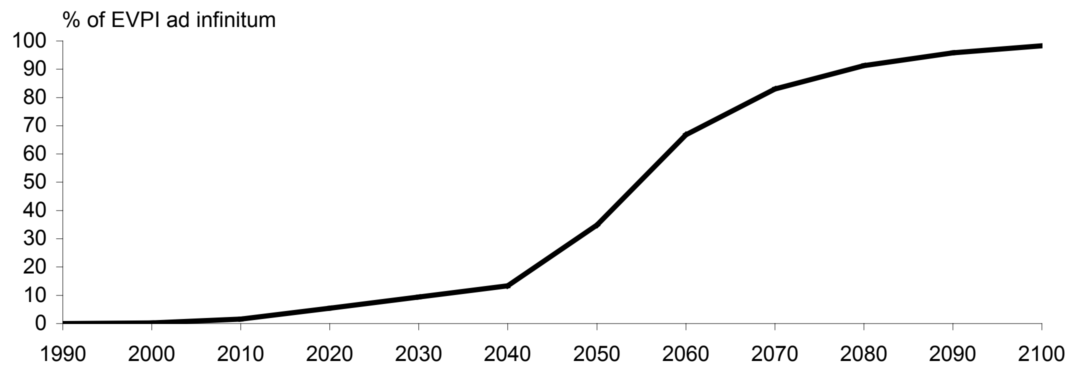

Figure 3 : Expected Value of Perfect Information with respect to the date of resolution of uncertainty on climate sensitivity. As shown, information value raises brutally after 2040, that means there is a significant interest in revealing this value before this date (Ambrosi et al, 2002).

The main criticism to be addressed to stochastic cost-efficiency analysis is that it gives too high a weight to the tightest constraint. A minority arguing for such a target, say a fringe of 10% of people for a 390 ppm target, would automatically exert a disproportionate influence on decision because costs of postponing action for this target tend towards infinity. In practice though, faced with such a situation, societies would rather admit that a window of opportunity has been missed (Hourcade *et al.*, 1995) and would prefer overshooting the ceiling at the risk of some damages, rather than the social costs of an exaggerated deceleration of emissions. This force to examine analyse this trade-off though some form of cost-benefit approach.

II. The Pure Preference for Current Climate Regime.

An attitude of distrusts regarding any numerical comprehensive assessment of damages is not exclusive of a willingness to pay for mitigating climate change in case of real concern. This can be translated in the form of a *pure preference for current climate regime* (PPCCR) by reinserting E_t in the utility function.

We specify U(.) such as:

$$U\left(C_t, E_t\right) = \ln\left(C_t\right).E_t^{\beta}$$

$$with\, C_t\left(>1\right) > 0 \quad and \quad E_t = \left(\overline{\theta} - \theta_t\right) > 0 \quad 0 < \beta < 1$$

E_t expresses climate variation (*e.g.* global mean temperature rise, θ) and $\overline{\theta}$ denotes an absolute threshold beyond which climate change impacts would be absolutely disruptive; we set arbitrarily this parameter to +4°C. With this specifications, willingness to pay increases with the expected level of climate change and preservation of the current climate is treated as a superior good (see Box 4).

Box 4 : WTP for climate protection.

Let WTP(θ) be the maximum amount of current income, C, we are willing to pay to prevent a climate change of magnitude θ:

$$\ln(C).\left(\overline{\theta} - \theta\right)^{\beta} = \ln\left(C - WTP(\theta)\right).\left(\overline{\theta}\right)^{\beta} \quad (1)$$

leading to

$$WTP(\theta) = C - C^{\left(\frac{\overline{\theta}-\theta}{\overline{\theta}}\right)^{\beta}} \quad (2)$$

Hence, marginal willingness to pay is:

$$\frac{\partial WTP(\theta)}{\partial \theta} = \frac{\beta \ln C}{\overline{\theta}}\left(\frac{\overline{\theta}-\theta}{\overline{\theta}}\right)^{\beta-1} C^{\left(\frac{\overline{\theta}-\theta}{\overline{\theta}}\right)^{\beta}} > 0 \quad (3)$$

Therefore WTP(θ) is a growing function temperature change θ.

Let π(θ) denote the ratio between WTP(θ) and income:

$$\pi\left(\theta\right) = \frac{WTP(\theta)}{C} = 1 - C^{\left(\frac{\overline{\theta}-\theta}{\overline{\theta}}\right)^{\beta} - 1} \quad (4)$$

Equation (4) yields to:

$$\frac{\partial \pi(\theta)}{\partial C} = -\left(\left(\frac{\overline{\theta}-\theta}{\overline{\theta}}\right)^{\beta} - 1\right) C^{\left(\frac{\overline{\theta}-\theta}{\overline{\theta}}\right)^{\beta}-2} > 0$$

Thus, for the same climate change magnitude θ, π(θ) is an increasing function of income hence climate protection is a superior good. This condition is equivalent to the more classical definition: elasticity of demand w. r. t. income being strictly greater than unity.

We have so far no opinion polls on the willingness to pay (WTP) for climate stability; would such opinion polls exist, their results would be very sensitive to the political and/or media life cycles which determine the way information is conveyed to public opinion. A more secure approach is to reveal the implicit utility function behind figures circulating about the acceptable maximum value for temperature change (for example +2°C in the EMF ongoing round or in some NGOs). To do so, for each set of α_i and ρ, we determine the value of β which exactly balances the marginal welfare impacts of C and E in the optimal abatement trajectories previously obtained for this target in the certainty case: practically for the value of β the marginal welfare impact of the consumption loss resulting from a tightening of the environmental objective from +2.05°C to +1.95°C is exactly compensated by the marginal welfare improvement due to lower temperatures. This procedure ensures consistency between claims for a given target and expectations on baseline emissions, abatement costs and climate sensitivity. For example, for a given abatement cost curve, a +2°C objective implies higher mitigation costs under high climate sensitivity; it is thus consistent with a higher WTP for climate mitigation than under assumption of a low sensitivity (see table 1).

Climate sensitivity	2.5°C	3.5°C	4.5°C
PTP = 1%.year^{-1}	0.000141	0.00077	0.001383
PTP = 3%.year^{-1}	0.000265	0.00164	0.003444

Table 1: Parameter β values in function of climate sensitivity and pure time preference

An important property of the new program which aims at maximising U(.,.) without absolute constraint on the quality of the environment, is that an overshoot is now allowed in case of delayed action: this occurs if the cost of maintaining the temperature below the desired target is greater than the marginal WTP to avoid extra warming.

Box 5: PCCR Approach in certainty case The model may be run alternatively for three values of climate sensitivity: 2.5°C, 3.5°C and 4.5°C.

Objective function: $$\underset{Ab_t}{Max} \sum_{t=1990}^{2300} N_t \ln\left(c \frac{\left(Y_t - f(Ab_t, \dot{Ab}_t, t)\right)}{N_t} \right) \left(\overline{\theta}-\theta_t\right)^{\beta} e^{-\eta(t-1990)} \quad (1)$$

GHG emissions (em_t): exogenous baseline, based on A1-m scenario (5)

Concentration Nordhaus

dynamics: $M_{t+1} = H\left(M_t, em_t(1-Ab_t)\right)$ *et al.* (1999) (6)

Climatic change: $\theta_{t+1} = L(\theta_t, M_t)$ 3 values for climate sensitivity (7) (see appendix A)

N_t: population level (source A1-m), Y_t: gross world product (source A1-m)
per capita income is in US90$.pc-1
c: propension to consume (0.8)
β: set according to η and climate sensitivity values (see Table 1)
η: pure time preference (1 or 3%.yr^{-1})

Model time step is decadal.
See appendix A for specification and calibration of functions *f(.), H (.), L(.)*, and data (em_t, N_t, Y_t).

In the case of a +2°C target with three possible values for climate sensitivity (see box 5) there is no overshoot of the target under perfect expectation for a 1% pure time preference even in the most pessimistic case (negligible overshoot). A moderate overshoot (up to 0.15°C) during 50 years is found with a pure time preference as high as 3% (see Fig. 4). But this does not lead to lower abatement in the first periods: up to 2020 mitigation costs are twice as high as in a cost-efficiency framework. This paradox, noted by Hammitt (1999), can be easily explained: in a cost-efficiency framework, agents give a high value to climate (the costate variable at a given point in time) only when the target is approached whereas in this PCCR approach, climate change is given a significant value by current generations. Being a superior good, it will be given a higher value by future (and richer) generations.

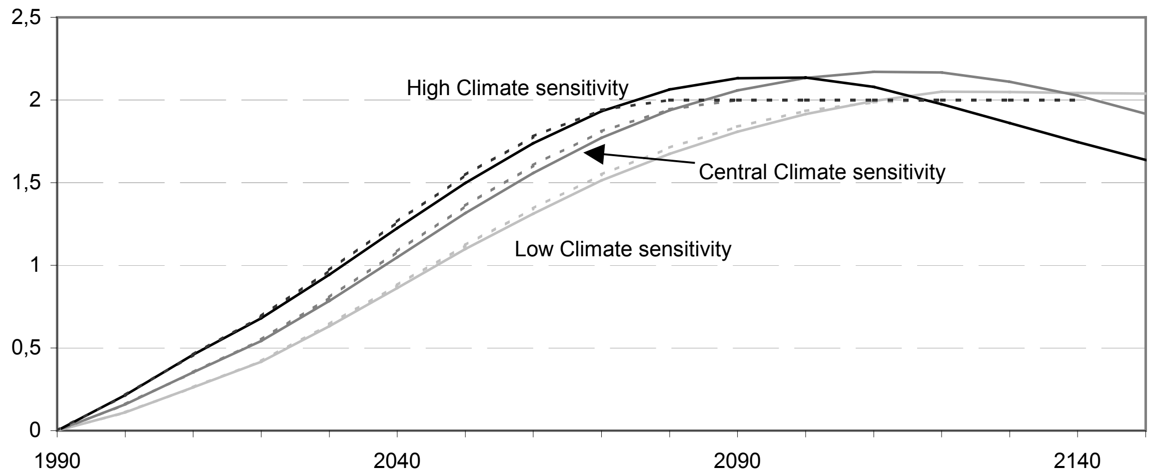

Figure 4 : Global Mean temperature increase with respect to time for 3 climate sensitivities for a cost-benefit analysis with Pure Preference for Climate Current Regime based on a desired 2°C temperature ceiling and 3%.year^{-1} of pure time preference.

<u>Box 6:</u> PCCR Approach in uncertainty case with learning on climate sensitivity.
There are three states of the world (s): climate sensitivity (T_{2x}) may be {2.5°C,3.5°C,4.5°C} with the corresponding e*x ante* subjective probability (p_s) {1/6;2/3;1/6}. Therefore climate dynamics is dependent upon the state of the world (note that L(.) is indexed by s).

Objective function:

$$\underset{Ab_t^s}{Max}\sum_s p_s \sum_{t=1990}^{2300} N_t \ln\left(c\frac{\left(Y_t - f(Ab_t^s, \dot{Ab}_t^s, t)\right)}{N_t}\right)\left(\overline{\theta}-\theta_t^s\right)^{\beta^C} e^{-\eta(t-1990)} \quad (1)$$

$$\forall t \le t_{\inf o},\ \forall (s,s') \in S,\ Ab_t^s = Ab_t^{s'}$$

GHG emissions (em_t): exogenous baseline, based on A1-m scenario (5)

Concentration dynamics: $M_{t+1}^s = H(M_t^s, em_t(1-Ab_t^s)$ Nordhaus *et al.* (1999) (6)

Climatic change: (see appendix A) $\theta_{t+1}^s = L^s(\theta_t^s, M_t^s)$ 3 values for climate sensitivity (7)

N_t: population level (source A1-m), Y_t: gross world product (source A1-m)
per capita income is in US90\$.pc^{-1}
c: propension to consume (0.8)
η: pure time preference (3%.$year^{-1}$)

t_{info}: date of arrival of information on climate sensitivity (1990,2020,2040,2060&2080). Before disclosure of information, command variable (Ab_t) are equal whatever state of the world occurs *expost*.

β is set according to η and believes of central planner on climate sensitivity value ($E_s[T_{2X}]$=3.5°C), so β = 0.00164 (see Table 1). As learning occurs, T_{2X} is set to its true value whereas β value is not revised.

Model time step is decadal.
See appendix A for specification and calibration of functions *f(.), H (.), L(.)*, and data (*em_t, N_t, Y_t)*.

Let us now come to a situation where, given the mandate of staying below a +2°C target for an expected +3.5°C value of climate sensitivity, the central planner calibrates accordingly the β (β = 0.00164) coefficient and considers the resulting utility function as expressing the real preferences of its constituents (see Box 6). For a resolution of uncertainty as late as 2080, the optimal first period response leads to a +0.7°C overshoot if the +4.5°C sensitivity is proven to be true (dashed grey curve in fig. 5). This has to be compared to the modest overshoot in the certainty case (+0.1°C) (black thin curve in fig. 5). The importance of this overshoot must however be compared with the very significant deviation from the global mean temperature increase in the baseline scenario (bold black curve in fig. 5).

