Quasi-Option Value and Climate Policy Choices

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SUMMARY

In the climate change issue, the environmental irreversibility (risk of an acceleration of mitigation policies if the worse happen) has to be balanced with the investment irreversibility (risk of over-cautious policies). To explore this balance, we define an option value for a precautionary climate policy. Using the simplest decision-making model, we expose how option value relates to the expected value of future information. Using quantitative data from an integrated assessment model, we find that most of the times the environmental irreversibility dominates the investment irreversibility. For all cases explored here, the order of magnitude of the option value was significant, about 50% of the opportunity cost.

KEYWORDS

Option value, Climate change, Irreversibility

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1 Introduction: The twofold irreversibility issue

The United Nation Framework Convention on Climate Change objective suggests to consider a "safety ceiling" for greenhouse gases concentration over which irreversible damage would occur. From a practical point of view, the accumulation of greenhouse gases in the atmosphere can indeed be regarded as irreversible: at the human generation timescale concentrations levels can only increase. The problem is that no safe ceiling is specified, as the Intergovernmental Panel on Climate Change (IPCC) recognises. Yet, doing nothing means giving up the option of reaching the lowest stabilisation levels.

For example, stabilisation of CO_2 concentration at 400 ppmv has already become an unrealistic goal. It will be the same for 450 ppmv in a couple of decades if present trends continue. The range in the estimates of climate sensitivity[1], used in (I 1997) is +1.5C to +4.5C. The combination of environmental irreversibility with unexpected bad news from climate science could lead to the need of a sudden acceleration of adaptation and mitigation policies. We would then consider the dilemma of choosing between economically disruptive policy measures, or face unfavourable climatic changes.

The interplay between irreversibility and uncertainty has been a central issue in environmental economics, since Henry (1974) and Arrow & Fisher (1974) demonstrated the existence of an 'Irreversibility Effect' in 1974. Historically, this has been illustrated by analysing the economics of a hydroelectric dam construction project that would flood a beautiful natural valley. Such a project is irreversible for two reasons: one is the destruction of the valleys ecosystems, the second has to do with the irrecoverability of the investment in the building itself.

These two reasons converge to imply that before starting the project, waiting to have more information is valuable. Historically, the irreversibility effect states that:

> Independently of risk aversion, the standard cost-benefit analysis, which omits this value of information, is biased against environmental preservation.

But in the climate change issue environmental preservation (that is, early CO_2 emission control efforts) needs investment, whereas environmental exploitation corresponds to business as usual. Consequently, the two irreversibilities outlined above do not converge but have opposite effects, as stated by IPCC(Bruce, Lee & Haites 1996, SPM, par.2):

> Uncertainties remain which are relevant to judgement of what constitutes dangerous anthropogenic interference with the climate system and what needs to be done to prevent such interference. [...] The challenge is not to find the best policy today for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information.
>
> Earlier mitigation action may increase flexibility in moving toward stabilisation of atmospheric concentrations of greenhouse gases. The choice of abatement paths involves balancing the economic risks of rapid abatement

[1] The long term (equilibrium) change in global mean surface temperature following a doubling of atmospheric equivalent CO_2 concentration, noted ΔT_{2x}

now (that premature capital stock retirement will later be proven unnecessary), against the corresponding risks of delay (that more rapid reduction will then be required, necessitating premature retirement of future capital).

The investment irreversibility effect (Dixit & Pindyck 1994, esp. pp. 412–418) sets a brake to climate change mitigation policies. It implies that waiting to have more information is valuable, to avoid the risk of overprotecting the environment. The goal of this paper is to examine analytically and empirically the balance between environmental and investment irreversibility.

In the sequel of this introduction, I will examine how the literature has developed the initial intuition into different theoretical and applied directions. Theoretical developments surveyed by Graham-Tomasi (1995) lead to a more general definition of the irreversibility effect, that:

Better information leads to more flexible choices.

Explaining how "more flexibility" and "better information" have been represented helps to understand how this general definition extends the first one stated above, and to set the relative position of this paper.

Perfect irreversibility can rather clearly be seen as a limit case of very low flexibility. Mathematically, the former is often represented with inequality constraints. The latter can be represented in many more different ways such as: (a) ordering on the size of reachable sets, (b) accumulation and decay dynamics of a natural resource stock (c) adjustment costs. This paper will not use perfect irreversibility, but rather flexibility aspects (b) and (c).

There are many ways to define and represent what a better information is. One approach uses Bayesian considerations and orderings between information structures. I will remain here at a simpler level by assuming that all uncertainties are resolved at once at a date T, and that better information means an earlier T. This framework allows to identify three trends in the litterature to date :

- The sensitivity of results to an earlier resolution of uncertainties has been assessed in most stochastic models on the economics of climate change by comparing, for example, results with $T = 2020$ to results with $T = 2010$.

- A second point of view focuses on the expected value of perfect information (EVPI). This amounts to compute the difference between the expected total cost assuming $T = 2020$ (a case named the Act Then Learn hypothesis) with the total cost assuming $T = today$ (a case named Learn Then Act).

  Developing this approach, Manne & Richels (1992, p. 73) were pioneers in introducing sequential decision making in climate change models. Using GLOBAL 2100, they computed the optimal hedging strategy given a stochastic CO_2 emissions reduction target. Yet, the methodology they used does not separate the pure effect of hedging from changes in expected target.

  They assumed that the target could take one of three values: -50% from the 1990 emission level with probability 16%; -20% (probability 24%) and no restriction with probability 60%. Using this value, it would have been interesting to compare the optimal hedging strategy with the optimal policy assuming the average constraint, that is -12.8% reduction target known from the start.

- That idea is precisely what the option value approach is about: comparing the case $T = 2020$ with the case $T = infinity$[2]. The former case, $T = 2020$, does correspond to the Act Then Learn hypothesis. The latter could be named the Never Learn hypothesis, after Peck & Teisberg (1993). Here I will use a different vocabulary, and refer to $T = 2020$ as the *sequential decision framework*, and the other the *one shot decision framework*.

Theoretical research has shown the existence of wide classes of decision problems for which we knew a priori that the irreversibility effect holds. Earlier T leads to more flexible near term choices. Building upon this intuition, applied literature takes a logically different stance. The irreversibility effect can be used as a principle to interpret a model's results. It allows to explain intuitively what happens to the optimal near term choice when T is earlier.

Let us consider a model of the economics of climate change computing the optimal near term $\mathrm{CO_2}$ emissions reduction α under uncertainty. The sensitivity of α to T may be interpreted as the results of the trade off between the two irreversibility effects. If, for example, a model finds that the perspective of a better future information leads to a stricter control of $\mathrm{CO_2}$ emissions in the next decades, then for that model it may be asserted that the environmental irreversibility effect is stronger than the investment irreversibility effect.

The IPCC statement that "the uncertainty-based cost-benefit assessments completed thus far find higher optimal rates of abatement than do the deterministic cost-benefit models"(Bruce et al. 1996, ch. 10 sum., p. 372), seems to put forward the environmental irreversibility effect. Yet it depends essentially on an inter-model comparison, and as such does not allow to conclude decisively. A closer look at the irreversibility effect in the climate change issue literature shows indeed that published results cover the whole possibilities:

- Nordhaus (1994) finds that introducing uncertainty in DICE increases optimal control rates by about 50%. This supports the idea that the environmental irreversibility effect matters.

