IED
Working Paper 14
December 2010

Irreversibility and Optimal Timing of Climate Policy

Justin Caron and Markus Ohndorf

IED – Institute for
Environmental Decisions

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Irreversibility and Optimal Timing of Climate Policy

Justin Caron* and Markus Ohndorf**

* Economist - Chair of Energy Economics, ETH Zurich, Centre for Energy Policy and Economics (CEPE)
**Economist - Chair of Economics, ETH Zurich, Institute for Environmental Decisions (IED)

Abstract

We focus on the optimal timing of climate change mitigation policies, a decision which is complicated by multiple sources of irreversibility or inertia. The pertinence of Real Option Theory in understanding the optimal amount of necessary precautionary behavior is explored, as are the results from modeling exercises.

Generally, it appears that irreversibility associated with sunk abatement capital is stronger than that from accumulating greenhouse gas emissions, implying an "option value" to delaying climate change mitigation. The inclusion of tipping points, or non-linearities in environmental damages, could nevertheless lead to the opposite conclusion. These effects are however not easily quantifiable and are not generally included in modeling exercises. The timing decision will therefore have to be made by policy makers after having subjectively evaluated the importance of potential tipping points. It is for this reason that policy-makers need to be able to themselves understand the intuition behind Real Option theory - the interplay between irreversibility and uncertainty. Many climate-economic modeling exercises have implicitly recognized this fact by integrating strict environmental targets which serve as hard constraints and represent precautionary behavior.

Keywords: irreversibility, inertia, uncertainty, optimal timing, climate policy, real options

Acknowledgments

We acknowledge funding from the ClimPol project of the Competence Center Environment and Sustainability of the ETH Domain (CCES).

Furthermore, we gratefully acknowledge Renate Schubert, Helga Fehr-Duda, and Catharina Bening for useful comments and suggestions on a previous draft of this paper. All remaining errors are ours.

1 Introduction

Climate change is most probably the biggest global environmental externality that humanity will have to face in the next 100-200 years, as the associated net damages are potentially very large, and associated with possible tipping points. On the other hand, policies designed to mitigate climate change are also associated with large unrecoverable costs. Hence, any climate change mitigation policy will necessarily imply making, at some point, near irreversible decisions. Indeed, heavily investing in mitigation will imply sunk abatement costs as well as political and technological lock-ins. Not investing in any substantial mitigating action, conversely, might entail the transgression of tipping points, which would result in irreversible damages to environmental as well as human systems. The existence of these irreversibilities is particularly problematic if the uncertain damages resulting from different atmospheric GHG concentration levels are taken into account.

Generally, decision problems featuring irreversibility and uncertain outcomes are analyzed within the economic theory of Real option value. According to this theory, the two above-mentioned irreversibilities will affect the optimal timing of mitigation measures in opposite ways. The irreversibility linked to costly increases in pollution control capital establishes a case for delaying investment until more information is available about the efficiency of action. This line of argumentation is often used by proponents of a "learn-then-act" strategy. Conversely, the irreversibility of once-attained GHG concentrations and the associated damages would justify immediate action. Hence, to establish a case for either a 'learn-then-act' approach or an 'act-then-learn'-strategy, it is necessary to identify the relative strength these opposing effects.

A review of early models incorporating irreversibility to estimate optimal timing of climate policy indicates that the climate system is rather slow-changing, and that the stock externality component of the environmental irreversibilities does not decisively alter the optimal emissions path over time. However, these models do not include the possibility of tipping points in their analysis, which, will we see, leads to an "environmental option value".

However, more recent studies stress the importance of an additional class of environmental irreversibilities. These irreversibilities are associated with the transgression of systemic "tipping points" in different climate sub-systems. The inclusion of such non-linear effects could establish a strong case in favor of an 'act-then-learn'-strategy. Yet, the transgression of tipping points would have to be represented through the inclusion of singularities within the damage curve. This and the fact that the location, the impact and the probability of these effects are all very uncertain renders their direct consideration within a cost-benefit analysis particularly problematic. Hence, most integrated assessment models used to analyze the optimal timing of climate policy do not directly include such effects. It is, however, to emphasize that this does not alter the necessity to consider such events in an informed debate on optimal climate policy. For that reason, it is particularly useful, for analysts as well as policy makers, to understand the implications of Real Option theory. Indeed, the currently observable trend of using environmental targets (on GHG concentration levels or temperature) as hard constraints in integrated assessment models can be interpreted as a step into this direction. This is also reflected in recent developments in the political realm, where the stipulation of temperature targets have gained in importance.[1] In principle, this can be interpreted as a step towards a precautionary strategy with respect to potential environmental irreversibilities. Further formal justification for precautionary behavior can be found with the help of stochastic control models which find that, as long as we are unsure about the correct location of tipping points, we should aim for the most stringent environmental target. Such models can, in fact, be interpreted as a transfer of the implications of option value theory into a continuous action space.

In the the following we will first describe the problem of climate change mitigation as an investment decision made under uncertainty and irreversibility. We will then discuss how and to what extent this interpretation has been addressed in the literature on the optimal timing of climate policy. The paper is structured as follows. Section 2 discusses uncertainties and irreversibilities in the climate change context. Section 3 gives an overview over the literature on optimal climate policy as a real option problem. In section 4, we discuss the current methodological strategies to deal with the problem of large irreversibilities through the transgression of tipping points. Section 5 concludes.

2 Uncertainty and Irreversibility

Determining an 'optimal' climate policy is a complex endeavor. The underlying decision problems suffers from problems of intergenerational discounting, political feasibility, free-riding induced by its global public good nature, and the different potential means of implementation. As the main focus of this paper is its interpretation from a Real Options perspective, we will abstract from these problems and focus on the interplay between uncertainty and irreversibility in the climate policy context, which by itself already entails a considerable amount of complexity.

2.1 Uncertainty in Climate Policy Decisions

The definition of an optimal response to climate change requires a deep understanding of the behavior of two complex systems, earth's climate system and the global economy. Human capacity to predict the behavior of each of these systems alone, let alone the results of their interaction over the next 100 to 200 years, is limited. Yet, the basic elements of anthropogenic climate change are not challenged even by serious scientific skeptics. In fact, only the magnitude and timing of climate change are controversially discussed, not its existence.[2] Thus, rational policy-advice needs to develop responses that are capable of handling the uncertainty that is associated with climate change methodically.

As to the modeling of the mean global temperature on continental scales and above, there is considerable confidence in the quantitative estimates produced by such models. Still, uncertainty persists with respect to the most important variable, the level of the *climate sensitivity* that measures the response of the climate system to sustained radiative forcing caused by greenhouse gases.[3] While the model fun-

[1] At the Conferences of the Parties in Bali and Copenhagen, the members of the UNFCCC have in principle agreed to a temperature target of 2 degree Celsius. However, up to the present, no binding commitments were agreed to for the period after 2012.

[2] Such a naive political stance has been analyzed on the basis of simple logic by Brown (2002).