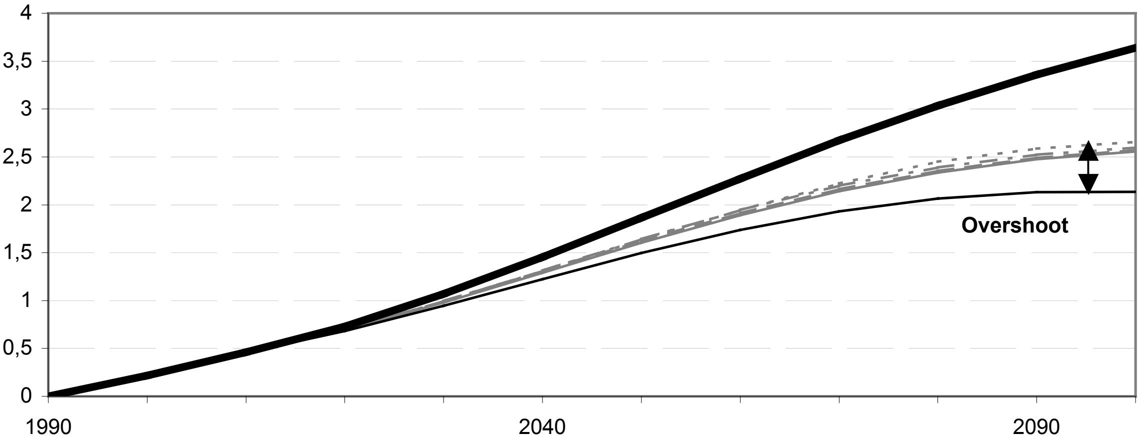

Figure 5 : Comparing the cost of misestimating belief on climate change damages and climate dynamics. In all cases, climate sensitivity has a high value(either known ex-ante or revealed ex-post). Global mean temperature increase with respect to time for baseline case (bold black curve), for optimal strategy with perfect information (thin black curve)(i.e. central planner knows ex-ante climate sensitivity value and corresponding believes of people) and for optimal strategy with uncertainty (grey curves) (i.e. central planner learns that climate sensitivity is high whereas belief on damages are set to a mid-range value)

The corresponding mitigation costs at the Kyoto commitment period are significantly lower than in the perfect information case: 0.02 % of GWP (ex-ante mid range expected value of climate sensitivity and therefore mid-range climate change adverse effects) to be compared with 0.08 % of GWP (high climate sensitivity and high climate change adverse effects). Sensitivity tests about the date of arrival of information on climate sensitivity show a remarkably constant share of GWP and has no dramatic consequence (see Figure 5) on consecutive temperature at the peak since the overshoot amounts to 2.6°C (early learning) to 2.7°C (late learning). This suggests that misestimating WTP has a higher influence on the timing of abatement than the misestimating *ex ante* climate sensitivity.

The key question related to the real magnitude of WTP is to what extent climate may be considered, at least in some quarters, as a superior good? In this case indeed, the expectation of future temperature increase would lead to more significant departure from current emissions trends than in the opposite case. The same question can be posed at the regional scale. This would allow to scrutinise compensation schemes between countries necessary to reach a consensus on a global temperature target. Some regions might indeed wish to adopt a very low temperature ceiling corresponding to a global constraint too tight to be agreed at an international level. Would this global constraint be slackened, these regions would legitimately demand for compensations.

III. Lessons from a strong form of cost-benefit analysis

Some authors[8] are reluctant to resort to a monetary valuation of climate damages because, they claim, this approach cannot but underestimate the value of environmental damages. This seems the case in the EMF[9] review of the few existing cost-benefit analysis of climate policy which concludes univocally to a very slow departure from current emissions trends up to the revelation of 'bad news' regarding climate damages.

The main strand of criticism focuses on the role of discounting: contrary to a PCCR approach where environmental variations affects immediately the welfare of the first periods agents, climate impacts occur only several decades after mitigation efforts are undertaken and, once discounted, marginal benefits of those actions are easily outweighed by their costs. This is the reason why a null coefficient for pure time preference (PTP) has been argued (Cline, 1993). But this option confronts serious problems. First, as shown by Koopmans (1960), time consistent decision-making over infinite consumption plans requires a strictly positive PTP. In addition, introducing a zero or very low PTP in growth model entails high savings and low consumption for the current (and poorest) generation. This, it can be argued, is not consistent with intergenerational equity principle.

We will not address in this paper the alternative proposals suggested in literature to avoid the sacrifice of both current and future generations (e.g. Chichilnyski, 1996). Despite their interest, they either raise serious dynamic consistency problems or do not change so much the response for the early periods (Lecocq *et al.*, 2002). We rather concentrate on the interplay between discounting and the assumptions regarding the future states of the world that will determine the shape of damage functions, the economic growth and emissions baselines. To this aim, we will introduce a nil PCCR (β=0).

3.1. Interplay between discount rate and damage shape

Let us start from a simple two-period decision model (Figure 6). At date t_1, a first decision is made to spend c_1 in abatement expenditures. At that time damages are uncertain: there are n possible future damage functions indexed by i=1,…,n, with a distribution of subjective probability p_i. The true damage function is revealed at t_2, at which point we make a second decision on abatement expenditures. We denote c_2^i this level, which depends on the state of the world effectively realized.

[8] Cf. for instance, on a very close topic, the forum on valuation of ecosystem services (special issue of *Ecological Economics*, vol. 25 no. 1, april 1998) which has been emulated by Costanza on the basis of his Nature paper (Costanza *et al.*, 1997). Many respondents have indeed pointed out the risk of underestimating the environment, as for example Toman (Toman, 1998) elegantly puts it "a serious underestimate of infinity".

[9] Manne (1995) cited in IPCC/TAR/WGIII/chapX.

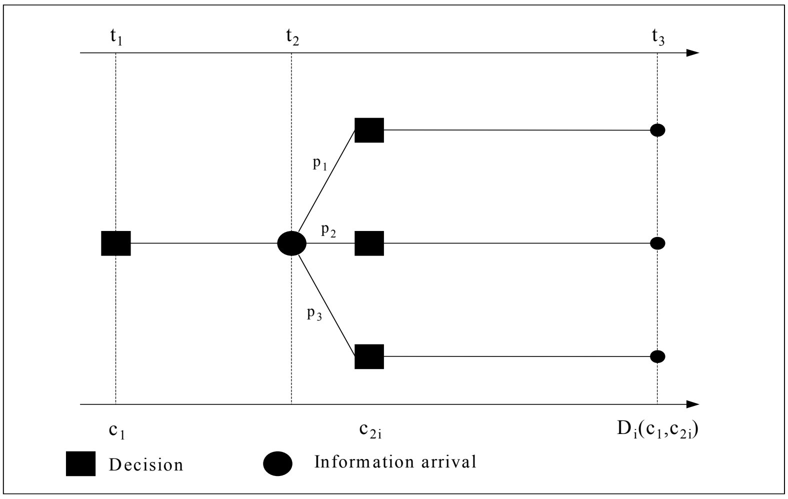

Figure 6: Two-period climate policy decision model (n=3).

We define φ (the discount factor) as:

$$\varphi=\frac{1}{1+\rho} \quad \text{with } \rho\text{: social discount rate.}$$

Let $D_i(c_1,c_2^i)$ be the remaining damages at the end of the second period associated with abatement decisions c_1 and c_2^i in state of the world i. We assume D_i to be twice differentiable decreasing function of abatement expenditures.

Assuming risk neutrality, the planner's optimal abatement expenditure at first period is solution of the following expected cost minimization problem, with n the number of years between t_1 and t_2 and m the distance between t_1 and the time at which damages occur (m>n).

$$\underset{c_1,c_2^i}{Min}\left(c_1+\varphi^n\sum_i p_i\cdot c_2^i+\varphi^m\sum_i p_i\cdot D_i(c_1,c_2^i)\right) \quad (4.1)$$

The optimal abatement policy can be defined recursively as follows. First, for each possible state of the world, and given period 1 abatement expenditure c_1^*, the second period abatement expenditure $c_2^{i,*}$ should be such that marginal damages (discounted back from the end to the beginning of the second period) are equal to marginal costs (equation (4.2)). Second, the period 1 abatement expenditures should be such that the total expected marginal damage (discounted from the end of the second period to the beginning of the first) be equal to marginal costs (equation (4.3)). In both equations, the minus sign simply translates the fact that D_i are decreasing functions of c_1 and c_2^i.

$$\frac{\partial D_i}{\partial c_2}(c_1^*,c_2^{i,*})=-\varphi^{n-m} \quad (4.2)$$

$$\sum_i p_i\frac{\partial D_i}{\partial c_1}(c_1^*,c_2^{i,*})=-\varphi^{-m} \quad (4.3)$$

This result is illustrated graphically in Figure 7 (assuming only one future state of the world to limit the graph to two dimensions). The horizontal and vertical axes give the first and second period abatement levels respectively. The continuous line is an "isodamage" curve, defined by

$D(c_1,c_2^i) = C$. The dotted line is an "isoabatement" curve showing all the pairs of abatement expenditures (c_1,c_2) such that the total discounted cost $c_1 + \varphi^n c_2^i$ = constant. The higher the discount rate, the steeper is this curve.

On the graph, the solution (c_1^*, c_2^*) to problem (4.1) is a point such that "isoabatement" and "isodamage" (a) are tangent, i.e. it is not possible to reduce damages without raising total discounted costs, (b) have the same gradient, in other words are such that one additional dollar of abatement would reduce damages by an exact same amount.

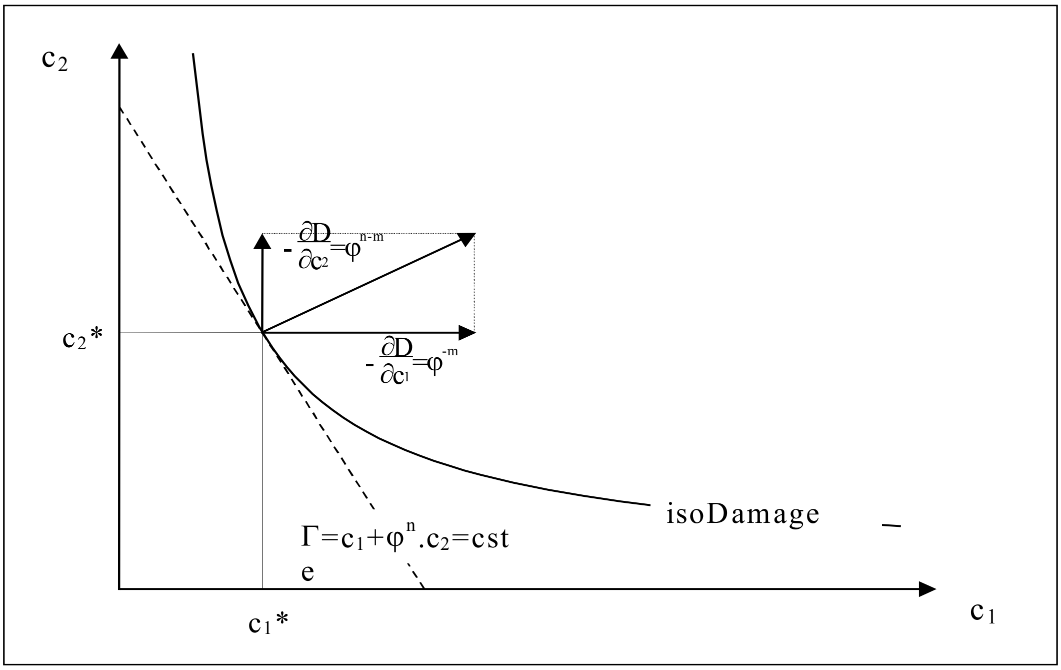

Figure 7: Graphical representation of the solution to the optimal expenditures problem (4.1). The horizontal and vertical axis indicate the first period and second period abatement respectively.

With this framework, we can illustrate the impact of the discount rate on first period abatement expenditures.

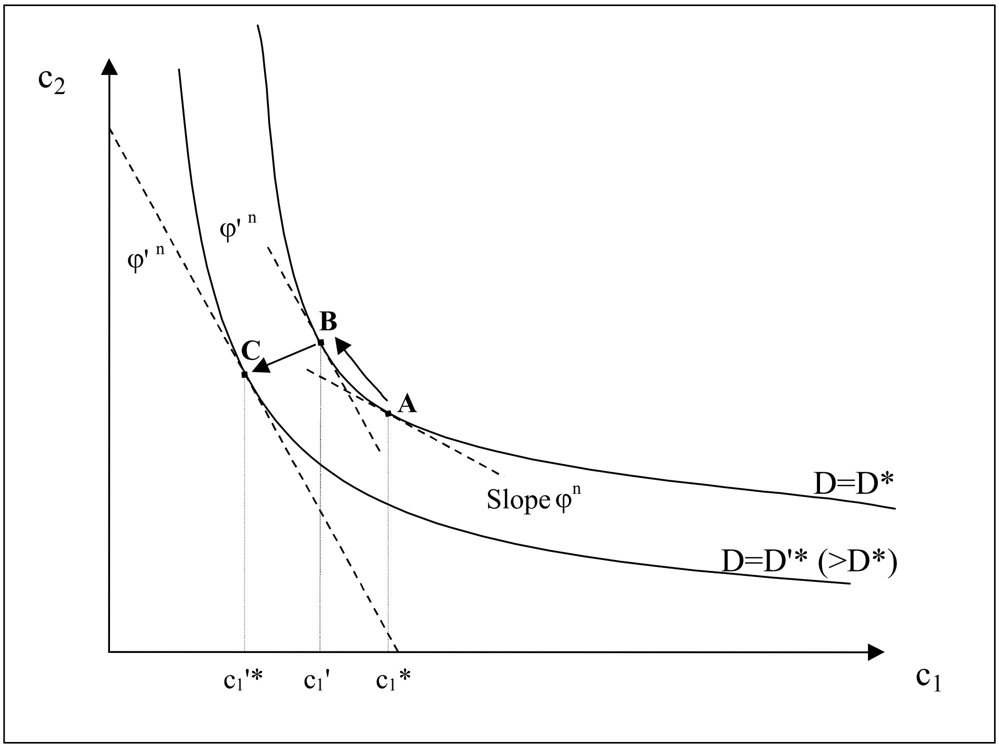

Figure 8: impact of a variation of the discount rate on first period decision (horizontal axis).