- On the contrary, Kolstad (1994), using a stochastic version of the DICE model, suggests rather that

  > The irreversibility of investment capital has a stronger effect than irreversibilites in climate change (other than catastrophic effects).

  These results are confirmed by Ulph & Ulph (1997), who find that

[2]When $T = infinity$, learning never occurs, so the payoffs take their expected value. This idea is close to but different from the notion of certainty equivalent, the case defined by "$T = infinity$ and all parameters take their expected value". Both can be used as surrogates for the stochastic $T = 2020$ case (Simon 1956).

> For most parameters values, current abatement of emissions of greenhouse gases should be lower when we allow for the possibility of obtaining better information.

- In between, Peck & Teisberg (1993, fig. 9 and 10), found that regarding CO_2 emission in the short run, 20 or 40 years,

  > optimal policies are roughly the same regardless of how uncertainties are resolved.

In sum, it appears that empirical results to date are far from unanimously justifying the political concern over the risks of environmental irreversibility, the precautionary principle. Beyond methodological issues with integrated assessment, which should not be neglected, different reasons could explain this discrepancy. We cannot exclude a priori that the two irreversibility risks are large but balanced, so that the net effect may be actually small. Another point we have to consider here is that the irreversibility effect is not the only component of option value supporting the precautionary principle.

- For the sake of clarity, *risk aversion*, which leads to the more general questions of intergenerational and interregional decision making, was deliberately not included in the model defined below. This is the reason why the option value in this model is only a quasi-option value when viewed from a more general point of view.

- An important component of quasi-option value not studied in this paper has been named *dependant learning* by Fisher & Hanemann (1987):

  > It surely require no algebra to show that, if the information about the consequences of an irreversible development action can be obtained only by undertaking development, this strengthen the case for some development.

  Less CO_2 emissions would slow the rise of the climate change signal over the climate natural variability noise. But this effect, which supports pollution, may actually be small given that even under the most extreme reduction proposals to date, the concentration reduction is only 12 ppmv in 2020, a small figure compared to the difference between the 400ppmv expected at that date and the preindustrial CO_2 concentration of about 280 ppmv. On the other hand, emission control policies are likely to bring significant scientific, technical and institutional learning. Thus, it appears that the effects of dependant learning are also ambiguous in the case of climate change.

Here, I focus on the irreversibility effect and option value theory applied to CO_2 emissions policies. In the next section, I wish to frame the discussion theoretically by highlighting the notion of the expected value of future information. Then, I will examine empirically under which hypothesis one irreversibility dominates the other, and if the net irreversibility effect is significant.

The approach to analysing the climate change issue followed in the paper is intertemporal optimisation: seeking an emission strategy x which minimizes the total cost. Within this methodology, the model presented here uses stochastic discrete choices decision framework. This may be original. To date, discrete choices analysis between predefined pathways has been led in (Wigley, Richels & Edmonds 1996) without uncertainty; while in the other hand most integrated assessment models with uncertainty used continuous choices, taking feasible x to be any arbitrary non negative function of time (Nordhaus 1994), (Manne & Richels 1992).

2 Analysing climate policy choices with the expected value of future information

Figure 1 illustrates the two stages, binary choices decision problem considered here. In a very stylised way, the issue boils down to a near term choice and a long term choice, each being between two alternatives only. Thus, the climate policy issue is represented by a choice x between four alternatives.

- The near term choice, α, corresponds to the effort of CO_2 emission abatement in the next two decades. It models the discussion about the timing of CO_2 emission abatement (IPCC 1995) known as the WGI vs. WRE[3]controversy. An aggressive reduction policy is represented by $\alpha = WGI$, whereas a policy that lead to emissions remaining close to business-as-usual for two decades are represented by $\alpha = WRE$.

- The long term choice, made in 2020 in the emissions profiles used here, regards the level of the ceiling of atmospheric CO_2 concentration. Stabilising at 450 ppmv would ask more efforts than at 550, but would lead to lower climate change impacts[4].

- Overall, these climate impacts depend upon a stochastic variable $\tilde{a}$, which can be either high or low[5]. The probability p of high damages a^+ , and the probability $1-p$ of low damages a^-, are assumed known from the start and independant of α.

I note $TC(\tilde{a}, x)$ the total cost, that is the sum of the reduction cost and the climate damage, to be minimised. As explained in the introduction, I adopt the option value approach, and thus consider two decision frameworks, denoted with the letter i:

- In the $i = oneshot$ decision case, it is assumed that policymakers act as if they did not expect to receive new factual elements to revise their decisions. Here,

[3]WGI stands for 'IPCC Working Group I', and WRE stands for Wigley et al. (1996).

[4]The problem is similar to a natural resource management issue by considering that the quality of the atmosphere, measured by how far the CO_2 concentration is away from 550 ppmv, is an unique environmental good. Choosing 450 is similar to preserving the resource. Choosing WRE in first period is irreversible as it decreases the quantity of resource available in second period.

[5]I will note $\bar{a} = pa^+ + (1-p)a^-$ the expected $\tilde{a}$, and $\mathsf{E}f(\tilde{a}) = pf(a^+) + (1-p)f(a^-)$ the expected value of any function $f(\tilde{a})$