[3] The IPCC estimations of the average surface warming following a doubling of carbon dioxide concentrations are as follows: "It is likely [i.e. within a confidence interval of 66%] to be in the range 2 to $4.5\,^{\circ}C$ with a best estimate of about $3\,^{\circ}C$, and is very unlikely to be less than $1.5\,^{\circ}C$

damentals are based on established physical laws, and are supported by a growing number of observations, the climate system features many subsystems, the interrelations of which are still not fully understood.[4]

Climate sensitivity is, however, only one variable necessary to predict the consequences of human-induced climate change. Large uncertainties are also associated with the scope and timing of *future greenhouse gas emissions*. Conceptually, this source of uncertainty can be best understood by taking a look at the highest level of disaggregation of future emissions as reported by Fisher et al. (2007) in IPCC (2007a):

$$\text{Yearly Emissions } = \text{Population } \times \text{ GDP per person } \times \text{ Emissions per GDP} \quad (1)$$

Thus, in a long term view, future emissions depend on future *demographic development*, the *growth of global economic activity*, and the *greenhouse gas intensity of the economy*. The latter is primarily dependent on technological progress, especially within the field of energy generation. Even at this level of disaggregation it becomes apparent that all determinants of future emissions are associated with large uncertainties.

Climate models themselves are only capable to predict the scope of climate change and (some of) its impacts. An informed policy response, however, is only possible if the impacts due to unhampered climate change are rendered comparable to the welfare losses that are engendered by mitigation policies. In environmental economics it is standard to express both in monetary terms by attributing cost and benefits. The aim of such a cost-benefit analysis is to generate an optimal emissions path over time and the optimal emissions pricing scheme necessary to induce adherence to the path. Such an optimal pricing scheme over time is usually calculated by comparing the Social Cost of Carbon and the marginal abatement costs. Both are associated with additional uncertainty, part of which is difficult to quantify. Determining the Social Costs of Carbon requires a valuation of concrete impacts associated with the different levels of climate change. Thus, within this process there are two main sources of uncertainty. First, there is uncertainty in the *prediction of specific impacts* of climate change.[5] Second, there is considerable uncertainty in the *valuation of these impacts* in monetary terms.[7]

There exists also a considerable amount of uncertainty on the side of the abatement costs. These are crucially dependent on the technological progress in the field of less carbon-intensive technologies. Most cost-benefit analyses model technological progress exogenously by applying a learning rate with respect to technological

[i.e. with a probability of occurrence of less than 10%]. Values substantially higher than $4.5\,°C$ cannot be excluded, but agreement of models with observations is not as good for those values." IPCC (2007b)

[4]According to Randall et al. (2007) in IPCC (2007b) the largest uncertainty can be attributed to the various feedback mechanisms associated with water vapor and clouds. Other sources of uncertainty are the changing surface reflection of radiation (albedo), the ocean uptake of CO_2 and heat, and the stability of regional climatic phenomena, like the El Nino-Southern Oscillation.

[5]With increasing *geographic resolution* and inclusion of *complexer systems* the uncertainty becomes less structured, hence "deeper".(See Solomon et al. (2007) in IPCC (2007b)). Furthermore, the reliability of regional climatic projections over time is difficult to assess, as a validation of modeling results becomes more and more difficult with increasing complexity.[6]

[7]In particular, the valuation of *non-market goods* entails significant problems. Even more uncertain are, what Watkiss et al. (2005) call "socially contingent effects". Such effects, like regional conflicts or poverty and a possibly resulting regional collapse, potentially triggered by climate change are so vaguely understood that their occurrence and monetary valuation are 'purely' uncertain. See Watkiss et al. (2005) for a more thorough analysis of the different levels of uncertainty in the valuation of impacts.

progress steering the marginal cost of abatement. More recent modeling approaches also take a certain amount of endogenous technological change into account.[8] Obviously, there is large uncertainty associated with respect to this technological progress. This situation is comparable to a researcher in the 1950s supposed to forecast the arrival of the Internet.

Most of the literature focusing on optimal climate policy as a Real Option problem abstracts from the fact that the climate change problem is associated with multiple sources of uncertainty. These studies are usually based on the results from integrated assessment models providing a single probability distribution with respect to abatement costs and/or benefits. Most studies hence summarize uncertainty into one variable, which generally represents the uncertain effect of greenhouse gases on temperature levels. Alternatively, it sometimes represents uncertainty about the effect of temperature levels on economic damages, the uncertain baseline level of emissions, or all of these combined. An important, yet plausible, assumption within all of these analyses is that this uncertainty is bound to partially resolve over time, as the precision of climate models increases and more information is gathered about the technological costs of mitigation.

2.2 Irreversibilities in the Climate Change policy context

Determining an optimal emission reduction path under the above-mentioned uncertainties is further complicated by the fact that both abatement costs and environmental damages are associated with some level of irreversibility. Mitigation options that involve the replacement of non-amortized capital are necessarily associated with large adjustment costs that cannot be recovered if it turns out that the impact of non-mitigation will be small. This irreversibility of disinvesting part of the long-lived capital stock has its counterpart in the inertia of the climatic system: hysteresis or tipping points in the climate system might make some changes to it irreversible in nature.

As the concept of irreversibility is crucial to the Real Options approach, it is worthwhile to further investigate into its meaning. In economic terms, an investment is reversible if the system and environment affected by it can be "restored reproducibly".[9] Although irreversibility is, under a strict definition, essentially "a normal state of affairs" (Denbigh (1989)), economic science has only seriously started to recognize its relevance in two 1974 papers: Arrow and Fisher (1974), and Henry (1974).

There are two possible forms of irreversibility: in the first, an action directly modifies the environment in a way that directly limits future choices, in the other

[8]For an overview on the comparison of innovation models with endogenous technological change, see Edenhofer et al. (2006)

[9]The concept of irreversibility is complex and has long been studied by physicists, mathematicians and philosophers (see Earman (1986). Several definitions of irreversibility have been proposed. According to Denbigh (1989), irreversibility "is best defined as the negation of reversibility" where a process is said to be reversible if the system and environment which it affects can be "restored reproducibly". Or, otherwise said, irreversibility implies that "all relevant parts of the universe must be capable of being put back to how they were". This definition of reversibility is demanding, and Denbigh goes on to say that "complete reversibility is not actually attainable in the real world". Any process, then, is to some degree irreversible. This is largely due to irreversibility's link with time and motion. If the passage of time is considered to be irreversible, then any process evolving time is bound to be irreversible as well. Irreversibility, says Denbigh, has no spatial analogue, and is, therefore, hard to grasp. For many purposes, though, the "concept of reversibility remains a useful idealization".

the action affects another part of the relevant system in a "non-restorable" manner, which will indirectly affect future choice options. In both cases, it is not possible to restore initial conditions. Henry (1974) has defined a decision to be irreversible if it "significantly reduces for a long time the variety of choices that would be possible in the future". What is determinant, however, is not necessarily that the future options disappear, but that their economic benefit decreases. In short, and for most modeling purposes, irreversibilities can be interpreted as constraints on future alternatives which raise the cost of taking an (even partially) irreversible investment decision. Furthermore, it is to note that irreversibility need not be complete, in the sense that, with time, the systems might come back to their initial state. Such "limited-time" irreversibility will be our definition of "inertia" for the remainder of this paper.

The concept of irreversibility is often to be found in climate change related scientific and economic literature as well as in mainstream media articles. The literature (see Pindyck (2002), Pindyck (2007), Kolstad (1996) and others) has identified two major sources of irreversibility in the climate change policy problem. The first, which will be referred to as the "abatement capital irreversibility", stems from the necessary sunk costs that any policy will incur on society. These may be of technological nature, such as "locked-in" investment in a new technology, or of political nature, as some policies will be hard to back out of. Note that this form of irreversibility is common to most investment decisions. The second major source of irreversibility is in the damages to the global ecosystem incurred by an irreversible accumulation of emissions in the atmosphere, which can be subdivided into two categories. We will now describe these different sources of irreversibility in some detail.