Let us assume that the discount rate rises from ρ to $\rho^{'}$, and thus that the discount factor diminishes from φ to φ'. The equilibrium then shifts from A to C, as a result of two effects:

– A → B: inter-temporal re-allocation of spending at constant damage level. As the discount rate rises, the balance of efforts shifts to the second period. First period abatement diminishes (from c_1^* to $c_1^{'}$ in the above figure), and the magnitude of this change depends on the local curvature of the isodamage curve.

- B → C: modification of the damage/abatement expenditure equilibrium. Since the discount rate is higher, the present value of damages is lower and the planner accepts lower total efforts. The magnitude of this effect depends on the rate at which damages increase when abatement decreases. The higher the slope of the damage function, the lower the variation of abatement expenditures.

The relationship between the slope of the damage function and the impact of the discount rate can be further illustrated analytically by decomposing the damage function in two terms: an indicator of impacts $\theta(c_1,c_2)$ and a damage function *per se* $\Psi(\theta)$.

$$D(c_1,c_2)= \Psi[\theta(c_1,c_2)]$$

For illustrative purposes, let us assume that the environmental indicator has the following form, where α is strictly lower than unity to represent the fact that abatement becomes increasingly less efficient as emissions are reduced,

$$\theta (c_1,c_2) = a.c_1^{\alpha} + b.c_2^{\alpha}$$

Under the above assumptions, a rapid calculus shows that the variation of optimal first-period abatement when the discount rate varies from ρ to $\rho^{'}$ is as follows:

$$\frac{c_1^{*\prime}}{c_1^*} = \left(\frac{1+\rho}{1+\rho'}\right)^{\frac{m}{1-\alpha}} \cdot \left(\frac{\psi_\theta(\theta')}{\psi_\theta(\theta)}\right)^{\frac{1}{1-\alpha}} \tag{4.4}$$

where Ψ_θ is the derivative of Ψ with respect to θ.

If damages are linear in the environmental indicator (i.e. if $\Psi_\theta(\theta)$ is constant) then the variation of first-period abatement becomes:

$$\frac{c_1^{*\prime}}{c_1^*} = \left(\frac{1+\rho}{1+\rho'}\right)^{\frac{m}{1-\alpha}} \tag{4.5}$$

If α=1/3 (which corresponds to quadratic marginal abatement costs) and m=100 years, a 1% increase of the discount rate implies a 76% decrease in first period marginal abatement costs.

On the other hand, marginal damages vary with the environmental indicator ($\Psi(\theta) = \theta^{-k}$); the variation of first period abatement becomes

$$\frac{c_1^{*\prime}}{c_1^*} = \left(\frac{1+\rho}{1+\rho'}\right)^{\frac{m}{1-\alpha}} \cdot \left(\frac{1+\xi\theta'^{\frac{-n\alpha}{1-\alpha}}}{1+\xi\theta^{\frac{-n\alpha}{1-\alpha}}}\right)^{\frac{k+1}{\alpha k+1}} \quad \text{with } \xi = \left(\frac{b}{a}\right)^{\frac{1}{1-\alpha}} \tag{4.6}$$

If k=5 and b/a = 2 (technical change makes abatement twice less costly in the second period), the optimal first-period abatement diminishes only by 17% when the discount rate rises by 1%. Even if k=1 (quadratic damage function), first period abatement diminishes only by 45%. The impact of the discount rate is thus strongly dependent on the slope of the link between the indicator of climate change and the damage function.

3.2. Parameters other than the shape of damage curve

The preceding analysis confirms the results of a) Dixit and Pyndick using a real-option model (1994) that the environmental irreversibility effect is lower than the investment irreversibility effect in the case of a linear damage function, b) Narain and Fisher (2002) or Gjerdppe (1999) who find an opposite result including an avoidable climatic catastrophe in the analysis. However, given the likely controversies about the shape of the damage function it would be misleading to focus on this sole parameter despite its critical character. This would mask indeed three other key determinants of the timing of abatements: a) the underlying growth scenario which dictates the level of the discount rate and the emissions baseline, b) the short term response of climate system to a given inflow of carbon and c) the abatement costs.

Let us for example introduce the following modifications in the DICE model[10] (Nordhaus, 1994, 1999) while keeping its quadratic damages function of temperature rise[11] with which a modest departure from current emissions trends for the coming decades is recommended:

[10] For this numerical exercise we used DICE-99 model version as available at http://www.econ.yale.edu/%7Enordhaus/homepage/dice_section_IV.html

[11] Actually, DICE-99 damage function is a polynomial of degree 2. Both coefficients are positive so they do not allow for global benefits of climate change for low temperature change. Benchmark corresponds to a 1.5% GWP loss for a 2.5°C global mean temperature rise. Furthermore, argument of DICE-99 damages function is global mean temperature rise since 1900. To keep results comparable, we reformulated DICE including the following modification: argument of damages function becomes global mean temperature rise relative to first period of the model (1995).

- A1 SRES scenario as the baseline emissions (10,88 GtC and 12,64 GtC emissions in 2010 and 2020) instead of the DICE baseline which is very close to B2 SRES scenario (8,78 GtC and 9,05 GtC emissions in 2010 and 2020 respectively),

- modification of the short term climate response ($\theta(c_1,c_2)$). The reduced-form climate model presented in Appendix A is very similar to DICE two-box temperature sub-model. The main difference arises from the specification of upper and lower compartments. Indeed, in DICE, modeller choice retains atmosphere and superficial ocean for upper compartment and deep ocean for lower compartment; it provides a fair description of long-term climate change but underestimates short term atmospheric temperature rise. This is not the case with the climate model presented in Appendix A which has been calibrated so as to describe more precisely short-term climate change.

- abatement cost curve: we retained marginal abatement costs curve as exposed in Appendix A. The specification is quadratic and accounts for socio-economic inertia. It leads to an equivalent burden for 2010 (0,35% of GWP and 0,36% of GWP following DICE specifications) but with a moderately lower price of carbon: 60$/tC instead of 75$/tC.

Figure 9 demonstrates that changing the specification $\theta(c_1,c_2)$ or choosing an alternative emissions baseline rises abatement rates in 2015 from 5.6% to 7.2% (resp. 5.6% to 8.6%). When both effects are combined, the abatement rate is increased by 50% (from 5.6% to 8.6%). It is more than doubled (from 5.6% to 12.5%) if abatement costs are 20% lower.

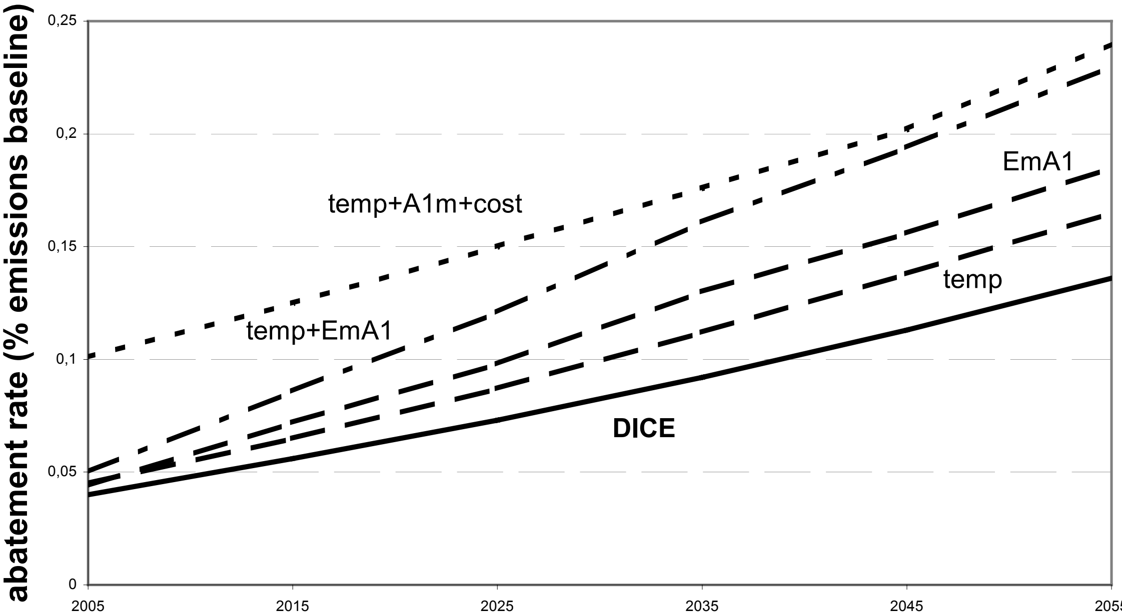

Figure 9: Abatement rate with respect to time, for DICE and for DICE including the modified temperature model ("temp"), a different baseline ("EmA1"), both former modifications ("temp+EmA1") and finally same than before with new cost curve ("temp+A1m+cost").

These results do not pretend to be conclusive about the validity of Kyoto Protocol. They simply underline that, even without non linearity in damage functions, the level of departure from current trends in optimal responses to the short term climate response and emissions trends, in addition to the level of the discount rate.

3.3. Interplay between the shape of damage curve and climate sensitivity

Let us now turn to the linkages between the timing of GHGs abatement, the value of the discount rate and of the time derivative of damages which are critical for early decades actions. This raises the question of singularities triggered by the interplay between climate change[12] θ(.) and the responses of environmental and socio-economic systems ψ(.).

Recently, concerns about such singularities have been evoked beyond environmentalist quarters[13]: "[My] biggest fear is that international policy is being made based on smooth climate change" (G. Yohe). It is hardly disputable that potential sources of abrupt impacts exist along the chain from global warming to changes in local ecosystems. Large scale catastrophic events are the most obvious examples: slow down of the thermohaline circulation in the North Atlantic, West Antarctic ice-sheet disintegration, transformation of monsoons patterns or of El Niño cycles. Local climate surprises may also be triggered by smooth evolutions as soon as a threshold is exceeded: for example the coral reefs, already living close to their upper thermal limit, are threatened by a warming of surrounding surface water, as demonstrated by the intense coral bleaching episode of 97-98 due to El Niño.

But one major layer of uncertainty lies in the very translation from impacts to losses in social welfare. On the one hand, archaeologists (Weiss and Bradley, 2001) establish coincidences between sudden climate shifts and deep societal mutations; on the other hand, it can be argued that technologically advanced societies are far more resilient. But this response in turn shows that damages depend strongly on the mobilization of adaptation capacities, among which compensations between 'winners' and 'losers'. For example, variation of crops productivity, triggered by changes in temperature, CO_2 concentrations, rainfall regime or soil degradation, will also depend upon the capacity to invest in water management systems of affected regions and/or to cover the basic needs of their populations through a world market accessible to poor populations. In the same way, higher frequency of extreme events may aggravate the vulnerability of countries with fragile economic and political systems: for example the political disorganization in Guatemala cannot be fully isolated from the catastrophes affecting this country since several years.

3.3.1 Smooth vs threshold function: levels and rates of climate damages

IPCC/TAR/WGII chap XIX reviews the main shortcomings of widely-used impact functions linking global mean temperature increase and damages as a percentage of Gross World Product (GWP). It suggests replacing them by more accurate functional forms as our knowledge of impacts improves. However, it will likely be very difficult to have this knowledge in due time. This is why it matters, for the time being, to understand better how the choice of a specific functional form is of importance for the optimal response.

DICE-94 damage function (Nordhaus, 1994), for instance, is close to $a_1 \left(\theta\right)^{a_2}$, where θ stands for global mean temperature rise since 1900[14]. Base value of θ_2=2 has greatly influenced previous studies and most widely discussed functions are of cubic or quadratic nature. But such a function has intrinsic drawbacks:

[12] For sake of simplicity, we will here neglect the eventuality of abrupt climate shifts, possible runaway of carbon cycle or the possible release of huge quantities of methane from permafrost regions or coastal zones.

[13] The Boston Globe (dec, 12 2002) on the occasion of the publication announcement of the National Academies report "Abrupt climate change: inevitable surprises" (2002).

[14] Benchmark estimate is a 1.33 % GWP loss for a +3°C global mean temperature increase therefore for a_2=2, we obtain a_1=1.33/9.

- climate surprises leading to high GWP losses can only be represented by adopting unrealistically high global mean temperature rise values. As an example, referring to DICE-94 damages function, the global mean temperature rise corresponding to a shock equal to a 10% GWP loss (which is higher than the economic shock of WWI) amounts to more than +8°C.

- if a higher exponent is selected so as to lower the global mean temperature rise corresponding to this 10% GWP loss (for a_2=4, this rise is +5°C), this leads to the paradoxical consequence that the larger the long-term damages, the smaller the short term ones (because of an increased convexity). As shown in table 2, doubling a_2 has a strong positive influence on optimal abatement rate in the long run but a small negative influence in the short term.