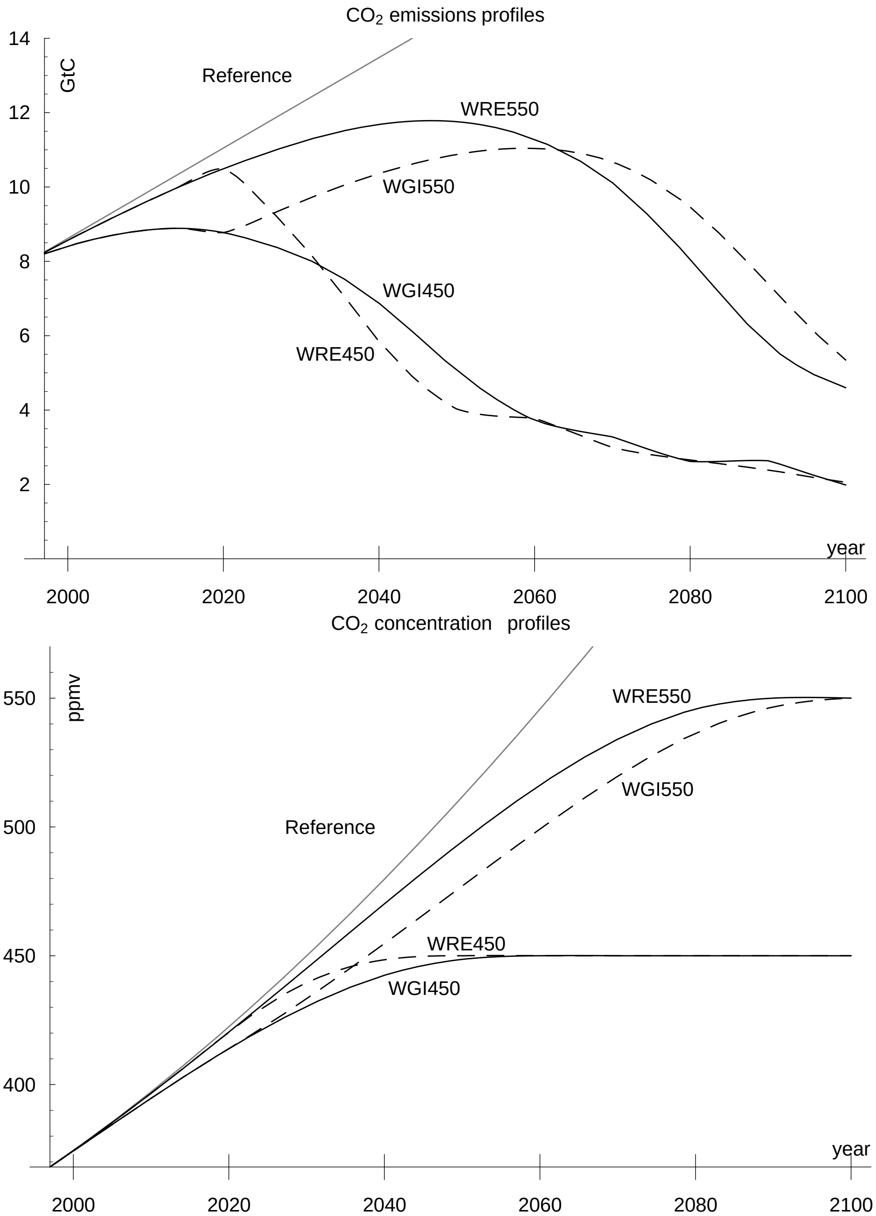

Figure 1: Four different CO_2 scenarios for next century

These four time profiles are defined here to represent the WGI vs. WRE controversy. They were computed by minimising the total emission reduction cost, as specified Box 2, under the following constraints:

WRE550 respects the concentration ceiling $M_t \leq 550$

WGI450 respects the concentration ceiling $M_t \leq 450$

WRE450 respects the ceiling $M_t \leq 450$ and coincide with WRE550 for $t \leq 2020$

WGI550 respects the ceiling $M_t \leq 550$ and coincide with WGI450 for $t \leq 2020$

short term decisions are not influenced by the fact that, in the long run, choices will adapt as we learn more about the climate and socio-economic system. Thus, analysing the expected costs and benefits is enough.

- In the $i = sequential$ decisions case, it is assumed that policymakers defer the long term decision until technical and scientific knowledge is available (here in $T = 2020$).

The difference between these two decision frameworks can be illustrated considering that there is today a non zero probability for a dramatic surprise implying that climate damages are more extreme than expected. The first case assumes that such probability will not be revised between now and T. Conversely, the second assumes that new information will allow to be more conclusive about extreme damages before T.

Because it considers only an average case, the one shot decision framework is analytically easier to handle than the sequential framework. Yet, policymakers have learned a lot from climate sciences over the last 20 years, and probably can expect to learn much more before 2020. Thus sequential decision, although more technical to formalise as it relies on stochastic dynamic programming, is maybe a more accurate description of reality.

Figure 2 shows how these two decision problems can be solved using backward induction. The results appearing row c are the $ExpectedCost_i(\alpha)$. Before elaborating with these somewhat complicated expressions, let us review some basic elements of the option value theory.

The four $ExpectedCost_i(\alpha)$ fits into two middle rows, two middle columns of Table 1. Notice that they are laid out exactly as in Figure 2 row c, with $i = sequential$ to the left, $i = oneshot$ to the right, $\alpha = WRE$ top and $\alpha = WGI$ bottom. This table allows a convenient definition of the key notions of opportunity costs, expected value of future information, and option value.

For a given decision framework i, the rational near-term decision is to choose the α which lead to the lower $ExpectedCost_i$. This comparison can be done by examining the sign of the opportunity costs, defined by reading the table vertically, for each the information case i. As set in Equation 1, the opportunity cost of the WGI strategy is the difference between its expected total costs and the cost of the alternative WRE strategy. That opportunity cost is positive when and only when WRE is a better choice than WGI.

$$OpportunityCost_i(WGI) = ExpectedCost_i(WGI) - ExpectedCost_i(WRE) \tag{1}$$

Equation 2 defines the expected value of future information (EVFI), as the difference expected cost one shot minus expected cost sequential. This appears Table 1 horizontally. It is intuitive that EVFI is always positive[6]. To stress that EVFI is conditional

[6] Mathematically, this can be demonstrated by using the results on Figure 2 and the fact that for any (x_1, x_2, x_3, x_4) we have:

$$\min(x_1, x_2) + \min(x_3, x_4) \leq \min(x_1 + x_3, x_2 + x_4)$$

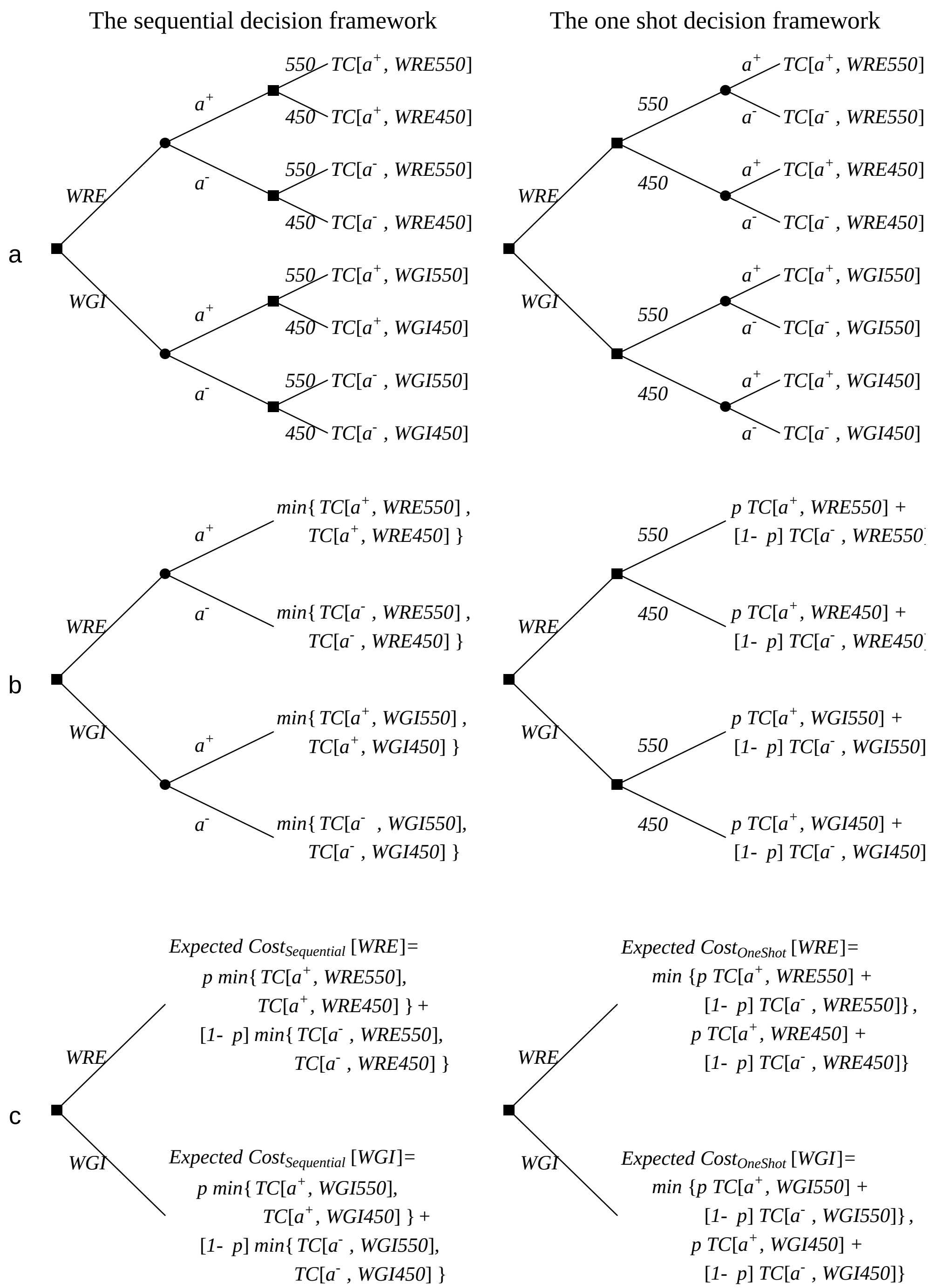

Figure 2: WRE vs. WGI decision analysis

Columns read from top to bottom. The optimal strategy that minimises expected total cost is computed using the algorithm of averaging-out-and-folding-back. The little black squares represent nodes of the decision tree under the control of the decision maker, and little black discs represent stochastic nodes. More on dynamic programming can be found in (Bruce et al. 1996, par. 2.3.1, p. 62).

	Sequential	One shot	difference $oneshot - sequential$
WRE	$ExpectedCost_{sequential}$(WRE)	$ExpectedCost_{oneshot}$(WRE)	Expected Value of Future Information(WRE)
WGI	$ExpectedCost_{sequential}$(WGI)	$ExpectedCost_{oneshot}$(WGI)	Expected Value of Future Information(WGI)
difference $WGI - WRE$	$OpportunityCost_{sequential}(WGI)$	$OpportunityCost_{oneshot}(WGI)$	Option Value(WGI)

Table 1: Option Value and conditional Expected Value of Future Information
This table allows to read the definition of (quasi-)option value (lower right) in two ways, either as the difference in Opportunity Costs or as a difference in expected value of future information. Since it represents costs (utility losses) and not values (utility gains), we consider the difference one shot minus sequential, contrary to (Fisher & Hanemann 1987).

to what near term choice α we consider (WGI or WRE), I will note it $\mathrm{EVFI}(\alpha)$.

$$\mathrm{EVFI}(\alpha) = \mathrm{ExpectedCost}_{\mathrm{oneshot}}(\alpha) - \mathrm{ExpectedCost}_{\mathrm{sequential}}(\alpha) \qquad (2)$$

Equation 3 is a classical definition of option value. It corresponds to the bottom right cell in Table 1 , as the difference of the two cells to its left. By definition, $OV(WGI)$ is positive whenever $OpportunityCost_{oneshot}(WGI)$ is greater than $OpportunityCost_{sequential}(WGI)$. In this situation, conventional cost-benefit analysis (set in a one shot framework) overestimate WGI opportunity cost, when compared to the real-world sequential decision framework.

$$OV(WGI) = OpportunityCost_{oneshot}(WGI) - OpportunityCost_{sequential}(WGI) \qquad (3)$$

Equation 4 is another definition of OV, which is equivalent to Equation 3, as one can see by reading Table 1 row first instead of columns first. Fisher & Hanemann (1990) stated that equality by saying

> the option value is a conditional value of information.

$$OV(WGI) = \mathrm{EVFI(WGI)} - \mathrm{EVFI(WRE)} \qquad (4)$$

Finally, let us define Equation 5 the relative importance of the option value. Note that this ratio r is not theoretically limited between zero and one, but can take any value, positive or negative from zero to infinity. This is related to the fact that the expected value of future information, and therefore option value, depends only upon to the future benefit of flexibility, but not upon its near-term cost.

$$r = \frac{OV(\alpha)}{OpportunityCost_{oneshot}(\alpha)} \qquad (5)$$

In this ratio, the sign of the numerator shows which of the two irreversibility effects is larger. The sign of the denominator shows which choice would appear optimal in a traditional (one shot) cost benefit analysis framework. Whenever $r < 0$, the irreversibility effects tends to support the result of the one shot analysis. When $r = 0$, there is no option value. For r in $]0, 1[$, the option value decreases the advantage of the one shot analysis optimal choice it. At $r = 1$, the sequential decision maker would be indifferent between the two alternatives WRE and WGI. Its only when r lies above one, that the two decision frameworks would lead to choosing a different near term alternative.

Although to date, option value has played a central role in the literature, I may conjecture that $\mathrm{EVFI}(\alpha)$ will turn out to be a more operational concept than $OV(\alpha)$ for the following five theoretical and practical reasons.

1. The EVFI approach allows to give a quick proof of the irreversibility effect, based upon the positiveness of EVFI[7].

2. Empirically, Fisher & Hanemann (1990) proposed some ways to estimate $\mathrm{EVFI}(\alpha)$. This contrasts with the conceptual difficulties with estimating OV using Equation 3, paradoxical in the way that, as Favereau (1991) notes,

   > If the agent can compute it, then he does not need it. If he needs it, he can not compute it.

3. The words *value of future information* may be more self explaining than *option value*, and having a clear vocabulary could help economists to deliver a clear message to policy makers. This is all the more important that the distinction between option values and quasi-option values is rather subtle (Bruce et al. 1996, par. 5.5.2).

4. A central hypothesis to prove the positiveness of $OV(\alpha)$ is that the resolution of uncertainties is independent of whatever choice has been made in first period. The option value concept tends to obscure that hypothesis, and hides the fact that it is the perspective of learning new information that is critical with regard to irreversibility, not uncertainties in themselves. If we did not expect to be better informed tomorrow[8], there would be no advantage to invest in flexibility today. The EVFI is explicit on all this: a choice a giving more information will lead to a higher $\mathrm{EVFI}(\alpha)$.

5. The option value is a difference, and as such it is only defined as long as a choice α is compared to another irreversible choice β. On the contrary, $\mathrm{EVFI}(\alpha)$ is intrinsic, it depends only of the choice a being examined. This implies that $\mathrm{EVFI}(\alpha)$ can be used to compare symmetrically any number of alternatives,

[7] By proving the irreversibility effect, we mean to show that if an alternative α is irreversible, then the option value of the opposite alternative is positive.

Let us assume that, for example, the WRE450 path is infinitely costly. In the framework described here, if WRE is followed now, there will be no other alternative in 2020 than to aim at 550 ppmv. This can be interpreted as resource exploitation in first period (i.e. WRE) is an irreversible choice (i.e. 450 is no more reachable). In this case, no decision will be needed in 2020, and therefore future information has no value: EVFI(WRE) is zero.

Mathematically, if $TC(a, WRE450)$ is large enough, then $\mathrm{EVFI(WRE)} = 0$ because for both i we have:

$Expectedcost_i(WRE) = pTC(a^+, WRE550) + (1-p)TC(a^-, WRE550)$

In this situation, $OV(WGI)$ = EVFI(WGI), and since we know that the EVFI is always positive, so is option value.

with no need to give a special attention to the irreversible one (if it exists). This workaround the arbitrary pick up of a baseline reference scenario, which is recognised to be one of the biggest methodological difficulty for a long term issue such as climate change.