2.2.1 Irreversibility in abatement capital

Mitigating climate change implies reducing the amount of anthropogenic emissions of GHGs. There is a variety of possible climate change mitigation policies available to policy-makers, some direct (emission trading markets, carbon taxes, subsidies, direct emission limitations), some indirect (investment in research and development) (See Aldy et al. (2003)). All of these require some form of costly investment on society's part. An emissions trading scheme, for example, should move industry away from carbon-intensive technologies to more costly carbon-neutral technologies. Without going into the details of possible replacement technologies, one can see they will all require changes in production and consumption patterns, as well as major shifts in energy-producing and energy-consuming infrastructure (such as buildings or roads). There are also strong linkages between the different elements of the energy supply systems which need to be taken into account as they might make transitioning more difficult. These elements are linked to the notion of path dependence. As with any investment, there will be necessary sunk costs which will not be recoverable in case the chosen technology is revealed inefficient in reducing GHG emissions, or in case such reductions are proven to be unnecessary. Moreover, there are many other forms of inertia in socioeconomic systems which could play a similar role, for example slow-moving political processes or slow-changing consumer preferences. All of these effects are hard to quantify and any estimate of both the cost of these policies and the inertia contained in them will be tied to huge uncertainties. However, as Pindyck (2007) argues, rough estimates of the costs of different abatement technologies are known. The "abatement cost" function is typically convex and can be reasonably assumed to be continuous. Hence, there are no obvious sources of singularities (or tipping points) which, as we will see below, are more plausible in the case of the damage function.

Note that the abatement capital irreversibility described in this section is actually common to most investment decisions and is not unique to climate-related issues. We now turn to a different class of effects which are grouped under the name of "environmental irreversibility". Much can be read about the possibility of anthropogenic greenhouse-gas (GHG) emissions causing irreversible changes to the global eco-system. There is a wide array of such potential changes which will be classified in the following into two categories: stock externalities and the transgression of tipping points.

Another possible effect of inertia in abatement capital, which goes in the opposite direction, would be potential learning-by-doing (LBD), in which investment in abatement capital implies reduced cost of that capital in subsequent periods. We will analyze how this counter-balances the abatement capital irreversibility.

2.2.2 Stock externality

From an economic standpoint, GHG emissions constitute a "stock externality": emissions accumulate in the atmosphere and only very slowly degrade. Otherwise said, the current level of GHG in the atmosphere is, on the short and medium terms, not recoverable (if one ignores possible but still uncertain carbon removing technologies such as ocean fertilization or Biochar). It is widely understood that many of the potential damages which could be caused by climate change increase with the concentration (or the stock) of GHG in the atmosphere, not the actual emissions. Mean global temperature increases, ice sheet melting, changes in weather patterns being common examples. These changes will continue even if emissions are reduced to zero, as the stock of GHG in the atmosphere will stay stable for long periods. Ice, for example, could continue melting long after concentration levels are stabilized. Therefore, it is justifiable to consider the emission of a unit of GHG into the atmosphere as a (partially) irreversible act, as this unit of GHG will not be removable. As we will see, most of the surveyed literature considers the stock externality effect as an irreversibility on the side of the damages, which are, however, considered to remain a monotonously increasing function of emissions. Yet, as will be argued below, the more recent modeling approaches implicitly consider another, more problematic set of irreversibilities, which are associated with the transgression of tipping points.

2.2.3 Hysteresis and tipping points

Obviously, human-induced climate change does not necessarily imply only phenomena that are continuous in greenhouse gas concentration levels. Climate scientists often stress that there exists a potential for 'abrupt' events, which could arise once global main temperature reaches specific tipping points in the climate system. The possible transgression of such tipping points represents an additional source of irreversibilities as the affected climate and biospheric systems feature multiple equilibria that are potentially unstable. As we will argue below, these irreversibilities are—more or less indirectly—taken into account in more recent cost-benefit considerations with respect to climate change. Yet, before introducing these approaches it is useful to understand the nature and potential extent of irreversibilities arising with the transgression of tipping points.

In general, the harder and faster a chaotic system is perturbed, the higher is the likelihood of system surprises.[10] In the context of climate change, potential surprises associated with an increase in global main temperature are manifold. The most prominent example is the slowdown or even the breakdown of the thermohaline circulation responsible for the gulf stream in the North Atlantic, which is driven by different levels of salinisation in the ocean. These levels might be affected by an increased freshwater influx from the melting of large amounts of the Greenland ice sheet. Such a slowdown could lead to larger changes in regional climate systems, a shift in the tropical rain belts, and an additional sea level rise of about 1m in the North Atlantic until 2100.[11] The climate system could potentially react abruptly due to several positive feedback mechanisms. Such feedbacks are for example associated with the collapse of the great ice sheets in the polar regions, changes in the reflective capacity of land cover (albedo), the release of methane hydrates in the deep ocean, the release of methane from permafrost soils, and changes in the equilibrium between vegetation and regional climate in Sub-Saharan Africa.[12] These positive feedbacks might lead to either an acceleration in change in temperature or in an increase of specific impacts which are not reflected in those Integrated Assessment models designed to provide a continuous damage function. Note that these events represent typically non-linear or 'abrupt' effects that might set the development of the regional or even the global climate onto an entirely different equilibrium path. Once a system is in a new equilibrium, it may not be possible to bring it back to the initial equilibrium even if the cause for the change, namely the increase in anthropogenic greenhouse gas emissions, has been reversed.[13]

Such irreversibilities based on changes in system equilibria will occur if pace and scope of change in global mean temperature lie above a specific threshold level, referred to as 'tipping point'. The tipping point for the collapse of the Greenland ice sheet lies, according to simulations in Gregory et al. (2004) and Ridley et al. (2005) within the region of an average temperature increase of $3\,^{\circ}C$. In the long term this would lead to an additional sea level rise of about 7m.[14]

2.2.4 Economic Damages with Tipping Points

The possibility of transgression of such a transgression of tipping points can, as we will see in the following section, lead to the emergence of a Real Option value. Let us now describe how this might be modeled in economic terms. The results of the analyses presented in the previous section are based on the assumption that the damage function of greenhouse gas emissions is continuous, monotonously increasing, and slightly convex. Yet, tipping points imply singularities within this function which might be approximated by locally-concave portions. For example, increasing concentrations might cause increasing damages up to a certain threshold, after which some subsystem switches to a new equilibrium.

[10] See, for example, Schneider (2004).
[11] See WBGU (2008).
[12] See Watkiss et al. (2005) and Schneider (2004).
[13] See Schneider (2004) or Heal and Kristrom (2002).
[14] The time frame within which such a complete meltdown would take place is according to WBGU (2008) quite uncertain. Hansen (2005) estimates the most probable time for complete meltdown to be about 1 to 3 centuries.