- lastly, multiplying the scale parameter of the damage function (a_1) to get more realistic damages on the short term (without altering the convexity of the function) also quickly leads to unrealistic high damages on the longer term.

	Optimal abatement of global CO_2 emissions	
	In 1995	In 2095
Base case	9.0	14.3
Doubling damage function intercept a_1	13.0	20.5
Doubling damage function exponent a_2	8.9	25.9

Table 2: DICE-94 sensitivity of optimal carbon abatement levels to the impact function parameters, from Nordhaus (1994).

To represent the episodes of very significant damages without assuming unrealistic GWP losses one technical option is to use sigmoid-like functional forms (figure 10)

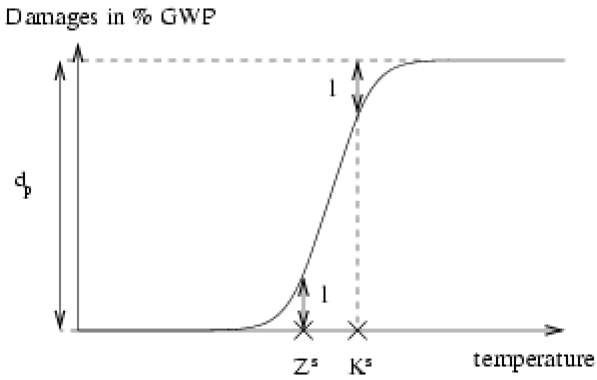

Figure 10: Sigmoid-like functional forms.

Such a threshold function can be given by the following analytical expression (as a percentage of GWP loss), with θ as the global mean temperature increase:

$$f(\theta) = \frac{d}{1+\left(\frac{2-e}{e}\right)^{\left(\frac{K+Z-2\theta}{K-Z}\right)}} \qquad with \quad e = \frac{l}{d} \tag{4}$$

To carry out simulations comparable with our previous cost-efficiency analysis, we set the middle of the threshold to +2°C (with a transition range from Z=1.7°C to K=2.3°C). Parameter *e* stands for the speed of the transition from low damage to high damage: the higher the parameter, the faster the acceleration (we set e to 0.1). The maximum damage, *d*, is set to 4% GWP loss. In the context of a 2% per year GWP growth rate, it is equivalent to a 0.2% slowdown of economic growth during a span of 20 years.

For sake of clarity, we will first examine, for two alternative specifications of damage functions (thresholds vs quadratic), a case where climate sensitivity is unknown. Second, we will perform a set of simulations where climate sensitivity is known (set to its central value) whereas damages are subject to beliefs on the occurrence of singular events.

3.3.2 Thresholds vs quadratic function under climate dynamic uncertainty

Under assumption of episodes with accelerated damages, the interplay between climate sensitivity is of critical importance because it determines the time period at which the time derivative of damages becomes higher than the discount rate. This is demonstrated in figures 11 and 12: the 4% GWP loss is reached in 2050 or 2100, depending upon assumptions on climate sensitivity which cannot but affect the timing of mitigation policies.

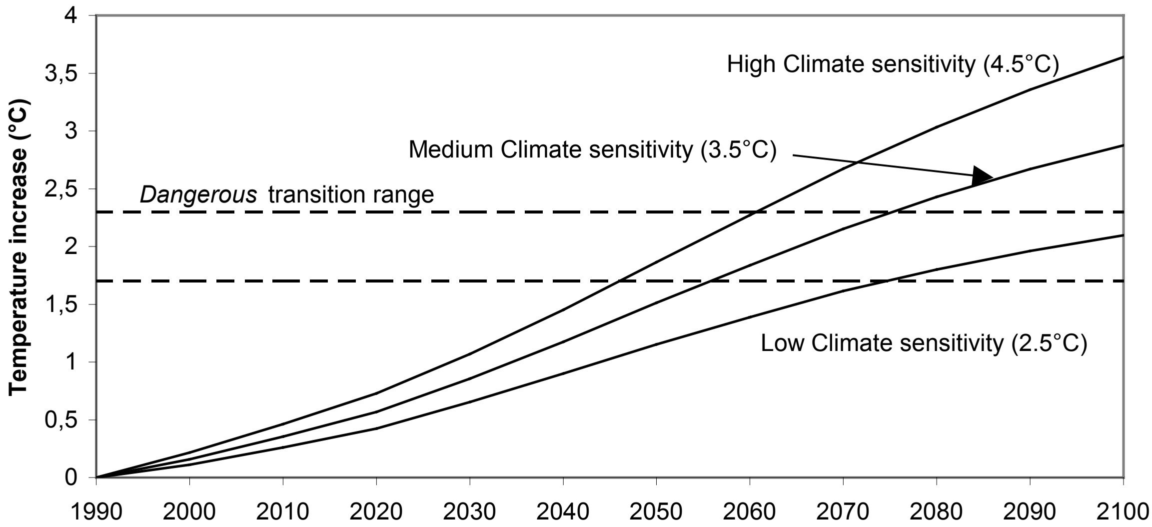

Figure 11: Global mean temperature rise with respect to 1990, with A1 emission baseline and different hypothesis on climate sensitivity.

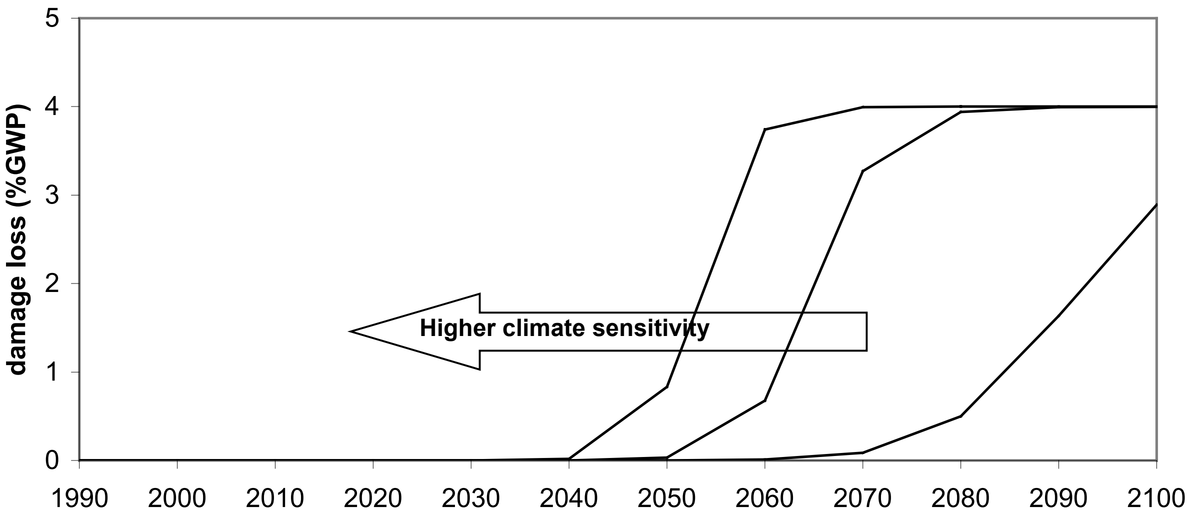

Figure 12: Depending on the value of climate sensitivity, in the case of singularities around a +2°C warming threshold, abrupt shifts (in the baseline case) occurs sooner as climate sensitivity is increased.

Let us assume three possible values for climate sensitivity (2.5°C, 3.5°C and 4.5°C) with subjective probabilities of 1/6, 2/3, 1/6 respectively. The resolution of this uncertainty may occur at different points in time during the 21st century. Damage functional forms are assumed to be known and are either quadratic or sigmoid-like. They have been calibrated so that their total expected damages follow comparable trajectories in the reference case. However beyond 2100 quadratic damages are far higher than threshold ones, with significant consequences on abatement pathways (see detailed description in box 7).

Box 7: Cost-benefit framework in uncertainty case with learning on climate sensitivity. There are three states of the world (s): climate sensitivity (T_{2x}) may be {2.5°C,3.5°C,4.5°C} with the corresponding e*x ante* subjective probability (p_s) {1/6;2/3;1/6}. Therefore climate dynamics is dependent upon the state of the world (note that L(.) is indexed by s).

Objective function:

$$\underset{Ab_t^s}{Max} \sum_s p_s \sum_{t=1990}^{2300} N_t \ln\left(\frac{\left(Y_t - f(Ab_t^s, \dot{Ab}_t^s, t) - \Psi(\theta_t^s, t)\right)}{N_t}\right) e^{-\eta(t-1990)} \qquad (1)$$

$$\forall t \le t_{\inf o},\ \forall (s,s') \in S,\ Ab_t^s = Ab_t^{s'}$$

quadratic damages function — threshold damage function

$$\Psi(\theta_t^s, t) = a(\theta_t^s)^2 Y_t \qquad \Psi(\theta_t^s, t) = \left(\frac{d}{1+\left(\frac{2-e}{e}\right)^{\left(\frac{K+Z-2\theta_t^s}{K-Z}\right)}} + b\theta_t^s\right) Y_t$$

Note that a linear trend has been added so that temporal profiles of damages do not differ too much in both situations

GHG emissions (em_t): exogenous baseline, based on A1-m scenario (5)

Concentration dynamics: $M_{t+1}^s = H(M_t^s, em_t(1-Ab_t^s))$ Nordhaus *et al.* (1999) (6)

Climatic change: $\theta_{t+1}^s = L^s(\theta_t^s, M_t^s)$ 3 values for climate sensitivity (7)
(see appendix A)

N_t: population level (source A1-m), Y_t: gross world product (source A1-m)
per capita income is in US90$ per capita
η: pure time preference (3%.year^{-1})

t_{info}: date of arrival of information on climate sensitivity (1990,2020,2040). Before disclosure of information, command variable (Ab_t) are equal whatever state of the world occurs *ex post*.

Quadratic damages function parameters:
a=0.6%GWP

Threshold damages function parameters:
d=4% of GWP, e=0.01, Z=1.7°C, K=2.3°C, b=0.5 %GWP

Model time step is decadal.
See appendix A for specification and calibration of functions *f(.), H (.), L(.)*, and data (em_t, N_t, Y_t).

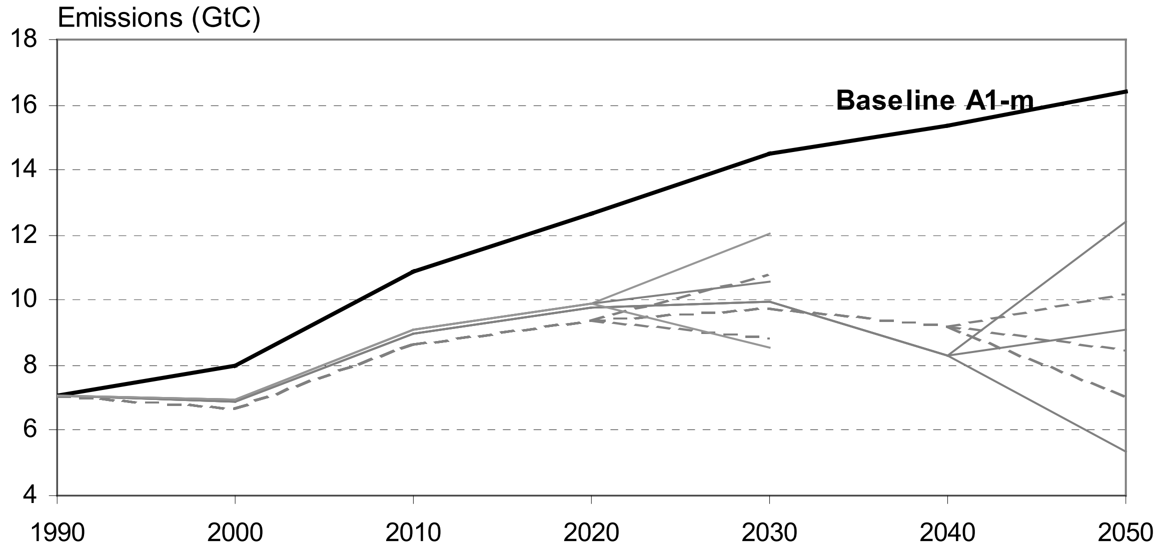

Figure 13: Emissions with respect to time, for different damage function shapes (quadratic shape in dashed grey and threshold shape in continuous grey) and arrival of information on climate sensitivity in 2020 or 2040. The baseline is in bold continuous line.

In figure 13 are shown optimal abatement rates for quadratic (dashed grey curves) and threshold damage functions (grey curves) when learning on climate sensitivity occurs in 2020 or 2040. No policy conclusion can be derived from comparison between both emissions paths[15] since the ultimate damages levels for each shape are not equal. When information on climate sensitivity arrives later than 2030, optimal strategies with threshold functions lead to higher abatement rates. This is consistent with the significant increase of value of information on climate sensitivity (Fig. 14) when one gets close to the threshold (which does not appear with quadratic functions). This confirms the Peck and Teisberg findings (1993) that information value gets higher the more non-linear damages are. In policy terms, this suggests the existence of a window of opportunity, already found in the cost-efficiency analysis with temperature ceiling and in the PCCR approach.

[15] In particular the fact that optimal emissions paths are similar until 2030 should be considered as a calibration artefact.