Let us now analyse the EVFI by making more explicit the costs and the benefits associated with climate change policies. Results of Figure 2 row c with Equation 2 imply:

$$\mathrm{EVFI}(\alpha) = \min\big(\mathsf{E}\mathrm{TC}(\tilde{a}, \alpha 550), \mathsf{E}\mathrm{TC}(\tilde{a}, \alpha 450)\big) - \mathsf{E}\min\big(\mathrm{TC}(\tilde{a}, \alpha 550), \mathrm{TC}(\tilde{a}, \alpha 450)\big) \tag{6}$$

Now assume explicitly that, for a given emission trajectory x, the total cost is the sum of deterministic reduction costs and stochastic climate change impacts:

$$TC(\tilde{a}, x) = ReductionCost(x) + Impact(\tilde{a}, x) \tag{7}$$

The critical variables for the discussion are the future opportunity costs (the cost difference between the 450 ppmv and the 550 ppmv scenario) and benefits (the additional avoided climate damage). These future opportunity costs $C(\alpha)$ are conditional to the near term policy α. Formally, they are defined as:

$$C(\alpha) =_{def} ReductionCost(\alpha 450) - ReductionCost(\alpha 550) \tag{8}$$

Assume that the future opportunity benefits $\tilde{B}$ depends not significantly upon the near term policy α. This approximation is made to clarify the exposition, but is not essential and was not used in numeric results shown at the end of this paper (Figure 5).

$$\tilde{B} =_{def} Impact(\tilde{a}, \alpha 550) - Impact(\tilde{a}, \alpha 450) \tag{9}$$

A few calculations omitted here allow to rewrite Equation 6 in a more compact form:

$$\mathrm{EVFI}(\alpha) = \min\big(\mathsf{E}\tilde{\mathrm{B}}, \mathrm{C}(\alpha)\big) - \mathsf{E}\min\big(\tilde{\mathrm{B}}, \mathrm{C}(\alpha)\big) \tag{10}$$

This expression can be regarded as a function of $C(\alpha)$, as plotted Figure 3. It appears that $\mathrm{EVFI}(\alpha) > 0$ whenever $C(\alpha)$ is within $]B^-, B^+[$, otherwise it is zero. The economic interpretation of that is the following: Future benefits $\tilde{B}$ of reaching the lower ceiling 450 ppmv is stochastic. Ex ante, before knowing the realised value B^- or B^+, comparing costs and benefits leads to three cases:

- If $C(\alpha)$ is lower than B^-, then we can already decide that after α, it will be interesting to aim at 450 ppmv.
- If $C(\alpha)$ is greater than B^+ , then we can already decide that after α, only 550 ppmv will be interesting.

[8] In the political agenda chaotic progress, climate change issue may suddenly receive a high priority even without significant new scientific findings. Learning about public and private preferences, and about technical change may be as decisive as learning about the ocean-atmosphere dynamics. Indeed, Mégie (1992) recalls that the most important policy measures against the hole in the ozone layer have been adopted at the time of greatest scientific uncertainties.

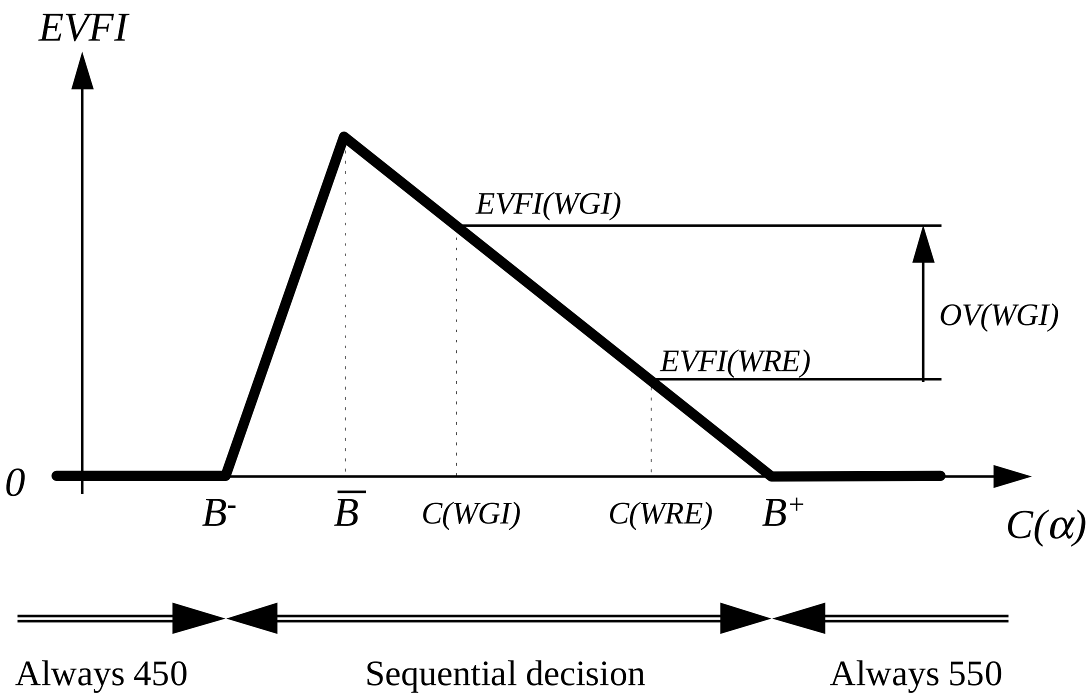

Figure 3: Value of information

Figure shows the expected value of information EVFI(α) as a function of the cost $C(\alpha)$ compared to the stochastic benefits $\tilde{B}$. It is assumed here that uncertainty is multiplicative, that is $Impact(\tilde{a}, x) = \tilde{a}f(x)$. The EVFI is maximum when the cost exactly equals the expected benefit:

$$C(\alpha) = \overline{B} \Rightarrow \text{EVFI}* = \text{p}(1 - \text{p})\overline{\text{B}} \tag{11}$$

- Otherwise, $C(\alpha)$ is within the uncertainty range, and after α we will have to learn more about benefits of climate change mitigation $\tilde{B}$ before choosing a ceiling.

In the first two cases, the information on the level of climate damages is useless since we know already enough to define the optimal long term decision. It is only in the third situation that α is only the first step of a sequential decision strategy and that information has a value.

3 Comparing environmental and investment irreversibilities

As stated Equation 4, the option value here can be seen as the difference EVFI(WGI) minus EVFI(WRE). Consequently, Figure 3 allows to represent graphically how the

		A	B	C	
			$c_1 = WRE$		
		$C \leq B^-$	$B^- \leq C \leq B^+$	$B^+ \leq C$	
$c_1 = WGI$	$B^+ \leq C$			Only 550	**1**
	$B^- \leq C \leq B^+$		Controversial	Environmental Irreversibility	**2**
	$C \leq B^-$	Only 450	Investment Irreversibility	Two consistent views	**3**

Table 2: Qualitative analysis framework

This table is represent the possible outcomes of an a priori cost benefit analysis of the two-stages decision problem with uncertainty represented Figure 1. The assumption that $C(WRE)$ is greater than $C(WGI)$ excludes A1, A2 and B1. In C2, for example, it can be said that WGI is more flexible, since WRE is irreversible, and thus WGI option value is positive.

sign of the option value is determined. The situation described Figure 3 can be characterised by three key aspects:

1. From 2020 onwards, it will be less costly to achieve stabilisation at 450 ppmv if aggressive policies have been started early. It implies that the point corresponding to WRE is located to the right of the point corresponding to WGI or that $C(WRE) > C(WGI)$.