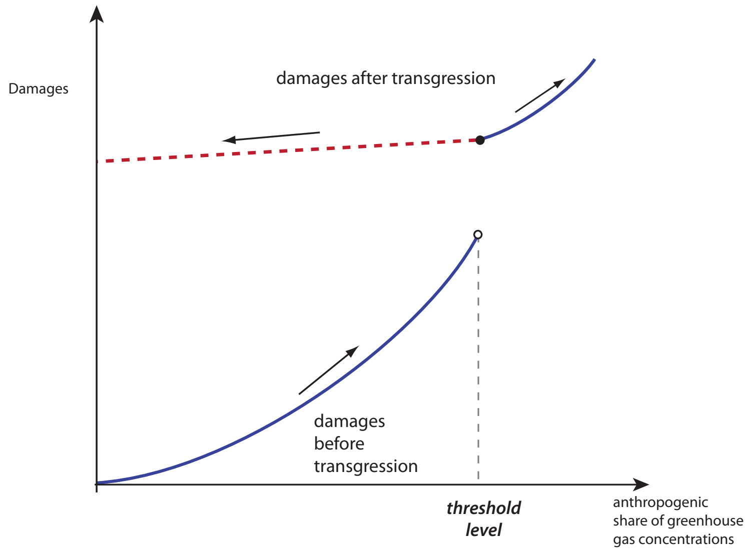

Figure 1: Stylized medium-term damage function with Tipping Point

However, as switches in equilibria can be persistent even if the anthropogenic share in atmospheric greenhouse gas concentrations decreases, this implies that the medium-term damage function for anthropogenic emissions might be significantly altered once a tipping point has been reached. Figure 1 shows a stylized representation of such an event.

Hence, as long as greenhouse gas concentration lie below a specific level, the damage function has the familiar, monotonously increasing and convex form. Yet, with the transgression of the tipping point, the damage function is shifted upwards and further increasing in concentration levels. A continuous approximation of such a mapping does yield an S-shaped damage curve. Such damage curves featuring local concavities are increasingly used in environmental and climate economics in order to adequately represent the problem of tipping point transgression.[15] Note that once the tipping point is transgressed, hysteresis of the climate system might also lead to an alteration of the short-term mapping of lower concentration levels. This would mean that once a critical concentration is reached, a reduction in concentrations does no longer lead to a substantial reduction in damages. For example, with a perturbed climate system, extreme weather events would continue to occur at a high rate for a longer time span, even if greenhouse gas concentrations decreased below the threshold level at which the perturbation was triggered. Such a shift in the damage function is represented in a stylized manner by the dotted line in figure 1. Note that the vulnerability of human systems to abrupt changes in the climate system might be reduced through investments in *Adaptation*, e.g. higher dykes against stronger storm tides. Such precautionary investments could hence reduce the potential damages, but would also have to be considered within an economic optimization.

[15] See for example Dumas and Ha-Duong (2004), Brock and Starrett (2003), Kossioris et al. (2008), and Kossioris et al. (2010)

3 Real Option Theory and Value of Future Information

Given the above-made considerations, the optimal timing of climate policy can be interpreted as an investment problem under uncertainty and irreversibility. These conditions typically lead to the existence of "quasi-option" values which have an influence on the optimal timing of implementing a policy (Arrow and Fisher (1974), Henry (1974), etc.). Indeed, by delaying an irreversible investment, one keeps the "option" to not invest if the uncertainty about the project's profitability resolves unfavorably ("bad-news principle", see Pindyck (2007)). On the other hand, if climate change leads to irreversible damages non-investment in abatement will also lead to a reduction in future policy options. Therefore, the sign of the aggregated option value—and hence the efficiency of immediate or delayed action—depends ultimately on the relative strength of all irreversibility effects involved.

A closely related concept to that of option value is that of Expected Value of Future Information (EVFI). It corresponds to the difference between the net present value of an investment when it is known how uncertainty will resolve- and therefore the optimal strategy can be chosen - and its net present value when the decision will have to be made under uncertainty. This value is positive if information helps making a more profitable decision, and if making the "wrong" decision is at least partially non-reversible. The concept of EVFI contains information which is analogous to the option value defined above, which corresponds to the difference in EVFIs between two strategies. However, Ha-Duong (1998) has conjectured that the concept of EVFI, although not as often used, might be preferable as it allows to explicitly describe the irreversibility effect embedded in a single strategy, whereas an option value is only defined as the comparison between two alternatives.

Most integrated assessment models (IAMs), designed for climate policy assessment, have not directly integrated irreversibility effects as they do not explicitly include resolving uncertainty or sequential decision making. They are inspired by cost benefit analysis and compute the optimal paths of emissions (or, equivalently, of abatement) as seen from a certain point in time without taking into account the fact that uncertainty will resolve or that the decision can be adjusted in time. Furthermore, most of the early models used convex environmental damage functions to calculate emission paths, and, therefore, do not explicitly represent environmental tipping points.[16]

Yet, There exists a growing strand of literature within which the option value of climate policy is being assessed (e.g. Kolstad (1996), Ulph and Ulph (1997), Ha-Duong (1998), Pindyck (2000), Fisher and Narain (2003)). Typically, this literature focuses on the first two irreversibilities presented in the previous section, i.e. those associated with tied-up abatement capital and the stock externality effect. However, the problem of environmental tipping points has been neglected within option value considerations.

We now review a range of models which explicitly focus on the two counterbalancing irreversibilities described above and incorporate sequential decision making in climate-economic assessment. For tractability reasons, they neglect many of the more complex system characteristics included in many IAMs. Typically, these models have been calibrated in order to empirically identify the relative strength of

[16]One of the predominant models of this class is Nordhaus' DICE model (Nordhaus (2007) being its latest version).

the two effects. This is done by comparing optimal abatement rates with different levels of reversibility. Alternatively, the focus is sometimes on the comparison of abatement rates in cases with and without learning, or resolving uncertainty (which only has an impact in case of irreversibility). Most of these models use cost and damage functions which are derived from the ones found in Nordhaus' DICE model (Nordhaus (1992)).

3.1 Models with one irreversibility

Manne and Richels (1992) have, with their GLOBAL2100 model, constructed what is to our knowledge the first large scale model with sequential decision making. In this model a decision is taken every 10 years, with the first two being made under uncertainty and the rest under full information. They estimate the value of a research program which would solve all uncertainties, which is unrealistic, but gives an upper bound to the value of information. They do not however directly model an environmental irreversibility effect, but consider a range of exogenous emissions constraints. Although their results are probably to be interpreted in a qualitative manner, they give an estimate of the range of values the EVFI may take: between zero and upwards of $100 billion (for the USA alone), depending on the probability of emission constraints being ultimately advantageous.

They then analyze the value of improved information using conditional probabilities. They model a research program which produces something less than perfect and something better than no information using a parameter which measures the accuracy of the forecast. They find the value of information to be an increasing and convex function of information accuracy. This is due to the fact that perfect information eliminates the need to hedge against surprises. As no environmental irreversibilities are present, the only effect comes from the abatement capital irreversibility, which pushes towards delaying abatement until uncertainty resolves in order to avoid the potential risk of having over-invested. This results suggests that information acquisition is preferred to precautionary emission reductions.

Manne and Richels (2005) conduct an analysis of the "when to abate" question with the use of the MERGE model. For non-market damages, MERGE is based on the conjecture that expected losses would increase quadratically with the temperature rise. But they admit that the parameters to be used in this function are highly speculative, which helps explain why there is no current international consensus on climate policy. They compare act-then-learn to learn-then-act scenarios and find act-then-learn to be "an attractive paradigm". But, an actual application of these findings is difficult. A policy based on these results, would require to reach an agreement on the subjective probabilities of the uncertainties and defining a date by which these uncertainties are likely to be resolved.