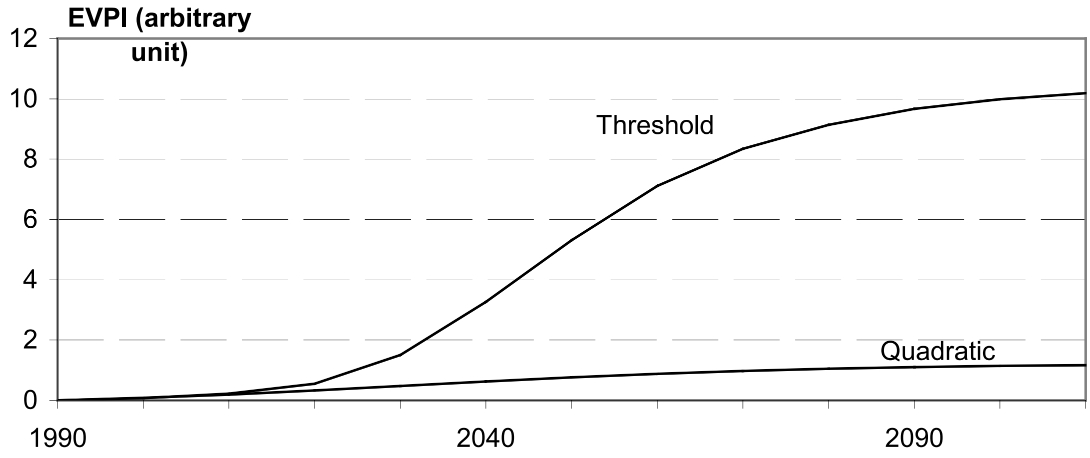

Figure 14: Expected Value of Perfect Information on climate sensitivity for two damage function shape hypothesis.

3.3.3 Uncertainty regarding damage function with known climate dynamics

To analyse the importance of uncertainty on the shape of damages functions, we calibrated both specifications on the same arbitrary benchmark value: 1% GWP loss for a 2°C temperature increase. Climate sensitivity is assumed to be known and set to its central value (ie 3.5°C). Moreover, expected damages exhibit similar temporal trends at least during the first half of the current century.

<u>Box 8:</u> Cost-benefit framework with contrasting believes on damages. There are two states of the world (s): either damages functions are quadratic (Q) or they exhibit threshold (T). *ex ante* subjective probabilities (p_s) are associated to these states. To reflect diverging opinions, we have tested four sets for p_s: $\{p_Q=1, p_T=0\};\{p_Q=0.95, p_T=0.05\};\{p_Q=0.5, p_T=0.5\};\{p_Q=1, p_T=0\}$.

Objective function:

$$\underset{Ab_t^s}{Max} \sum_s p_s \sum_{t=1990}^{2300} N_t \ln\left(\frac{\left(Y_t - f(Ab_t^s, \dot{Ab}_t^s, t) - \Psi_s(\theta_t^s, t)\right)}{N_t}\right) e^{-\eta(t-1990)}$$

$$\text{where} \qquad \Psi_s(\theta,t) = \begin{cases} a\left(\theta_t^s\right)^2 Y & s=Q \\ \left(\dfrac{d}{1+\left(\dfrac{2-e}{e}\right)^{\left(\frac{K+Z-2\theta}{K-Z}\right)}}\right) Y_t & s=T \end{cases} \qquad (1)$$

$$\forall t \le t_{\inf o},\ \forall (s,s') \in S,\ Ab_t^s = Ab_t^{s'}$$

GHG emissions (em_t): exogenous baseline, based on A1-m scenario			(5)
Concentration dynamics:	$M^s_{t+1} = H(M^s_t, em_t(1 - Ab^s_t))$	Nordhaus *et al.* (1999)	(6)
Climatic change: (see appendix A)	$\theta^s_{t+1} = L(\theta^s_t, M^s_t)$	climate sensitivity = 3.5°C	(7)

N_t: population level (source A1-m), Y_t: gross world product (source A1-m)
per capita income is in US90$.pc^{-1}
η: pure time preference (3%.year^{-1})
t_{info}: date of arrival of information on climate sensitivity (1990,2020,2040,2060&2080). Before disclosure of information, command variable (Ab_t) are equal whatever state of the world occurs *ex post*.
damages function parameters:
a=0.25% of GWP,d=3% of GWP, e=0.01, Z=1.7°C, K=2.3°C, b=0.5 %GWP

Model time step is decadal.
See appendix A for specification and calibration of functions *f(.), H (.), L(.)*, and data (em_t, N_t, Y_t).

Results (Fig. 15) show the same limitations than results of Fig. 13: because quadratic functions refer to ultimate damages far higher than threshold functions, abatement rate are similar in the early decades. However despite this artefact, abatement pathways diverge significantly after 2030. After this date, the optimal pathways depend on the subjective probabilities: it is remarkable that 5% subjective probability only for the threshold function (upper dashed line) leads to a significant departure from the quadratic case while 50/50 distribution of probabilities leads to emissions pathway very close to the optimal pathway in case of early certainty about the existence of the threshold.

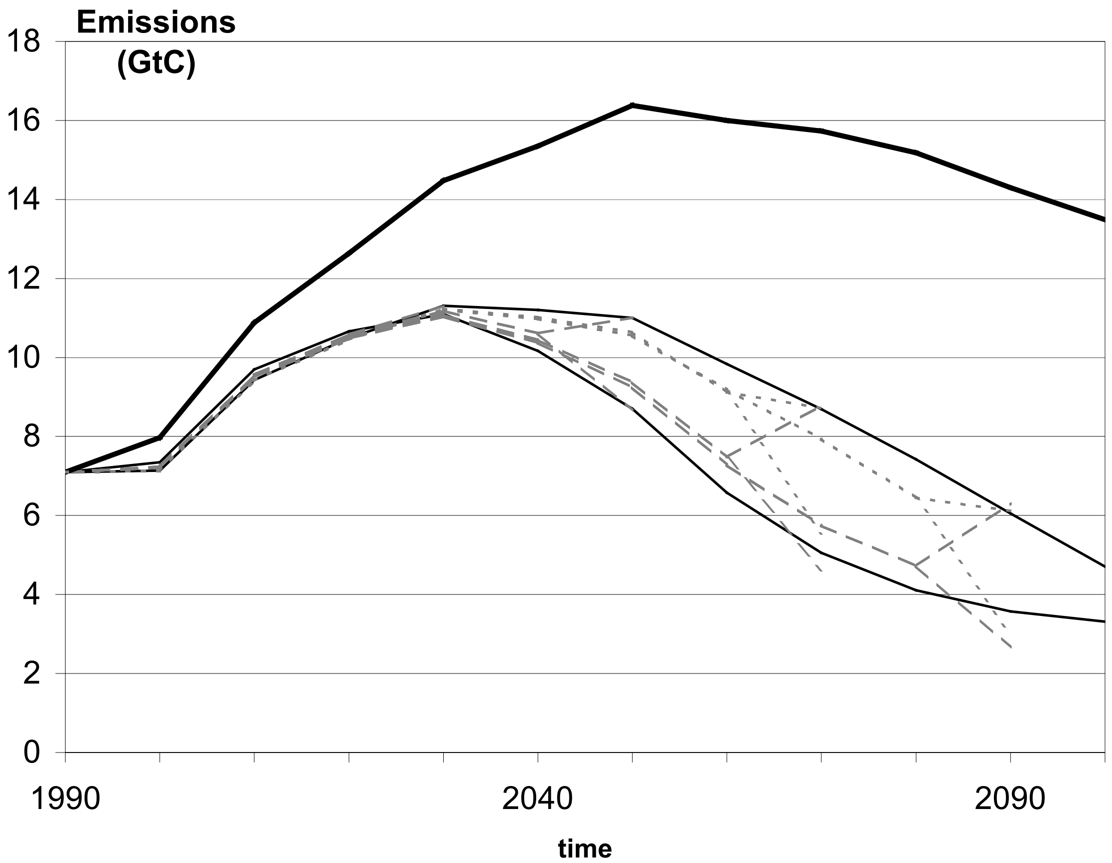

Figure 15 : Emissions for different hypothesis on subjective probabilities of the threshold function (threshold function probability : 0% for the upper thin black line; 5% for the dotted grey line, 50% for the dashed grey line; 100% for the lower thin black line).

Part 3: Assessing climate damages; what are we talking about?

We analyzed so far the implications of various attitudes towards climate risks, including those relying on doubts about the possibility of assessing climate change damages. If it is decided to make such an assessment, we demonstrated the importance of singularities on the damage curves i.e. episodes with accelerated increase of damages. It remains to be specified what is damage.

The starting point of damage assessment should be that climate impacts are not, per se, climate damages. Let us assume a new stabilized climate regime in which the Riviera climate would have migrated to Normandy or Cornwall. Current inhabitants of these regions may be willing to avoid such a move in order to bequeath current landscapes as cultural heritage (the PPCCR). But there is no reason why the new climate distribution will provide future generations fewer amenities than current distribution. Conversely, there are a lot of reasons why the transition from one regime to another will entail cost: to what extent will it be possible to find in due time technical solutions to allow populations on the Riviera to enjoy the same quality of life with a warmer and drier climate? Will it be possible to find in due time economic activities apt to substitute for tourism? If not, will it be possible to organize migration without economic and social tensions?

The generic model we started from shows the complex interplays between environment, economy and 'perceptions' by individual and collective agents through which impacts are transformed into damages. In this model, the time derivatives are as important as the absolute value of the variables. It shows the intrinsic limits of enumerative approaches where damages are the discounted sum of sector losses, weighted by their importance in the economy (Frankhauser (1994)). This comes to disregard amplification and propagation effects throughout the socio-economic system and to assume compensation between 'winners' and 'losers' both within and across generations.

The main sources of non-linearity in damage function lies a) in the interplay between the pace of climate change and socio-economic inertias, b) the limits of insurance mechanisms, c) the difficulty to organize compensations between losers and winners d) in the difficulty of detecting and assessing in due time climate signals in order to launch adaptation strategies.

Timing of damages, adaptation and mitigation:

When discussing climate impacts apt to trigger economic shocks, the notion of *large scale climate surprises* comes first into play. Paleo-climatologists show out such past catastrophic episodes [16] and archaeologists (Weiss & Bradley, 2001) establish coincidences between strong climate modification and societal collapses. A well-known example of such sudden transitions [17] is the slowdown of the North Atlantic thermohaline circulation (Rahmstorf & Ganopolski, 1999).

[16] For example, Greenland's temperature increased of 8° in (National Academies, 2002).

[17] Another example is the West Antarctic ice-sheet disintegration which could lead to a sea level rise of 4 to 6 m; IPCC suggests, in spite of the lack of knowledge of the dynamics of ice sheets that such an event is very unlikely in the XXIth century.

Under such circumstances, which occurred several times in the past, the temperature of oceanic Europe would fall by 5° to 10° in a few decades.

But economic shocks can also result from frictions between the pace of climate impacts and the economic inertia at a local scale if local ecosystems are suddenly modified as soon as a tolerance interval of the ecosystems is exceeded.

For example, the intensity of the coral reef white death episode of 97-98 due to El Nino confirms that some species necessary to maintain coral reefs live in water the temperature of which is close from their upper tolerance limit. A 1 or 2° warming could lead to a massive extinction of such ecosystems, all the more so as they are already under strong anthropogenic pressure (Bryant and al., 1998). Coral reefs play a major role in trophic chains, preserve sources of proteins for hundreds of millions of people and provide commercial income through tourism, fishery and fishing licenses (Spalding & al., 2001). Hoegh-Guldberg (2000) conclude to a 40 to 50% GDP loss for the concerned islands but the net loss will differ greatly depending upon the pace of the white death. Since the size of the affected economies is small, it is in principle possible to fund the redeployment of economic activity. But this may turn out to be impossible and too costly in case of acceleration of the disruption.

Another example of mistakes made by confusing the welfare impacts of being adapted to a new climate regime and the transition costs between two regimes is that Russia will be a winner of climate change because the permafrost retreat to higher latitudes, the soil warming, and the higher air temperatures will facilitate the cultivation of new surfaces. But the limit rate compatible with the ability of trees to migrate is estimated to be between 0.1 and 0.2° per decade and a smooth substitution between species may not be so easy. In addition, permanent or seasonal permafrost melting will cause serious damages to housing, road and railways, pipe-line and mining industry until new infrastructures are in place.

Limits of insurance mechanisms

It can be argued that part of these frictional costs will be mitigated through insurance mechanisms; but this is true as long as insurance companies are not forced to lower the base and level of risk coverage.

While the interpretation remains controversial, retrospective and prospective analysis indicate that changes in the frequencies and/or intensities or extreme climate events during the second half of the XXth century will be pursued in the XXIth century. For example, (Palmer et Räisänen (2002)) very rainy winters in Europe could occur every 8 years on large area of North Europe instead of 40 years currently, every 13 years on Central Europe and North of France. The last decade was unfortunately rich in examples which show the great vulnerability of human settlements and infrastructures to such extreme events and the vulnerability of insurance sector. Between 1960 and 1999, among the 30 most costly worst natural catastrophes, 28 are meteorological and 27 occurred since 1990 (Berz, 2001).