2. The expected damage $\bar{B}$ lies near the left of the interval, close to the low hypothesis damage B^-. This assessment of the subjective probability p is based upon the a real concern amongst climate scientist for the possibility of climate surprises, events of high consequences with low probability.

3. The decision making problem is always sequential, that is both $C(WRE)$ and $C(WGI)$ are within $]B^-, B^+[$, so that for both near term alternatives the EVPI is non zero.

The last two points combined implies that $C(WRE)$ and $C(WGI)$ are likely to lie between $\bar{B}$ and B^+. Combined with the first, they lead to the situation Figure 3, with EVPI(WGI) above EVPI(WRE). To the extend that these three points are typical, the option value of WGI is typically positive.

Discussing the third point leads to examine the different positions of $C(WRE)$ and $C(WGI)$ with respect to B^- and B^+. Given (1.) this leads to the six situations described Table 2. This table corresponds to Figure 4, which represents $OV(WGI)$ in the plane $(C(WRE), C(WGI))$.

In Figure 4, one notice at first sight the four flat square areas in the corners. These correspond to corner cells A1, C1, A3 and C3 in Table 2, and describe situations where

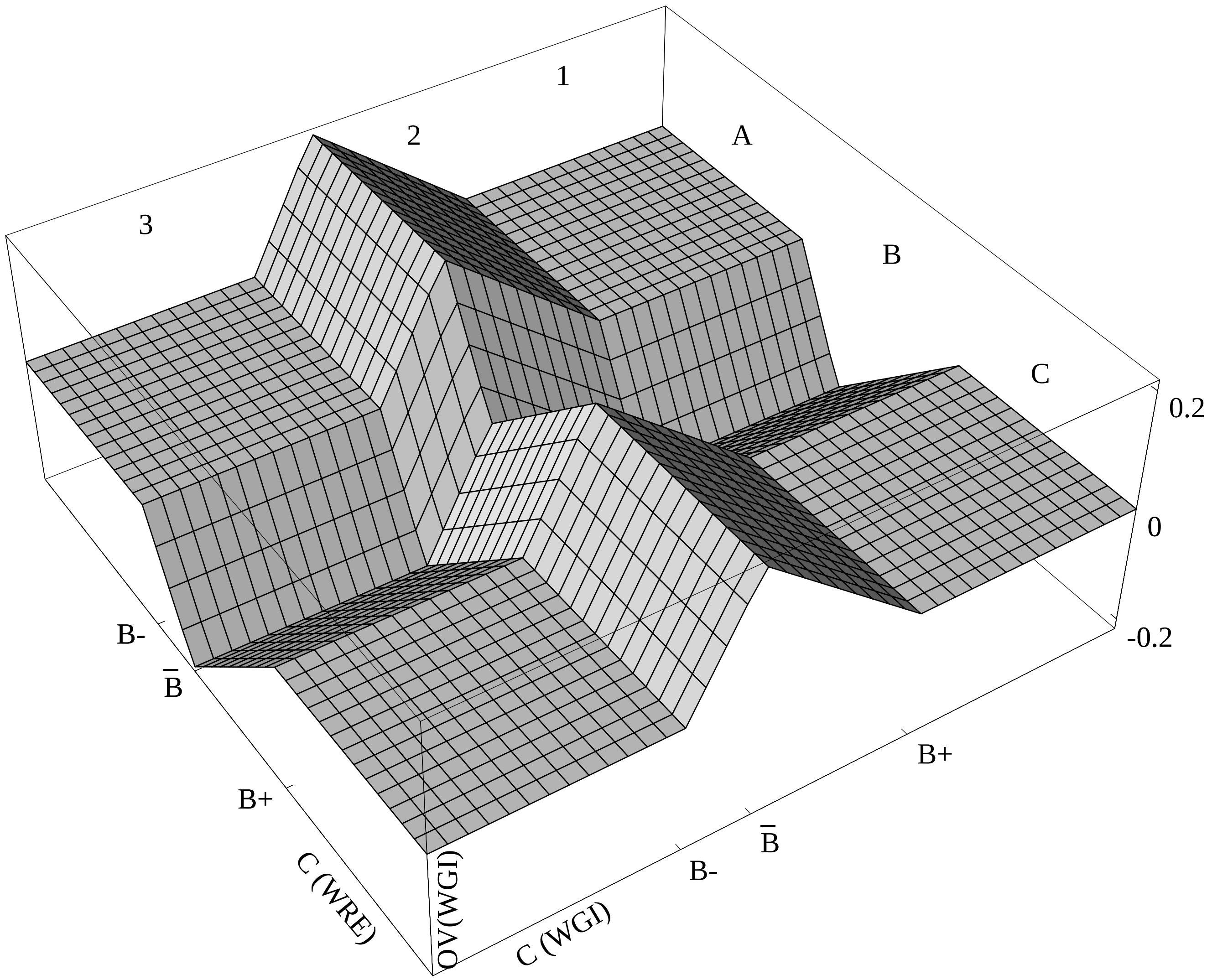

Figure 4: Difference of EVFI.

This figure shows the $OV(WGI)$, the option value of aggressive near term CO_2 emission reductions, in the plane $(C(WGI), C(WRE))$, see Figure 3. The nine areas corresponds to Table 2's nine cells. By definition, $C(\alpha)$ is the opportunity cost of reaching the 450 ppmv CO_2 concentration ceiling if we follow the α type of trajectory between now and 2020. Future opportunity benefits of reaching the 450 ppmv ceiling are: $B^- = 1$ and $B^+ = 2$, with a probability $p = 0.3$.

uncertainty does not matter at all, so the option value is zero. Even if climate damage $\tilde{B}$ is stochastic, we know already enough to decide.

Cell C3 corresponds to $B^+ \leq C(WRE)$ and $C(WGI) \leq B^-$. The first inequality means that if we choose today to delay $\mathrm{CO_2}$ reductions policies, we know we will choose in 2020 the 550 ppmv concentration target, whatever we learn about the climate damage. The second inequality, about WGI, means that if we choose aggressive near term reductions, then we will choose the low concentration ceiling in 2020. This describes a situation of mutually exclusive irreversibilities.

The environmental irreversibility effect situation corresponds to cell C2 in Table 2 and to the front hill in Figure 4. This is the situation described in footnote before, where we assumed that WRE could only lead to the 550 ppmv, and therefore was economically irreversible. In this situation, we see that the option value of WGI is positive. Cell B3 corresponds in the same way to the investment irreversibility effect. In the central area of Figure 4, corresponding to cell B2, the sign of the option value is not uniform. It describes the situation in which we may have to revise choices according to the new information in the future. In that situation, both environmental and investment irreversibilities have to be considered. I called this area decision under controversy situation in reference to (Hourcade, Salles & Théry 1992).

To explore further the issue, I used an explicit model of $\mathrm{CO_2}$ emissions abatement costs and climate damages, DIAM, in order to get a dollar value for $OV(WGI)$. I specify Equation 7 using functional forms summarised Figure 5. The most important economic parameters here are the discount rate r (4% per yr), the magnitude of climate damages at double $\mathrm{CO_2}$ equivalent d_{2x} (1.75% of Gross World Product) and an inertia parameter D (50 years).