3.2 Models with two irreversibilities

The first study to explicitly compare these effects with a simple two-period model is that of Kolstad (1996). The calibration data used is from Nordhaus' first DICE model (Nordhaus (1992)). It involves a capital depreciation rate of 0.35 per decade and a greenhouse gas decay rate of 0.0833 per decade. This model is continuous, allowing for variations in the rate of learning, in order to estimate the EVFI associated with action and inaction. He finds that, if investment in abatement capital is perfectly reversible, learning has no effect on the optimal abatement level. This implies that the irreversibility from the stock externality has only a very limited effect. This is explained by the fact that the climate changes very slowly, allowing for swift corrections of current under-investment in abatement in the future. Therefore, the expected gain of reducing emissions immediately as opposed to waiting 10 years is negligible (seen from 1995 onwards). Moreover, Kolstad finds that the irreversibility effect associated with abatement capital does matter. Therefore, his model suggests benefits to waiting for better information to emerge.

Ulph and Ulph (1997) have also set up a two-period analytical model to understand the implications of the irreversibility effects, the conclusion of which being that, under different conditions (the same as mentioned in the previous section), either one of the constraints may hold. The results are very similar to Kolstad (1996), as they find the environmental irreversibility effect to be non-binding for "plausible parameter values". In order to make the constraint bite, they also use more convex environmental damage functions, making temperature increases more costly. They then expand to a 4-period model and different potential levels of damages. The results show, once again, that the irreversibility effect related to the stock externality never bites. Furthermore, Ulph and Ulph find that the abatement capital irreversibility constraint is also only binding "in the case with a very low discount rate and considerable uncertainty". Therefore, learning generally has little or no impact on optimal abatement levels.

Fisher and Narain (2003) use updated functional forms and parameter values from Nordhaus' DICE2000 model. Their analysis is based on an adapted DICE model in that it does not itself directly model investment in abatement capital and can therefore not give any predictions on the effect of the abatement capital irreversibility (as one cannot vary the sunkness of capital). In order to model uncertainty in the damage function, the study uses information from a survey of experts to compute the subjective probabilities of three different scenarios and have fitted a convex function through each point. However, the basic functional form is once again quadratic in temperature. With this they find that irreversible capital investment has a much higher impact (irreversibility implies no abatement, where $30 billion would be warranted if investment could be reversed) than irreversible GHG accumulation (where complete irreversibility warrants $20 billion and no irreversibility a relatively close $18.6 billion).

Ha-Duong and Hourcade (1997) have preferred to think of this irreversibility effects as inertia, and incorporate an inertia parameter derived from the structure of abatement costs. This parameter, which corresponds to the inertia of the system (measured in time), multiplies a term which depends on the rate of growth of abatement. This, they explain, allows separating transitional costs from permanent costs and allows them "to capture crucial dynamic constraints without resulting either to the arbitrary upper bound on emission reduction rates" (as is the case in the above-mentioned specifications). They use an inertia parameter which can take the values of 20 or 50 years as a reasonable average for the rate of renewal of energy producing technologies. With these values, adjustment costs make up 18% to 71% of the total cost.

If one can draw a general conclusion from these models, it would be the fact that inertia in climate systems (represented here by the decay rate of GHG in the atmosphere) seems not as important as the inertia in abatement capital. The fact that climate systems evolve so slowly, coupled with the fact that emissions are diluted into a relatively large pre-existing stock of GHG in the atmosphere, makes the irreversibility caused by sunk costs in abatement technologies the limiting factor, and pushes towards waiting for more uncertainty to resolve (or invest in acquisition of information). However, these models only account for the stock externality effect and do not include any explicit tipping points: it is quite probable that the introduction of catastrophic events would change this conclusion.

4 Inclusion of imaginable tipping points

It is quite plausible that the above-presented analyses underestimate the actual option value derived from the environmental irreversibility effect. This is due to the fact that the stock externality modeled within these approaches is associated with a continuous—and rather flat—damage function.

While the considerations presented in section 2.2.4 delineate the construction of a damage function given the existence of tipping points, this is not how abrupt events are usually taken into account within Integrated Assessment Models. In fact, most of these analyses refrain from directly modeling the expected damages from non-linear effects.[17] The most obvious reason for this is that scientific knowledge about potential systemic surprises is still very limited.[18] As a consequence, many climate models do not take such effects into account and are "typically surprise free"[19] Correspondingly, the largest part of existing cost-benefit analyses do not take such effects into account either. This is the problem Pindyck (2007) calls "tipping point uncertainty". As this uncertainty remains to a large extent unstructured, deriving a damage function remains "a major source of modeling uncertainty"[20] in climate-economic models.

As a consequence, the Real Option approaches presented in the last section do necessarily fail to incorporate a potentially important part of the damages associated with climate change. Yet, there exist several strategies to add some structure to the decision problem. Tsur and Zemel (1996) present a dynamic model where a catastrophic events event is triggered when the stock of pollutant reaches an a priori unknown critical level. The optimal strategy identified within this analysis is to keep emissions within a strictly defined, fixed interval. Another strategy to at least get a notion of the probability of an abrupt event is to elicit expert opinions on the matter. Zickfeld et al. (2007) present the results of such a method with respect to the weakening of the thermohaline circulation in the North Atlantic. The authors report that that given a warming of up to $3\,^{\circ}C$ most of the 12 experts assessed the risk of a complete breakdown of the thermohaline circulation by the end of this century at up to 10 percent. Hence, while these strategies are not suitable to derive a probability distribution for catastrophic events, they indicate the existence of a somewhat diffuse, but potentially very large, option value favoring more stringent immediate mitigation action.[21] In order to account for the diffuse 'climate risk', the current trend in climate economics is to use constraints on greenhouse gas concentrations or temperature levels instead of a damage function. In the following we shortly present the most common approaches used within these models and

[17] A notable exception is Nordhaus and Boyer (2000).

[18] See Stern (2006) and Watkiss et al. (2005) for an overview.

[19] Schneider (2004), p. 245; On that matter see also Webster et al. (2003). Oppenheimer and Alley (2004) for example find that for the melt-down of the West Antarctic Iceshield the definition of the exact location of a critical threshold is impossible. Still these authors provide enough evidence to call for a precautionary approach with respect to climate policy.

[20] Nordhaus (2007)

[21] See Pindyck (2007).

explain in what way these can be interpreted as an implicit recognition of potential tipping point irreversibilities.

4.1 Probabilistic constraints in IAMs

Temperature targets, such as the 2 degree Celsius target, have been widely circulated in policy making circles, and offer a good and objective goal to stimulate action in spite of the huge uncertainties linked to the actual economic cost of going over the target. They constitute the implicit recognition of the need for precautionary behavior in climate change policy. The concept is for example recognized by the United Nations Framework Convention on Climate Change (UNFCCC), which declares its objective as being the "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"[22]. The value of such a "safe" level is, according the IPCC's Fourth Assessment Report (IPCC (2007b)), "likely to lie between 2°C and 4.5°C". However, being based on "fluffy" predictions about potential tipping points, any chosen level of precautionary behavior will be to some respect arbitrary.