It is still very uncertain whether that these statistics are due to more frequent extreme events, to the population growth in exposed areas, the higher value of insured goods or the higher vulnerability of technologies and networks. However, despite the absence of definitive conclusions in the IPCC Tar, many companies are very pessimistic. The point is that, would these concerns materialize, industry will lower the base and percent of risk coverage. This will not only make the compensation of affected zones dependent upon public solidarity; it will also endanger the continuation of certain activities (tourism, agriculture), make far more costly public infrastructure, which could trigger a depressing effect on overall activity.

Propagation effects and compensation

In addition to the pace of transformations, another source of potential singularities along the aggregate damage curve is the propagation effect of local shocks across regions in the absence of mechanism to compensate the losers.

Many of such shocks may be channeled through agriculture and food shortages. The sum of positive and negative impacts on agriculture is expected to be modest in case of perfect world for food. But, would the estimates of Mendelsohn materialize, the food sector in Africa would suffer a production loss amounting to 4.7% of the regional GDP; since the purchasing power of African countries would be lower and since this aggregate figure recover higher production losses in some regions, this may result into higher starvation. In the same way, a 2° mean temperature increase would reduce dramatically the available land to grow coffee in Uganda (Simonett, 1989) where this production generates 80% of employment, 45% of the GDP and 90% of exports. Desertification and water shortages could be exacerbated in the Mediterranean Basin [18].

Many other potential sources of local shocks have to be considered, above all in developing countries: sea level rise which will force the inhabitants of Pacific Ocean islands to migrate, increased hurricane and droughts in Latin America which, as demonstrated in Guatemala (hurricane Mitch in 1998, droughts in 1999, 2000 and 2001, hurricane Michele in 2001) can add to the economic and political disorganization in the country is mainly responsible, changes in the Asian monsoon, flooding in Bangladesh due to the combination between more frequent severe Monsoon and sea level rise.

Even if it is assumed that the order of magnitude of such shocks will stay small compared with total world wealth, both because they affect heavily poor regions, it is highly uncertain than rich regions will set up in due time compensation mechanisms apt to mitigate incurred social costs. There is indeed no reason why developed countries would be more willing to increase overseas aid to cope with climate risk than they are to support development. There is also no reason why it would be easier to set up in due time institution apt to minimize risks of misuse of this aid.

In the absence of efficient compensation, local or regional shocks could propagate either indirectly through many feedbacks in economic or social system (depressing effect on neighbor economies) or directly trough migration. Even if climate change is not the major factor, it could add to existing disequilibrium in countries experiencing a fast demographic growth. Obviously the risk of geopolitical tension may not be confined to the regions affected by severe local disruptions. On the one hand the *climate change refugees* issue will also concern Oecd countries[19], on the other, climate change may become one dimension of the world security.

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[18] water consumption per inhabitant is expected to go below 500 m3.inhabitant-1.an-1, considered as the scarcity threshold, in 5 Mediterranean countries in 2025 and in 8 in 2050.

[19] The prime minister of Tuvalu announced in 2000 that *"Tuvaluans are seeking a place they can permanently migrate to should the high tides eventually make our homes uninhabitables"* and New-Zealand announced to be ready to welcome up to half the population of Tuvalu, i.e. 5500 inhabitants (Barnett, 2001).

Climate signals and scientific conditions of the attribution debate

Independently from judgment on the previous points, the last parameter governing the assessment of climate damages refers to the questions of detection and attribution: what are the credible signal that climate is changing? What part of this change can be attributed to anthropogenic part GHG emissions? What part of damages can be attributed to climate impacts and what part to pre-existing socio-economic parameters?

The detection problem is automatically solved if the credibility of climate predictions is very high and if the amount of separated analysis existing on potential impacts is judged sufficient. If this is the case, a PCCR approach is to be logically adopted. Otherwise, the detection is closely linked with the timing of climate signals. But, since a sequence of climate anomalies is not, per se, a signal, it matters to know whether this sequence departs really from the normal 'noise' due to climate variability. This confronts the difficulty to measure climate sensitivity. That parameter is only defined in a 'model point of view': First it is calculated at a given and constant GHG concentration level, which is of course an unrealistic situation; Second it derives from a climate model disturbed by a GHG inflow and reaching a new equilibrium. Over the short term, the problem is that the observed values of meteorological variables are stochastic and the real "mean regime" of climate is hidden behind the natural variability. So having a robust measure of climate sensitivity requires long enough time series and a climate change large enough compared with natural variability. We may also need climate change patterns from GCM[20] to help us to distinguish the change signal from noise. So, because GCMs are strongly involved in the detection process, it is out of our reach in the near future to distinguish in a unquestionable manner a climate change signal. The problem is thus to decide which level of observed impact or climate change we consider as a tangible proof of climate change confirming climatologists' predictions.

The attribution of climate change to human activities confronts the same problem; it cannot be done only trough observations since climate change can be due to other forcing such as solar forcing variations. As to the attribution of climate damages to climate impacts or to social parameters on climate change impacts, it confronts the difficulty that a small climate change may collapse already weakened economies in the same way that a marginal shock on an enterprise may suffice to transform profits into losses. The logical trap is the same as considering that a significant carbon tax cannot have a strong economic impact because the resulting cost increase is negligible compared with the total production cost. In fact, the cost increase has to be compared with the net profit margin, which is much lower, and a carbon tax has negligible impact only under provision of a precise set of conditions (tax recycling, grand-fathering…). From this point of view, pre-existing conditions and climate shock strongly interplay and attributing an economic collapse to one of them does not make sense excepted if it is assumed that changing these pre-existing conditions is easy and costless. But this assumption comes back to a well known debate about 'no-regret': how to explain that such measures have not been already taken.

The climate system is a very slow system with a characteristic time of several thousands of years. That means that any action (or inaction) nowadays may have consequences over centuries and that waiting for conclusive proofs to make decisions this is to take the risk of acting too late.

[20] e.g. fingerprints methodology, see Hasselmann, 1976.

There are currently good scientific reasons why these proofs may come too late. We are in the position of a driver on a mountain pass road in late winter, speculating about the presence of ice on a bend before a precipice. He wants to maximize his speed, but would he try to calculate a probability distribution on the presence of ice, he would risk a fall in the case of the non-zero probability of the ice. The risks are too high and the information about the ice would come to late given the inertia of the car. Consequently, his behavior is not to adopt one and for all an optimized trajectory but to push slightly on the brake, ready to slow down if he sees ice in the bend or to accelerate if the road is clear.

Part 4: A tentative proxy to translate impacts into damages.

The previous sections described some difficulties to evaluate climate change damages. We are conscious not to be able to deal with all these problems within the time constraints of this project. However we will try to design a methodology to make some progress in direction of damage assessment.

The diagnosis behind this proposal is that, because of the large uncertainties in impact and damage assessment, we need first proxies of them in order to organize other modules and to work on other problems as population heterogeneity or macroeconomic feedbacks. When our understanding on ecosystems and low scale processes is increased, we will be prepared to implement progressively more realistic modules. Indeed, models are improved through two ways: our top-down approach using proxies to reproduce the behavior of low scale systems and focusing on large scales; and a bottom-up approach, the impacts studies, neglecting the large scale feedbacks to focus on complex local processes. Both approach are necessary to improve our understanding of the global consequences of climate change and to link large scale and small scale effects of climate change.

A tentative proxy to translate impacts into damages may be based on a climate change indicator, which may eventually be a vector. This indicator has to be coupled to an approach of damages, which could be based on PPCCR or on any more sophisticated form of damages. The aim is to develop an indicator, as independent as possible from the way damages are modeled. To do this, the indicator has to take into account the following properties:

- The temperature increase is not the only relevant information : we often need other climatic variables (as precipitations or soil water content). Moreover, it seems necessary to use absolute values (for example, a change in temperature has more impacts if it makes the absolute temperature cross the 0°C threshold)

- The rate of climate change is also essential through two ways : the first one is a consequences of climatic non-linearity (climate change patterns may be different if the rate of change is modified); the second one concerns the impacts and the race between global change and adaptation processes.

- climate change damages may only be assessed regionally and the global mean change is not a sufficient information.

- Seasonality is very important for some impacts assessment, particularly on agriculture.

Others improvement may of course be envisaged but, in a first step, what we need is the following:

- Given a date T and given an emissions path from nowadays to T, as a real function E from [O;T], it is necessary to know, without heavy computational costs, the seasonal and regional mean variables changes at date T. Then, a tractable and computable function Ψ_T, based on GCM outputs, is need:

Ψ_T: emission path → Climate change patterns
$E(t)$; $0<t<T$ → $\Delta X_i(T)$; $i=1,..,n$

Climate models give the value of Ψ_T for a few concentration paths, but it is necessary to interpolate Ψ_T for any concentration path. In other words, given for example $\Psi_T(CO_2^1)$ and $\Psi_T(CO_2^2)$, an evaluation of $\Psi_T(CO_2^3)$ for any CO_2^3 (e.g. in figure 4) is to be determined.

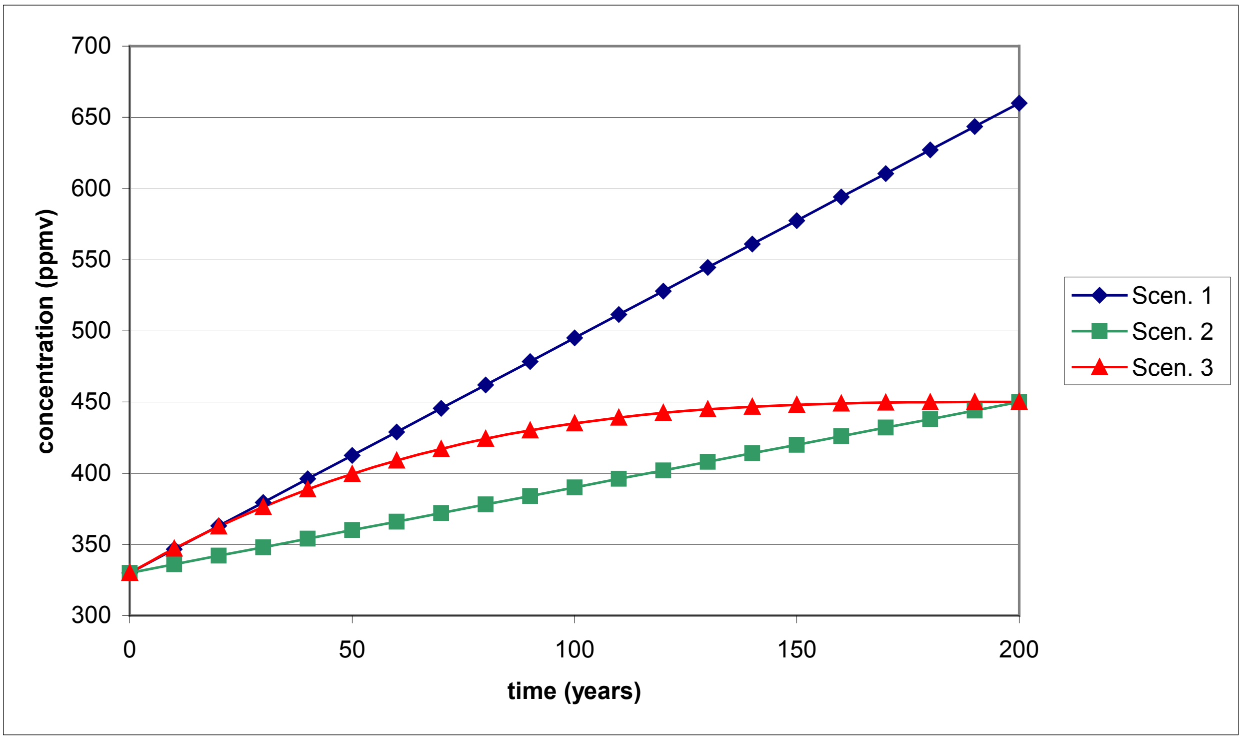


Figure 4 : Example of concentration paths.

Of course, because of uncertainties, we do not need a perfect function and we have to make a compromise between its quality and its complexity and tractability.

- Once the climate patterns reproduced, a climate change indicator function is needed, taking into account new parameters: initial climate, precipitations, rate, sensibility of societies...

As a first step, a few methodologies to summarize climate models behavior are proposed. Secondly, a way of building a first-step climate change indicator is suggested.

4.1 Climate patterns and transient response.

- **Linear methodology**

Mendelsohn used the outputs of 3 simulations for the present concentration (S1), the doubled (S2) and the quadrupled (S4) CO_2 concentrations. He used the change in temperature and precipitations as patterns of climate change : for the doubling and the quadrupling, he considered the local changes in temperature and precipitations compared with the present day simulation (i.e. (S2)-(S1) and (S4)-(S1)) and he normalized them by the global mean temperature change to get normalized pattern of change at the doubling and the quadrupling level. Then, he averaged both normalized pattern to get a map of local change in temperature (M_T(lon,lat)) and a map of local change in precipitations (M_P(lon,lat)) corresponding to a 1° increase in global mean temperature.