That last parameter demands more explanation. Dimensional analysis of Equation 12 shows that D is a duration. It can be interpreted as the characteristic time of the socio economic system producing emission reductions, a critical parameter when considering the irreversibility of a system evolution. Following the EMF14 guidelines set by expert survey by Nordhaus (1995), I consider that in the high case, occurring with a probability $p = 10\%$, climate damages are 7.8 times higher than in the low case.

Table 3 shows the different parameters set examined and corresponding results. Given the wide range of parameters explored here, it is not surprising to find a wide range for option values. Let us begin by explaining the central case A.

- The opportunity cost of WGI appears to be positive in both the one shot and the sequential framework. This means that the WRE appears less costly than WGI.

- It appears that the cost is smaller in a sequential framework: the option value $OV(WGI)$ is positive but not large enough to reverse the decision in a binary choice situation.

- Quantitatively, the opportunity cost of WGI, evaluated at 0.5% of 1990 GWP in the one shot framework, is divided in two in the sequential decision making framework. This means that the option value is about 0.25% of 1990 GWP.

$$
\begin{aligned}
RedCost &= \sum_{t=t_0}^{2300} [(1+\rho+r)]^{t_0-t} c_a(D) \frac{E^{ref}(t)}{E^{ref}(t_0)} [x_t^2 + D^2(x_t - x_{t-1})^2] \quad (12) \\
Impact &= \tilde{a} \sum_{t=1997}^{2300} (1+\rho-s)^{t_0-t} d_{2x} \frac{M_{t-L} - M_0}{M_{2x} - M_0} \quad (13) \\
M_t &= M_t^{ref} - 0.471 \sum_{u=t_0}^{u=t-1} R_{t-u} x_u E_u^{ref} \quad (14)
\end{aligned}
$$

Figure 5: DIAM model of explicit reduction cost and climate damages

Following Ha-Duong, Grubb & Hourcade (1997), reduction costs and climate damages are discounted using a social risk-free rate r (4%). They are defined for an emission reduction pathway that abate the fraction $x(t)$ of the IS92a reference scenario $E_{ref}(t)$, so that actual emission level at date t is: $_{Eref}(t)(1 - x(t))$.

Reduction costs are determined (Equation 11) by a technical progress rate r (1%) and a characteristic time of energy systems D (50 years). The costs scale $c_a(D)$ is normalised ($c_a(50) = 1.36$, $c_a(20) = 3.18$) so that total cost is comparable to DICEs one (Nordhaus 1994).

Climate damages are determined (Equation 12) by a linear function of lagged concentration M_{t-L}, using a climatic inertia lag $L = 30$ years. Damages are set to be zero in $t_0 = 1997$, so $M_0 = M_{1967}$ (314 ppmv), and increasing at a rate of $s = 1\%$ per year (to capture the idea that damages increase with, but not as fast as, global wealth).

The reference calibration level for damages is set at $d_{2x} = 1.75\%$ of Gross World Product (GWP), for a doubling of CO_2 equivalent concentration $M_{2x} = 486$ ppmv.

Equation 13 defines CO_2 concentration at date t, using a linear perturbation model. Reference concentration path $M_{ref}(t)$ is computed from IS92a total carbon emissions. $R(u)$ is the atmospheric response function, and the 0.471 factor converts emissions in GtC to atmospheric concentrations in ppmv.

	Parameters						Results					
	a^+	$p(a^+)$	D	d_{2x}	ρ		EVFI(WGI)	EVFI(WRE)	$OV(WGI)$	$OC_{oneshot}$ (WRE)	$OC_{sequential}$ (WGI)	r
A	7.8	0.1	50	1.75	0.04	A	2.89	2.64	0.25	0.51	0.26	50%
B	-	-	20	-	-	B	2.82	3.12	-0.30	-0.56	-0.26	54%
C	-	-	200	-	-	C	2.94	2.31	0.63	1.24	0.61	21%
D	-	-	-	-	0.05	D	0.61	0.14	0.47	2.12	1.66	22%
E	-	-	-	-	0.03	E	0.00	9.35	-9.35	-13.3	-3.99	70%
F	-	-	-	2.50	-	F	3.07	4.69	-1.63	-2.41	-0.79	67%
G	-	-	-	1.04	-	G	1.29	0.70	0.59	1.84	1.24	32%
H	3.9	-	-	-	-	H	0.91	0.24	0.67	1.27	0.60	53%
I	-	0.5	-	-	-	I	2.79	7.69	-4.89	-10.9	-6.05	45%
J	-	0.02	-	-	-	J	0.58	0.53	0.05	1.57	1.52	3%

-: same as case A

Table 3: Sensitivity analysis of WGI option value.

Parameters: discount rate r ; overall magnitude of climate damages d_{2x} ; socio economic inertia D and magnitude of damages in the high hypothesis a^+ with probability p (low damages $a^- = 1$ everywhere).

Results: expected values of future information EVFI, the option value OV and r, and present opportunity cost OC . These are in % of Gross World Product, except r which is a relative value as defined Equation 5.

This result shows that the option value is in the same order of magnitude as opportunity costs. If I take 20.10^{12}\$ as an indicator of 1990 GWP, option value is about 50 billion dollars. This figure is comparable to expected values of present information (EVPI) in (Manne & Richels 1992, p. 85), and (Nordhaus & Propp 1997).

The fact that option value is significant compared to opportunity costs is confirmed by sensitivity tests B to J: Opportunity costs in the sequential and one shot frameworks do differ significantly across range of parameters studied here, with $r = 20\%$ to 70% (except for the low uncertainty case $p = 0.02$).

The option value for WGI is positive only in six cases out of ten. Explaining this gives the key intuition on the sign of option value. As defined Equation 1, the opportunity cost of WGI is the difference of total expected cost between WGI and WRE. Thus its absolute value $|OC_i(WGI)|$ can be regarded as the cost of a non optimal near-term choice, or the cost of error. Observe then that for all ten scenarios:

$$|OC_{sequential}(WGI)| < |OC_{oneshot}(WGI)|$$

With this in mind, Table 3 shows that the sign of the option value corresponds to the idea that adaptability tends to decrease the near-term stakes: in sequential decision making, the cost of errors is always lower than in the one shot framework.

Two other results appear from the table. First, all parameters set explored here but one describe the decision under controversy situation (cell B2 in Table 2), since the EVFI is non zero except in the E case. This is not as much a result than a check that the values of parameters explored here are consistent with the more general view that sequential decision matters.

Second, r is never above one, which means that quasi option value alone would not justify a change in the optimal near-term choice. This does not really weaken our central result on the importance of the option value, as it is obviously a direct consequence of the binary-choice decision framework used here.

Figure 6 represents Table 3 results. It allows to understand how option value depends upon parameters D, r, p and d_{2x}. Points representing Table 3 results are plotted over a top view of Figure 4 central area. All variations can be explained:

When the characteristic time of socio economic system D increases from 20 to 200 years, the point moves to the right from B to C. This means that higher inertia D significantly increases the costs of going to 450 ppmv if we start by following the WRE path, but has little effect if we follow WGI. This is because higher inertia D makes adjustments of the economic system more costly, a fact represented in Equation 12 by $D^2(x_t - x_{t-1})$. If we start on a WRE type of trajectory, then the costs of switching later to a strict concentration ceiling as 450 ppmv are mainly adjustment costs, directly sensitive to the inertia D. On the other hand, if we start of a WGI-like pathway, the adjustment costs are not so significant, so $C(WGI)$ is not so sensitive to D.