Many IAM-based studies recognize that the environmental side of the equation will in all probability be given exogenously and analyze the effect of fixed radiation or temperature targets that should not be surpassed, called "hard constraints". These correspond to introducing an extreme convexity in the damage function at some predetermined threshold, or target, at which the function becomes vertical. These targets are given exogenously (that is, they do not necessarily correspond to the optimal temperature level) and are assumed to come from the political sphere.

Implementing such targets corresponds to the inclusion of a very strong "environmental irreversibility" effect, as they imply infinite costs to surpassing them. In economic terms, they represent a hard constraint which is analogous to having bounded damages up to a certain threshold and infinite damages after that. As Nordhaus (2007) points out, this seems "difficult to rationalize from a purely economic point of view". However, they allow irreversible and catastrophic effects to be included without the need to explicitly estimate the highly uncertain damages they will imply. Therefore, all models which aim at predicting the economic cost of staying below a certain target indirectly include a strong environmental irreversibility effect. This is done in an extreme way, where satisfying this constraint has absolute priority over any constraint or objective. Some models, such as DICE2007 (see Nordhaus (2007)) and Bahn et al. (2008) use temperature targets. Others, such as the MERGE model (see Richels et al. (2007)) use radiative forcing targets, and thus go one step further in that they eliminate uncertainty between radiative forcing and temperature levels.

Doing so, IAMs switch from maximizing utility minus costs to minimizing the costs under a certain constraint. As a result, they no longer claim to be able to find or predict optimal emissions paths, but rather examine the trade-offs between stronger environmental constraints and abatement costs. As Nordhaus points out, "it is particularly useful and interesting from an economic perspective to examine the implications of different thresholds for near-term policy." Therefore, they are

[22]UNFCCC (1992); At several Conferences of the Parties of the UNFCCC, the member states committed themselves to the 2 degree Celsius target. (See UNFCCC (2007) and UNFCCC (2010).) Yet, a binding agreement the translation of this commitment into actual policies is still subject to negotiations. See

well apt at estimating the economic cost of environmental irreversibility, even if this irreversibility is modeled through seemingly arbitrary thresholds.

4.2 Models with environmental constraints

Richels et al. (2007) extend the MERGE model to analyze the potential for "when-flexibility". They rely entirely on environmental hard constraints (radiative forcing targets in this case) and therefore avoid the problem of estimating a damage function. Their approach is innovative in that it introduces, in addition to the constraints on radiative forcing, a similar "hard constraint" on the abatement capital irreversibility: a reductions constraint which they arbitrarily assume to be two percent per year. This leads to what they call the third best policy, which is to be compared to the first best policy where emission abatement would be distributed across space and time in an economically efficient manner, but is impossible to implement. This 3rd best policy is in essence for the abatement capital irreversibility what the environmental hard constrains are for the environmental irreversibility effect, as it assumes that we will not be able to abate more than two percent per year, even if that is economically optimal. In the MERGE model, they assume a decline rate for new technologies which is limited to 3.5% per year, and no limit for existing technologies. This, they explain, "allows for the possibility that some emission ceilings may be sufficiently low to force premature retirement of the existing capital stock".

The results presented in Richels et al. (2007) are very dependent on the environmental target under which costs need to be minimized. If it is assumed that the environmental irreversibility is strong, that is, a tight (3.4 watts/m2, corresponding to 450 ppm) environmental constraint is chosen, then the abatement capital constraint is not binding (the first and third best policies generate the same optimal paths). When the environmental irreversibility effects are assumed to be less strong - a laxer target of 4.7 watts/m2, or 550ppm -, they show that the abatement capital irreversibility becomes the limiting factor. In regards to present-day emissions reductions, which are our variable of interest, their results are the following: under the lax environmental target, the first best policy is basically to wait (that is, emit as much as in the "business-as-usual" scenario) until about 2030, when emissions should start to be reduced. The third-best policy, on the other hand, calls for immediate emission reduction in order for the overall decrease to be less abrupt. This implies that, in this case, there is still some "when-flexibility" as different first-period abatement rates are possible. This is true unless the abatement technologies are assumed to suffer from high inertia, as the 2% constraint forces too much early abatement. Under the more stringent environmental constraint, though, both the first and the third best policies call for strong immediate reductions in emission levels. In this case there is no possible "when-flexibility". If we believe the 450 ppm concentration level to be safe, then, emissions should be reduced immediately.

This model does not however include sequential learning and decision-making, and cannot directly confirm whether environmental irreversibility effects are non-binding. If investment in abatement capital should be undertaken immediately, it would be because of the large potential environmental costs caused by climate change, but not because of resolving uncertainty. We now turn, finally, to some attempts at climate assessment modeling which do include sequential decision making as well as environmental irreversibilities.

4.3 Sequential Stochastic Control models

One class of model is capable of combining the sequential decision framework of the first models with the complexity of the later: stochastic control models. These are dynamic general equilibrium models which incorporate multi-period decision making under resolving uncertainty. The latest and most sophisticated attempt at implementing one is to be found in Bahn et al. (2008). They use a stochastic control model which is calibrated with parameters similar to the DICE2007 and MERGE models. Once again, environmental irreversibility is implemented with hard constraints and they use 2° and 4.5° Celsius limits (in line with the IPCC's FAR). These two limits constitute upper bounds on GHG concentration levels and are considered, from the point of view of a first period decision, to be a priori equiprobable. The time at which the uncertainty resolves is also random, and depends on the accumulated GHG stock. They assume an "abrupt jump" in the resolution of uncertainty. They use a piecewise deterministic control model to compute an optimal policy which maximizes the expected value of all policies which generate a control path which satisfies the constraints both before and after the uncertainty has resolved. Obviously, before the uncertainty has resolved, the stock of emissions must stay below the minimum of the two GHG accumulation allowed by the two targets. The way they model this is by giving an infinite penalty for being over the limit when the true climate sensitivity is discovered. This leads to the definition, at the initial time period, of a complex reward function which takes into account future switches to a better knowledge of climate sensitivity. The results are that, in the periods before the uncertainty resolves, the optimal strategy is to reduce emissions as though it was known that the tightest concentration goal will have to be satisfied. Therefore, they can claim that "a precautionary principle prevails for emissions". Furthermore, the model calls for "gradual R&D investments", at a level lying between the two scenarios. They do however recognize and stress that this precautionary effect only arises under the assumption of extreme risk-averseness which is implied by the hard constraints. They also stress the fact that their modeling attempt should mostly be used to reach qualitative conclusions. This study, in essence, teaches us that if the actual level of environmental damages is unknown, and it is therefore unknown which hard constraint should be chosen, we should adopt precautionary behavior: before the uncertainty as to which hard constraint is relevant resolves, we should act as if the most stringent will apply.

5 Conclusion

Evidently, real-world climate policy will necessarily be a political decision, prone to subjective interpretation of the potential damages. It is indeed ultimately up to decision makers (politicians, voters) to integrate the possibility of such "imaginable abrupt events" and decide how "precautionary" they want to be. For the best decision to be taken, they, at the individual-level, must be able to understand the interplay between uncertainty and irreversible action described in this paper. This, we claim, justifies the need for more research in the vein of behavioral economics investigating potential cognitive biases which might occur in individual decision making in the presence of two opposing sources of irreversibility. Such findings would be of relevance as systematic individual biases could filter to the final climate policy making process and therefore have a large impact on society's aggregated decision.