He supposed that, given a global mean increase in temperature, the local changes in temperature and precipitations are given by :

ΔT (lon,lat) = M_T(lon,lat) ΔT
ΔP(lon,lat) = M_P(lon,lat) ΔT

This methodology was a great improvement compared with previous studies but, because Mendelsohn was looking for an evaluation of the damages due to a fixed increase of temperature, his methodology does not evaluate the global mean temperature with respect to time. To overcome this limitation, one may:

- Use the following relationship, proposed by IPCC:

$$\Delta T_e = \Delta T_{2X} \cdot \frac{F(CO_2)}{F_{2X}}$$ where:

ΔT_e is the global mean temperature increase at equilibrium for a given CO_2 concentration.
ΔT_{2X} is the global mean temperature increase at equilibrium for the doubled CO_2 concentration.
F_{2X} is the additional forcing of CO_2 at the doubled CO_2 concentration.
$F(CO_2)$ is the additional forcing of CO_2 for a given level of CO_2. It may be approximated by:

$$F(CO_2) = 5.35 \cdot \ln\left(\frac{CO_2}{CO_2^{initial}}\right)$$

To take into account the transient response, a logarithm race to equilibrium with a characteristic time τ may be introduced:

$$\Delta T(t) = \int_0^t \frac{1}{\tau} \cdot \Delta T_e\left(CO_2(x)\right) \cdot e^{-x/\tau} \cdot dx$$

- Use a simple model, with low computational cost and which gives the global mean temperature evolution with respect to time. Several models fit to this application, among them the LMD/CIRED simple climate model.

This methodology does not take into account any real transition path, and assumes that precipitations and the temperature are proportionally linked. This limit is very restrictive given the strong non-linear behavior and transient effects in precipitations.

- **A methodology based on a set of equilibrium**

If we assume that transition patterns are negligible, which could be justified for temperature but is rather false for precipitations and other strongly non-linear variables, a set of equilibrium may be used to represent climate change.

From a set of equilibrium data, for a range of CO_2 concentrations from the present value to the maximum envisaged concentration (reasonably to the doubled or the tripled CO_2 concentration). The following set of data is defined:

$$X_k(lon,lat,CO_2) = V_k(lon,lat,CO_2) - V_k(lon,lat,CO_2^{initial})$$

where k is the number of the considered variable.
and $V_k(lon,lat,CO_2)$ is the equilibrium value of the variable k at (lon,lat) for a fixed concentration of CO_2.

From this set, two solutions may be proposed :

- for each grid-point, we can directly fit a continuous function $f_{k,lon,lat}(CO_2)$ on the series and get:

$$f_{k,lon,lat}(CO_2) = X_k(lon,lat,CO_2)$$

- an empirical orthogonal functions analysis may be used to extract large patterns of climate change. For each variable k, a set of patterns of climate change is extracted (called $P_{k,i}(lon,lat)$), sorted from the most to the less important. The corresponding coefficients (called $\alpha_{k,i}(CO_2)$) are related to the CO_2 concentration. A set of patterns is selected, with respect to their respective ability to explain the variability.

$$f_{k,lon,lat}(CO_2) = \sum_i \alpha_i(CO_2) \cdot P_{k,i}(lon,lat)$$

$$Xk(lon,lat,CO_2) \approx f_{k,lon,lat}(CO_2)$$

Of course, this pattern does not include the whole signal of climate change - to do that every EOFs have to be included - but the represented fraction of the signal is exactly known and noise is reduced because EOF analysis favors large patterns.

To evaluate this methodology, it was applied to a low resolution and very simple version of LMDZ, the GCM model of the Laboratoire de Meteorologie Dynamique, CNRS, Paris. The following figures reproduce the first EOFs and the value of the first indicators $\alpha(CO_2)$ for temperature (first line) and precipitations (second line).

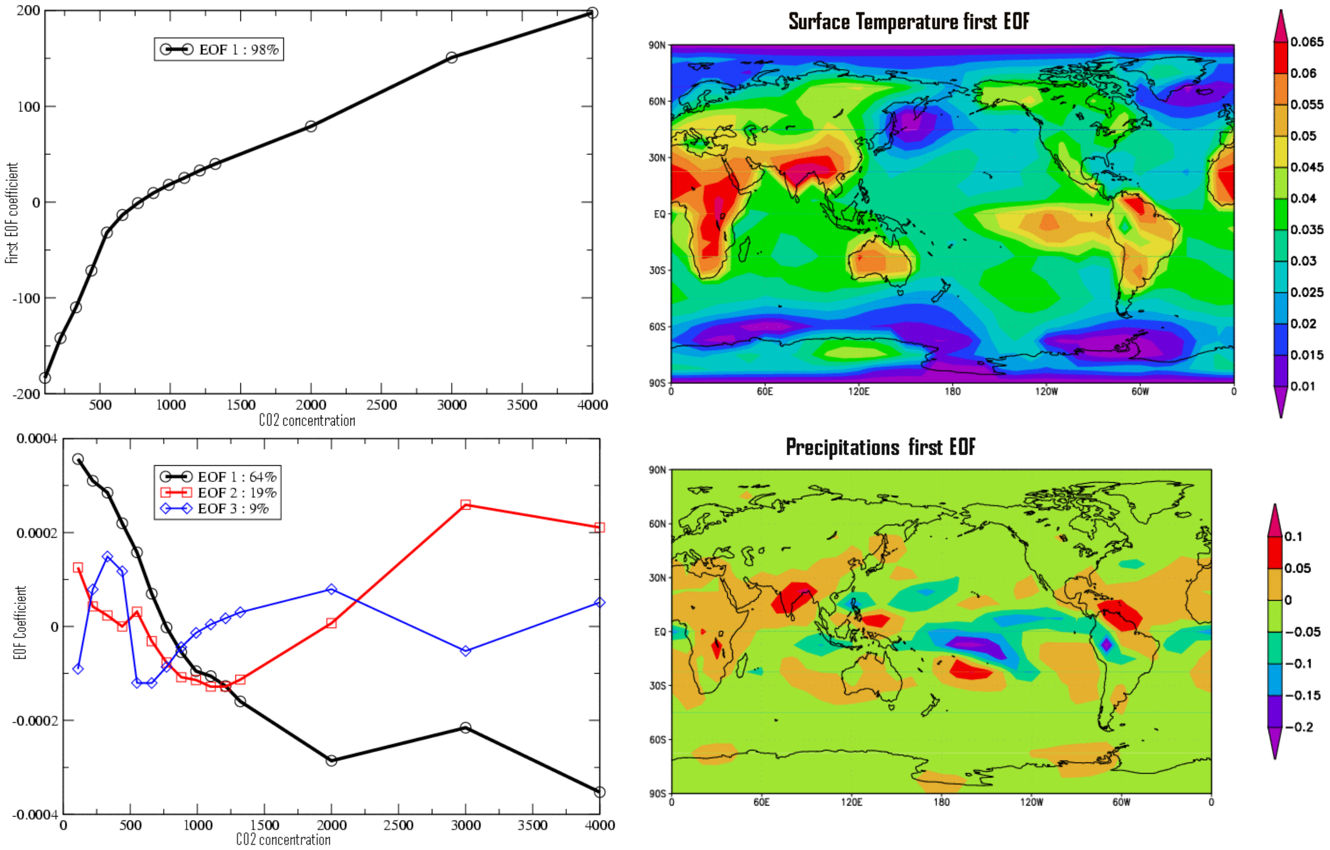


Figure 5 : Surface temperature and precipitations first EOFs and coefficients

In that case, the first EOF represents 98% of the signal for temperature and 64% for precipitations. The lower explanation of the first EOF for precipitations is a consequence of the more complex behavior of precipitations. This also show that the linear methodology is not sufficient.

What ever methodology used to define our patterns, introducing a transient response may be possible by using a simple model or a logarithm race to equilibrium. The main problems are nevertheless the numerical cost of the simulations needed to get the equilibrium climate state for several concentration levels and the lack of real transient response.

- **A transient run methodology.**

In order to introduce realistic transient responses of climate, it would be necessary to use transient GCM simulations. Nevertheless, the signal extracted from these simulation is biased by natural variability and only ensemble runs could give a pertinent evaluation of transient response of climate. Unfortunately, the numerical cost of such simulation makes unrealistic to envisage a systematic use of ensemble runs.

However, a way to take into account transient response may be to use, for each model, the PRUDENCE available runs for A1 and B2 scenarios as ensemble members and to build proxies of climate response by a weighted linear combination:

Given $CO_2^{A1}(t)$ and $CO_2^{B2}(t)$ the concentration paths in A1 and B2 scenario, $X^{A1}(t)$ and $X^{B2}(t)$ the mean climate response in these cases, and $CO_2(t)$ another concentration path, the climate response X(t) to this latter scenario may be approximated from the both formers through:

$$\Delta X(t)=\left\{\int_0^t f(t-x)\cdot\left[\frac{CO_2(x)-CO_2^{B2}(x)}{CO_2^{A1}(x)-CO_2^{B2}(x)}\right]dx\right\}\Delta X^{A1}(t)+\left\{\int_0^t f(t-x)\cdot\left[1-\frac{CO_2(x)-CO_2^{B2}(x)}{CO_2^{A1}(x)-CO_2^{B2}(x)}\right]dx\right\}\Delta X^{B2}(t)$$

Where f(x) is a function decreasing from 1 at zero to 0 at infinity, with a unit sum on [0;+∞[, and with a decrease characteristic time to be determined. This function f aims at representing the climate response delay and the fact that a difference in CO2 concentration at one date has decreasing but significant consequences on several decades.

This function aims at evaluating an intermediary response between simulations in A1 and B2 scenarios. An experimentation is of course necessary to evaluate the ability of this methodology to capture realistic climate responses.

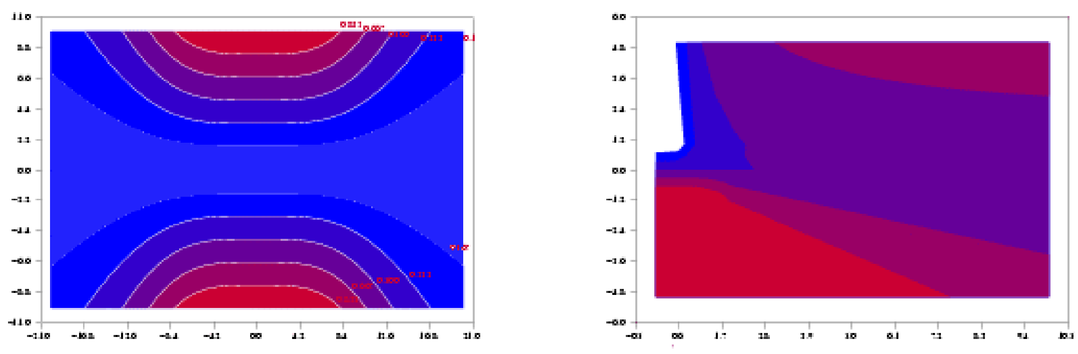
4.2. Climate change indicator.

To overpass the classical climate change indicator, i.e. the mean temperature change, a simple kind of climate change indicator functions may be proposed, depending on initial temperature, initial precipitation, change in temperature and change in precipitations:

$$CC\ (lon,lat,t) = F_{CC}\ (\ T(lon,lat)\ ,\ P(lon,lat)\ ,\ \Delta T(lon,lat)\ ,\ \Delta P(lon,lat)\ )$$

This is a very simple way to use more information than a classic climate change indicator and do not change the way of using it into the models. For example, if two regions are expected to support the same 1° temperature increase, it is necessary to make the difference between a very cold region (as Siberia) and a temperate region. Indeed, the same temperature increase may have dramatic impacts on the latter and negligible (or even positive) impacts on the former.

For example, imagine that $F_{CC}(T,P,\Delta T,\Delta P) = F_T(T,\Delta T) + F_P(P,\Delta P)$ with the following shapes for F_T and F_P : (Of course, these shapes are just examples of what it might look like.)



$F_T(T,\Delta T)$ $F_P(P,\Delta P)$

Figure 6 : Example of potential shapes of climate change indicator functions.

To define more precisely a climate change indicator, it could be interesting *to distinguish permanent effects and transition effects*: for example, on agriculture, a large change in precipitations can change a region into a less productive one. This damage is permanent and adaptation may only reduce the loss. But another change in precipitations in another region may only change the kind of culture which is adapted. In this case, adaptation can compensate the loss. We can even imagine that the permanent damage is negative (the region is changed in a more productive one, after adaptation) but that the transition damage is strongly positive (hard and costly adaptation). The climate information needed to evaluate permanent and transient effects are often different: for the second ones, the rate is more important than absolute value. One may imagine a multiplicative or additive coefficient to the damage function, depending on the climate change rate and representing the additional damages due to adaptation delay.

One of the major points these solutions are not able to deal with is the problem of the multiple thresholds : our function is still a regular one. We could imagine a *probabilistic function*, with damages following a distribution function depending of the climate state : as an example, we may assume that a strong damage in agriculture is always possible but is more and more likely as climate change is increased. By this way, uncertainties in our knowledge on potential impacts and damages might also be introduced.

To conclude on this, we have to emphasize on the need of a long work on these functions, in order to make them useful in policy assessment. But using such simple functions, just showing the trends, allows to work on modules integration, on large scales feedbacks and on other major problems involved in climate change assessment in a more realistic way than previous classical damage functions. Our focus here is not to propose impact or damage prediction, but to underline the major processes involved in the socio-economic system vulnerability and their interactions.

Conclusions

In this paper, we have compared optimal climate policy in the short run under three different decision-making frameworks: cost-effectiveness with deterministic or stochastic concentration or temperature ceiling objectives, cost-benefit analysis with pure preference for current climate regime and full cost-benefit approach with monetized evaluations of impacts. Five key lessons emerge from this analysis.