Lower discount rate or higher climate damages have the same effect: both points E and F are to the bottom left of A. This coincidence could have been expected, given that damages occur far in the future. The direction in which points move is also intuitive. Given that we project the results over a background where the damages remains fixed, an increase in damages is graphically represented as a decrease in reduction costs.

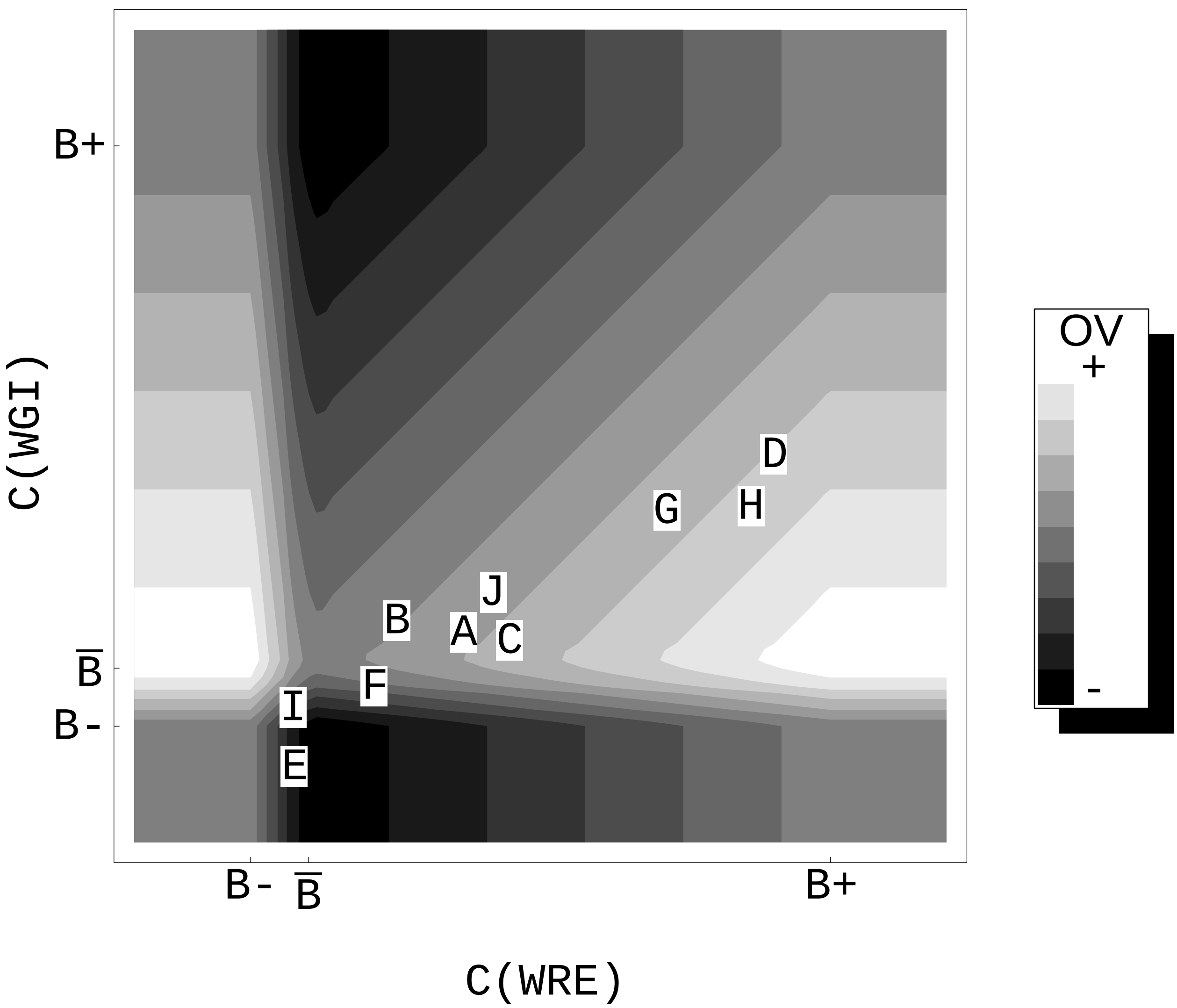

Figure 6: Empirical exploration of the most flexible choice.
The option value is represented by grey shades and contour lines. Points in clearer areas represents parameters set which lead to positive option value for early emission control. This figure corresponds to a top view of Figure 4, magnified over central area. Methodology: In the graphics background, probability for high damages is $p = 0.1$. The various $C(\alpha)$ and $B(\alpha)$ have been computed for each line of Table 3. Then the point (C(WRE), C(WGI)) was projected upon the background using the piecewise linear function mapping $\{0, B^-, \overline{B}, B^+\}$ onto $\{0, 1, 1.1, 2\}$.

The I case (high p) and J case (low p) illustrates Equation 11. Note that case C3 was not illustrated. This may be because there is no parameter to represent induced technical change in the model. Induced technical change has a direct effect on option value, since it decrease the cost of the long term environmental preservation (550) if and only if preservation action occur in the first period ($\alpha = WGI$). Figure 6, it moves the point to the South. To date, that critical aspect only begins to appear in integrated assessment models, and it is not unrelated to dependant learning.

4 Conclusions

This paper did not explore the effects of risk aversion and dependant learning. It outlined a methodology to compute a quasi-option value for environment preservation in the climate change issue, by comparing strategies involving aggressive near term $\mathrm{CO_2}$ emissions abatement with more moderate strategies.

The option value was defined as the variation of the expected value of future information between these two strategies. This allowed to examine qualitatively (Table 2) as well as numerically (Table 3) the balance between environmental irreversibility and investment irreversibility; and to evaluate whether the net irreversibility effect is significant.

The first result is that in the central case and for the majority of the parameters values explored here, the option value of early abatement is positive, that is the environnemental irreversibility effect dominates.

This supports the view that there is a large benefit in purchasing insurance against climate change by early action to mitigate greenhouse gases emissions.

More generally, numerical experiments found a positive option value for WGI when WRE was the least cost choice and vice versa. This supports the view that the effect of future adaptability is to decreases the cost of errors in near-term choices. This balanced result is not surprising, given that wide uncertainties remain with respect to the relative reduction, mitigation and climate damage costs and subjective probabilities.

The second result is that quasi-option value is very significant, about 50% of the cost. That was confirmed by all sensitivity tests carried out. Even if, framing the decision as a binary choice situation, the optimal near term choice was found to be the same for sequential or one shot framework, it remains that the opportunity cost of the alternative action is divided by a factor two in the sequential case.

This quantification of the magnitude of option value may be a relatively new result. I look forward to extend that analysis, as the discrete choices decision-making framework outlined here is rather general and could be used with other integrated assessment models. It has been widely said that uncertainties and irreversibilities should have important effects on policy choices (see for example (Int 1997)). These results confirm empirically that preserving flexibility is a policy objective to be ranked equally with the minimisation of reduction costs and the mitigation of climate damages.

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