The theory behind the counter-balancing effects induced by the two forms of irreversibility in the climate change mitigation policy problem is well-understood. The theoretical literature on the subject is helpful in its explicitation of the importance of learning and the need to keep "options" available in case uncertainties resolve and highlights the importance of inertia, or irreversibility. As such, it can serve as a relevant guide in the timing decision of climate policy-making. Most empirical studies come to the similar conclusion that delayed action only results in a relatively small increase of GHG concentrations as compared to the total stock of these gases already present in the atmosphere, and that, as a result, inertia in the climate system is much longer-lasting than that of abatement capital. Therefore, the optimal emission path does not depend too much on immediate emissions, and the stock externality component of the environmental irreversibility effects does not bite (will not constrain our future courses of action). There is less agreement in the literature about the abatement cost irreversibility constraint, but most studies seem to find it binding. This, according to Real Option theory, would imply the existence of an option value to delaying investment. However these models do not incorporate catastrophic events, or tipping points, which could reverse this conclusion. The inclusion of these effects, which would make the environmental irreversibility effect stronger than just its stock externality component, should not be neglected, as it might call for more precautionary behavior in the form of more immediate reductions in GHG emissions. The location and intensity of such tipping points is however extremely hard to estimate and has generally not been incorporated in IAM-based studies. This is the reason for the unavailability of any complete quantitative Real Option-based assessment of the climate policy timing problem.

Yet, recently climate economics turned to the use of environmental "hard constraints", like the well-known 2 degree C target, instead of optimizing with respect to a convex damage function. This is indeed an implicit recognition of the need for precautionary behavior. Generally, these constraints correspond to more or less arbitrarily chosen environmental targets (temperature, radiation, or even GHG concentrations) with infinite environmental damage when surpassed, and make the decision to emit an irreversible one. If policy makers do recognize the need for precaution, and set specific environmental targets, IAMs can estimate the optimal strategy to implement them. Finally, Stochastic Control models attempt to tie the realistic modeling of IAMs in a sequential framework. They seem to conclude that, if the precise location of irreversible tipping points is unknown, it is optimal to keep emissions at a level compatible with the worst case scenario.

However, given the unstructured nature of the uncertainty related to catastrophic events, the interpretation of the corresponding risk remains currently subjective, and modeling efforts will not be able to directly guide the political sphere in the consideration of these effects. Any complete uncertainty and irreversibility analysis will have to be done after this subjective assessment. We consequently argue that the recognition of the need for precautionary behavior (as exposed by Real Option Theory) will necessarily be done at the individual policy making level. As a consequence, individual-level understanding of the implications of irreversibility effects is crucial to the implementation of timely climate policy. It is however unclear to which extent decision-makers are able to understand the impact of resolving uncertainty and irreversibility. This is why we motivate further study of individual decision-making under such conditions. This could be investigated with the help of laboratory experiments in the vein of behavioral economics as undertaken within the ETH CLIMPOL A1 project.

References

Aldy, J. E., Baron, R. and Tubiana, L.: 2003, *Beyond Kyoto: Advancing the International Effort Against Climate Change*, Pew Center on Global Climate Change.

Arrow, K. J. and Fisher, A. C.: 1974, Environmental Preservation, Uncertainty, and Irreversibility, *Quarterly Journal of Economics* **88**(2), 312–319.

Bahn, O., Haurie, A. and Malhame, R.: 2008, A Stochastic control model for optimal timing of climate policies, *Automatica* **44**, 1545–1588.

Brock, W. and Starrett, D.: 2003, Managing Systems with Non-convex Positive Feedback, *Environmental and Resource Economics* **26**, 575–602.

Brown, D. A.: 2002, *American heat : ethical problems with the United States' response to global warming*, Lanham, Md. : Rowman & Littlefield Publishers.

Denbigh, K. G.: 1989, The Many Faces of Irreversibility, *The British Journal for the Philosophy of Science* **40**(4), 501–518.

Dumas, P. and Ha-Duong, M.: 2004, An abrupt stochastic damage function to analyse climate policy benefits, in: Alain Haurie and Laurent Viguier (eds.) , The coupling of climate and economic dynamics, Essays on Integrated Assessment, Kluwer Academic Publishers, Boston/Dordrecht/London.

Earman, J.: 1986, The Problem of Irreversibility, *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association* **2**, 226–233.

Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M. and Koehler, J.: 2006, Induced Technological Change: Exploring its Implications for the Economics of Atmospheric Stabilization: Synthesis Report from the Innovation Modeling Comparison Project, *Energy Journal - Special Issue* pp. 57–107.

Fisher, B., Nakicenovic, N., Alfsen, K., Morlot, J. C., de la Chesnaye, F., Hourcade, J.-C., Jiang, K., Kainuma, M., Rovere, E. L., Matysek, A., Rana, A., Riahi, K., Richels, R., Rose, S., van Vuuren, D. and Warren, R.: 2007, *Issues related to mitigation in the long term context*, in IPCC (2007a), chapter 3, pp. 169–250.

Fisher and Narain: 2003, Global Warm, Endogenous Risk, and Irreversibility, *Environmental and Resource Economics 25: 395-416* .

Gregory, J. M., Huybrechts, P. and Raper, S. C. B.: 2004, Climatology: Threatened loss of the Greenland ice-sheet, *Nature* **428**, 616.

Ha-Duong: 1998, Quasi-Option Value and Climate Policy Choices, *Working Paper* .

Ha-Duong, G. and Hourcade: 1997, Influence of socioeconomic inertia and uncertainty on optimal CO2-emission abatement, *Nature* .

Hansen, J.: 2005, A slippery slope: How much global warming constitutes "dangerous anthropogenic interference"?, *Climatic Change* **68**(3), 269–279.

Heal, G. and Kristrom, B.: 2002, Uncertainty and Climate Change, *Environmental and Resource Economics 22: 3ï¿½39, 2002.* **22**, 3–39.

Henry, C.: 1974, Investment Decisions under Uncertainty: The "Irreversibility Effect", *American Economic Review* **64**(6), 1006–1012.

IPCC: 2007a, *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC: 2007b, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kolstad, C. D.: 1996, Learning and Stock Effects in Environmental Regulations: the Case of Greenhouse Gas Emissions, *Journal of Public Economics* **60**(2), 221–233.

Kossioris, G., Plexousakis, M., Xepapadeas, A. and de Zeeuw, A.: 2010, On the Optimal Taxation of Common-Pool Resources, *DEOS Working Papers 1010*, Athens University of Economics and Business.

Kossioris, G., Plexousakis, M., Xepapadeas, A., de Zeeuw, A. and Mï¿½ler, K.-G.: 2008, Feedback Nash equilibria for non-linear differential games in pollution control, *Journal of Economic Dynamics and Control* **32**(4), 1312–1331.

Manne and Richels: 1992, Buying Greenhouse Insurance, *MIT Press, Cambridge* .

Manne and Richels: 2005, MERGE: An integrated assessment model for global climate change, *Energy and Environment - GERAD 25th Anniversary Series* .

Nordhaus: 1992, The DICE Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming, *Cowles Foundation discussion paper no. 1009* .

Nordhaus: 2007, A Question of Balance, *Princeton University press* .

Nordhaus, W. D. and Boyer, J.: 2000, *Roll the DICE Again: Economic Models of Global Warming (online manuscript edition)*, MIT Press, Cambridge, MA. Available at: http://www.econ.yale.edu/ (downloaded: November 2010).