(a) Given the cascade of uncertainty from emissions to damages, the difference between various decision-making frameworks (cost-efficiency, cost-benefit with pure preference for current climate regime, cost-benefit with money metric valuation of impacts) appears to matter less than the difference between stochastic and non stochastic approach.

(b) In a stochastic approach, it does not take catastrophic ultimate impacts to significantly increase earlier abatement. Singularities in the damage curves are sufficient. In fact, they increase the role of the uncertainty on climate sensitivity. In a stochastic framework, with uncertainty on the shape of the damage curve, the choice of the optimal strategy is dominated by the likelihood of occurrence of such singularities.

(c) The optimal timing of emissions abatement remains strongly sensitive to the way the carbon cycle, the climate sensitivity of the model and baseline emissions over the first decades (including their intrinsic uncertainty) are calibrated.

(d) A window of opportunity exists in all decision-making frameworks, cost-benefit analysis with smooth damage curves excepted. The value of information is low in the first periods but increases drastically after 2020 to 2040. This time-horizon has to be compared with the fifty years necessary to change energy systems, and to the fact that, according to the climate models, clear signals may not emerge from the noise of climate variability before 2050.

(e) The introduction of a pure preference for current climate both allows for an overshoot of desired temperature (or concentration) targets and counterbalances the influence of discounting, all the more so as the environment is treated as a superior good.

The core difficulties remain: a) the revelation of the pure preference for stability (including its volatility due to the media life cycles), b) the evaluation of the interplay between the various influences of climate change on the economy. Among these interplays we will insist, as an invitation to further thoughts, on the role of the time derivatives. One major source of singularity in damage curves comes indeed from the joint effect of uncertainty and of the inertia of human systems. For instance, a two percent of GDP loss may either represent a benign shock when spread over a century or on the contrary when concentrated on five years be similar to the huge cost of World War 1 for France. Another related source of singularity is the propagation effect (climate refugees for example), in case of un-compensated shocks at a local level.

Coping with these difficulties will confront the methodological difficulties of incorporating intrinsically controversial information at various spatial scales, including from 'grass-root' case studies, into an integrated modelling framework. The increase of the size of the models to be mobilized will make all the more necessary the development of compact models of the sort used in this paper. Both mathematically controllable and flexible enough, they are an appropriate communication tool between scientific disciplines and between science and stakeholders in a process of public decision-making under scientific controversy.

To conclude we will insist, as an invitation to further thoughts, on the two aggregation problems the importance of which being potentially of the same order of magnitude as other parameters discussed so far:

- the time aggregation problem: one possible misleading conclusion of an aggregate assessment of damages is a sentence such as “climate damages will cause a 2% GDP loss over one century”. In aggregate this means less than one year of delay in economic growth. The underlying aggregation problem is totally unrelated with the debates about discounting. To give an intuition of it let us simply remind that 2% is the total GDP loss incurred by the French economy (Ambrosi, Hourcade 2002) is aggregated between 1914 and 2000 for the Word War I. It is unsure than this capture really the human disaster caused by this war. The theoretical problem is that the social costs of a damage concentrated over a short time period cannot be compared with the damage span over one century. In economic terms this means that the ‘utility functions’ to consider should in principle account for non linearities due to basic needs, for non symmetry between the utility of increase and decrease of income or for the preference for non sacrificing some generations [21].

- the intra-generational aggregation problem: we pointed out that a source of singularity in damage curves is due to the propagation effects (climate refugees for example), in case of not compensates shocks at a local level. This blurs the distinction between winners and losers of climate change and has a direct implication of the way total damages are calculated. Indeed, while welfare losses falling on ‘poor’ economies have a little weight on total world welfare, their propagation effect should be accounted for in the welfare variation of ‘rich’ countries. This relates to a fundamental question: to what extent Oecd countries can consider themselves as isolated from any such propagation effect; to what extent their ‘intérêts bien compris’ (‘well understood or well shaped’ interests) imply that part of damages falling on other (poor) countries should be considered as concerning them and be valued consequently.

To go further on these points, it will be necessary as a first step to overpass the current impacts and damages evaluation issues and to focus on the identification of the major processes at stake and on the study of their interactions. To do so, using a simple climate change indicator is proposed. This indicator must be able to represent the main characteristics of the damages without trying to provide realistic numerical assessments and must be determined by a close interdisciplinary collaboration.

[21] Note that this preference for non sacrificing generations is the core ethic argument in favor of the pure time preference. With a null time preference indeed, current generation would be sacrificed.

Appendix A

A.1. Baseline growth scenario and exogenous related data (income and population)

All experiments are based on the SRES A1m scenario: "*The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income*” ([32]).The A1m marker scenario has been computed by NIES (National Institute for Environmental Studies, Japan) with the AIM model (Asian Pacific Integrated Model).

We choose the A1m scenario because it corresponds to rather optimistic beliefs about the future. A1m is indeed the picture of a prosperous and generous world where economic growth is high with a considerable catch-up of developing countries, continuous structural change and rapid diffusion of more efficient technologies yield to decreasing GHGs emissions as soon as 2050. A1m is thus consistent with beliefs such as “*it is better to invest in R&D in the energy sector and/or research in climate change-related fields than to deep-cut fossil fuel emissions at once while alternative technologies are expensive and climate change consequences might prove ultimately benign*” or “*abatement opportunity cost is lower than that of fostering development in potential vulnerable regions*”. It is therefore relevant to examine how statements like “*one should delay GHGs emissions reduction efforts*” are to be revised when using a proper precautionary approach.

A.2. Specification of abatement cost function

We use the following abatement cost function:

$$f(Ab_t, Ab_{t-1}, t) = \frac{1}{3} BK.PT_t.\gamma\left(Ab_t, Ab_{t-1}\right).em_t.\left(Ab_t\right)^3$$

where: $f(Ab_t,Ab_{t-1},t)$: total cost of mitigation measures at time t (trillion US$)

BK: initial marginal cost of backstop technology (thousand US$.$tC^{-1}$)

PT_t: technical change factor

$\gamma(Ab_t,Ab_{t-1})$: socio-economic inertia factor

em_t: baseline CO_2 emissions at time t (GtC)

Ab_t: abatement rate at time t (% of baseline emissions)

Under these specifications, marginal costs of abatament are convex (quadratic). This is consistent with assumptions by experts and the results of technico-economic models. Note that f(.) does not allow for so-called no-regret potential.

BK stands for the initial marginal cost of backstop technology, ie the carbon free-technology which would enable to completely reduce GHGs emissions were it to be substituted to current existing energy systems. Its value depends on a set of assumptions regarding its nature (windpower, nuclear, …), its development date, its penetration rate and technical change. Given our own assumptions on technical change, we retain an initial 1,100US$.$tC^{-1}$ cost.

PT_t captures the influence of autonomous technical change on abatement costs. It translates the decrease of the costs of carbon-free technology over time, but the improvement of energy intensity which is already taken into account in the baseline. We assume that the costs of the available abatement technologies decreases at a constant 1% per year rate. But we assume costs cannot decrease beyond 25% of their initial values. PT_t thus take the form below (which leads to an ultimate cost of 275 US$.tC^{-1})

$$PT_t = 0.25 + 0.75e^{-0.01\delta t}$$

where δ is the time step of the model (10 years)

$\gamma(Ab_t,Ab_{t-1})$ captures the influence of socio-economic inertia as a cost-multiplier (transition costs between a more and a less carbon-intensive economic structure). γ(.) is a multiplicative index. It is equal to 1 (no additional costs) if abatement increases at a rate lower than a given threshold τ between two consecutive periods. But it increases linearly with speed of variation of abatement rate when this rate is higher than τ. τ is the annual turnover of productive capital below which mitigation policies do not lead to premature retirement of productive units. Here τ is set to 5% per year (average capital stocks turnover of 20 years).

$$\gamma\left(Ab_t, Ab_{t-1}\right) = \begin{cases} 1 & \dfrac{Ab_t - Ab_{t-1}}{\delta\tau} \leq 1 \\ \dfrac{Ab_t - Ab_{t-1}}{\delta\tau} & otherwise \end{cases}$$

A.3. Three-reservoir linear carbon-cycle model

We use the C-Cycle of Nordhaus ([24]), a linear three-reservoir model (atmosphere, biosphere + surface ocean and deep ocean). Each reservoir is assumed to be homogenous (well-mixed in the short run) and is characterised by a residence time inside the box and corresponding mixing rates with the two other reservoirs (longer timescales). Carbon flows between reservoirs depend on constant transfert coefficients. GHGs emissions (CO_2 solely) accumulate in the atmosphere and they are slowly removed by biospheric and oceanic sinks.

Let the vector C_t denote the carbon contents (GtC) of each reservoir at time t:

$$C_t = \begin{pmatrix} A_t \\ B_t \\ O_t \end{pmatrix}$$

where A_t: carbon contents of atmosphere at time t
B_t: carbon contents of upper ocean and continental and oceanic biosphere at time t
O_t: carbon contents of deep ocean at time t.

The dynamics of C_t is given by:

$$C_{t+1} = C_{trans}.C_t + \delta(1 - Ab_t)em_t.u$$

where C_{trans}: net transfert coefficients matrix
δ: time step of the model (10 years)
Ab_t: abatement rate of period t (% of baseline emissions)
em_t: baseline CO_2 emissions at time t (GtC)
u: column vector (1,0,0)

As such, the model has a built-in ten-year lag between CO_2 emissions and CO_2 accumulation in the atmosphere, which reflects the inertia in C-cycle dynamics.

Nordhaus calibration on existing carbon-cycle models gives the following results (for a decadal time step):

$$C_{trans} = \begin{pmatrix} 0.66616 & 0.27607 & 0 \\ 0.33384 & 0.60897 & 0.00422 \\ 0 & 0.11496 & 0.99578 \end{pmatrix}$$

Note that the sum of each column of C_{trans} yields unity (mass conservation) and that there is no direct exchange between atmosphere and deep ocean.
Initial conditions for C_{1990} are (GtC):

$$C_{1990} = \begin{pmatrix} 758 \\ 793 \\ 19230 \end{pmatrix}$$

The main criticism which may be addressed to this C-cycle model is that the transfer coefficients are constant. In particular, they do not depend on the carbon content of the reservoir (*e.g.* deforestation hindering biospheric sinks) nor are they influenced by ongoing climatic change (*eg* positive feedbacks between climate change and carbon cycle).

A.4. The reduced-form climate model[22]

This model is very close to Schneider and Thompson's two-box model ([28]). A set of two equations is used to describe global mean temperature variation (eq. 2) since pre-industrial times in response to additional human-induced forcing (eq. 1). More precisely, the model describes the modification of the thermal equilibrium between atmosphere and surface ocean in response to anthropogenic greenhouse effect. Calibration was carried out with H. Le Treut (IPSL) from data kindly provided by P. Friedlingstein (IPSL).

All specifications correspond to decadal values, which is the time step of the model.

Radiative forcing Equation:

$$F(t) = F_{2X} \frac{\log\left(\dfrac{M_t}{M_{PI}}\right)}{\log 2} \qquad (1)$$

Where M_t: CO_2 atmospsheric concentration at time t (ppm)
F(t): radiative forcing at time t ($W.m^{-2}$)
M_{PI}: CO_2 atmospheric concentration at preindustrial times, set at 280 ppm.
F_{2X}: instantaneous radiative forcing for 2x M_{PI}, set at 3.71 $W.m^{-2}$.

Temperature increase Equation:

$$\left\{\begin{bmatrix} \theta_{At}(t+1) \\ \theta_{Oc}(t+1) \end{bmatrix} = \begin{bmatrix} 1-\sigma_1(\lambda+\sigma_2) & \sigma_1\sigma_2 \\ \sigma_3 & 1-\sigma_3 \end{bmatrix} \begin{bmatrix} \theta_{At}(t+1) \\ \theta_{Oc}(t+1) \end{bmatrix} + \sigma_1 \begin{bmatrix} F(t) \\ 0 \end{bmatrix}\right. \qquad (2)$$

[22] A more precise description of the model and calibration process may be found in [1].

Where $\theta_{At}(t)$: global mean atmospheric temperature rise wrt pre-industrial times (°C)
$\theta_{Oc}(t)$: global mean oceanic temperature rise wrt pre-industrial times (°C)

And λ: climate response parameter ($C^{-1}.W.m^{-2}$)
σ_1: transfert coefficient (set at 0.479 $C.W^{-1}.m^2$)
σ_2: transfert coefficient (set at 0.109 $C^{-1}.W.m^{-2}$)
σ_3: transfert coefficient (set at 0.131)

Climate sensitivity (T_{2x}) is given by $T_{2x} = F_{2X} / \lambda$. We assume that uncertainty is mainly due to uncertainty on (atmospheric) climate feedbacks process (represented by λ) rather than uncertainty on F_{2X}. A high climate response parameter will lead to a low climate sensitivity. We explore three values for climate sensitivity and λ is set accordingly to F_{2x}/T_{2X} see following table:

State of the World	*LOW*	*CENTRAL*	*HIGH*
Climate sensitivity (T_{2x})	2.5°C	3.5°C	4.5°C
Ex ante subjective probability (p_s)	1/6	2/3	1/6
λ	1,484	1,06	0,824444

A.5. Numerical resolution

To avoid boundary effects, we did not specify terminal conditions in 2100 but set the time horizon of the model at 2300. All the models have been run under the GAMS-MINOS non-linear solver. The model codes are available from the authors on request.

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