Oppenheimer and Alley: 2004, The west Antartic ice sheet and long term climate policy, *Climatic Change* **64**(1-2).

Pindyck, R. S.: 2000, Irreversibilities and the timing of environmental policy, *Massachusetts Institute of Technology* .

Pindyck, R. S.: 2002, Optimal timing problems in environmental economics, *Journal of Economic Dynamics & Control* **26**.

Pindyck, R. S.: 2007, Uncertainty in environmental economics, *NBER working paper* **12752**.

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Pitman, V. K. A., Shukla, J., Srinivasan, J., Stouffer, R. J., Sumi, A. and Taylor, K. E.: 2007, *Climate Models and Their Evaluation*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., chapter 8.
URL: *http://www.ipcc.ch/SPM2feb07.pdf*

Richels, R., Rutherford, T., Blanford, G. and Clarke, L.: 2007, Managing the transition to Climate Stabilization, *AEI-Brookings Joint Center for Regulatory Studies, Working Paper* **07-01**.

Ridley, J. K., Huybrechts, P., Gregory, J. and Lowe, J.: 2005, Elimination of the Greenland Ice Sheet in a High CO2 Climate, *Journal of Climate* **18**(17), 3409–3427.

Schneider, S. H.: 2004, Abrupt non-linear climate change, irreversibility and surprise, *Global Environmental Change* **14**, 245–258.

Solomon, S., Qin, D., Manning, M., Alley, R., Berntsen, T., Bindoff, N., Chen, Z., Chidthaisong, A., Gregory, J., Hegerl, G., Heimann, M., Hewitson, B., Hoskins, B., Joos, F., Jouzel, J., Kattsov, V., U. Lohmann and, T. M., Molina, M., N. Nicholls, J. O., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T., Whetton, P., Wood, R. and Wratt, D.: 2007, *Technical Summary*, in IPCC (2007b), pp. 19–91.

Stern, N.: 2006, The Economics of Climate Change, *The Stern Review*, Cabinet Office - HM Treasury, UK. Available at: http://www.hm-treasury.gov.uk.

Tsur, Y. and Zemel, A.: 1996, Accounting for global warming risks: Resource management under event uncertainty, *Journal of Economic Dynamics and Control* **20**, 1289–1305.

Ulph, A. and Ulph, D.: 1997, Global Warming, Irreversibility and Learning, *Economic Journal* **107**(442), 636–650.

UNFCCC: 1992, United Nations Framework Convention on Climate Change, international treaty, entered into force on 21 March 1994. Text available at: http://www.unfccc.int.

UNFCCC: 2007, Report of the Conference of the Parties on its thirteenth session, held in Bali from 3 to 15 December 2007, *Cop decisions*, United Nations Framework Convention on Climate Change. available at: http://www.unfccc.int.

UNFCCC: 2010, Outcome of the work of the Ad Hoc Working Group on long-term Cooperative Action under the Convention, *Cop decisions*, United Nations Framework Convention on Climate Change. available at: http://www.unfccc.int.

Watkiss, P., Anthoff, D., Downing, T., Hepburn, C., Hope, C., Hunt, A. and Tol, R.: 2005, The Social Costs of Carbon (SCC) Review - Methodological Approaches for Using SCC Estimates in Policy Assessment.

WBGU: 2008, *Sicherheitsrisiko Klimawandel*, (Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveraenderungen) Springer: Berlin.

Webster, M., Forest, C., Reilly, J., Babiker, M., Kicklighter, D., Mayer, M., Prinn, R., Sarofim, M., Sokolov, A., Stone, P. and Wang, C.: 2003, Uncertainty Analysis of Climate Change and Policy Response, *Climatic Change* **61**(3), 295–320.

Zickfeld, K., Levermann, A., Morgan, M., Rahmstorf, T. K. S. and Keith, D.: 2007, Expert judgements on the response of the Atlantic meridional overturning circulation to climate change, *Climatic Change* **82**(3-4), 235–265.

List of IED working papers

- Renate Schubert, Julia Blasch, and Kristin Hoffmann (2007). Environmental Protection, Energy Policy and Poverty Reduction – Synergies of an Integrated Approach. *IED Working Paper 1*, ETH Zurich, Institute for Environmental Decisions, Chair of Economics.
- Robert Finger and Werner Hediger (2007). The application of robust regression to a production function comparison – the example of Swiss corn. *IED Working Paper 2*, ETH Zurich, Institute for Environmental Decisions, Agri-Food and Agri-Environmental Economics Group.
- Stefanie Engel and Charles Palmer (2008). "Painting the forest REDD?" – Prospects for mitigating climate change through reducing emissions from deforestation and degradation. *IED Working Paper 3*, ETH Zurich, Institute for Environmental Decisions, Chair of Environmental Policy and Economics.
- Lasse Wallquist and Mischa Werner (2008). Carbon dioxide Capture and Storage – CCSStudie zum Entwicklungsstand von CCS in der Schweiz. *IED Working Paper 4*, ETH Zurich, Institute for Environmental Decisions, Chair of Consumer Behavior.
- Roland W. Scholz and Michael Siegrist (2008). Low Risks, High Public Concern? The Cases of Persistent Organic Pollutants (POPs), Heavy Metals, and Nanotech Particles. *IED Working Paper 5*, ETH Zurich, Institute for Environmental Decisions, Chair of Natural and Social Science Interface, Chair of Consumer Behavior.
- Astrid Zabel, Karen Pittel, Göran Bostedt, and Stefanie Engel (2009). Comparing Conventional and New Policy Approaches for Carnivore Conservation – Theoretical Results and Application to Tiger Conservation. *IED Working Paper 6*, ETH Zurich, Institute for Environmental Decisions, Environmental Policy and Economics.
- Astrid Zabel and Brian Roe (2009). Performance payments for environmental services: Lessons from economic theory on the strength of incentives in the presence of performance risk and performance measurement distortion. *IED Working Paper 7*, ETH Zurich, Institute for Environmental Decisions, Environmental Policy and Economics.
- Stefanie Engel and Charles Palmer (2009). The Complexities of Decentralization in a Globalizing World. *IED Working Paper 8*, ETH Zurich, Institute for Environmental Decisions, Environmental Policy and Economics.
- Michael Hartmann, Robert Huber, Simon Peter, and Bernard Lehmann (2009). Strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model. *IED Working Paper 9*, ETH Zurich, Institute for Environmental Decisions, Environmental Policy and Economics.
- Julia Blasch, Renate Schubert, Birgit Soete (2010). Grün aus der Krise – Was können «grüne» Konjunkturpakete leisten? *IED Working Paper 10*, ETH Zurich, Institute for Environmental Decisions, Environmental Policy and Economics.
- Moritz Rohling und Markus Ohndorf (2010). Prices vs. Quantities with Fiscal Cushioning. *IED Working Paper 11*, ETH Zurich, Institute for Environmental Decisions, Environmental Policy and Economics.
- Thomas Bernauer and Lena Maria Schaffer (2010). Climate Change Governance. *IED Working Paper 12*, ETH Zurich, Institute for Environmental Decisions, Environmental Policy and Economics.

ETH Zurich
Institute for Environmental Decisions IED
WEH G
CH-8092 Zurich
SWITZERLAND

Phone +41 44 632 47 18
Fax +41 44 632 10 42
URL http://www.ied.ethz.ch