DECISION MAKING UNDER CATASTROPHIC RISK AND LEARNING: THE CASE OF THE POSSIBLE COLLAPSE OF THE WEST ANTARCTIC ICE SHEET

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Abstract

A collapse of the West-Antarctic Ice Sheet (WAIS) would cause a sea level rise of 5-6 metres, perhaps even within one hundred years, with catastrophic consequences. The probability of such a collapse is small but increasing with the rise of the atmospheric concentrations of greenhouse gas and the resulting climate change. This paper investigates how the potential collapse of the WAIS affects the optimal rate of greenhouse gas emission control. We design a decision and learning tree in which decision are made about emission reduction at regular intervals. At the same time, the decision makers receive new information on the probability of a WAIS collapse and the severity of its impacts. The probability of a WAIS collapse is endogenous and contingent on greenhouse gas concentrations. We solve this optimisation problem by backward induction. We find that a potential WAIS collapse substantially bring the date of the optimal emission reduction forward and increases its amount if the probability is high enough, if the impacts are high enough, or if the decision maker is risk averse enough. We also find that, as soon as a WAIS collapse is a foregone fact, emission reduction falls to free up resource to prepare for adapting to the inevitable.

Keywords

Decision making under uncertainty, West-Antarctic ice sheet

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1. Introduction

The possibility of a catastrophe is one of the main reasons for concern about climate change (Smith *et al.*, 2001; Wright and Erickson, 2003). The climate is a non-linear system. It may be that the gradual change in the concentrations of greenhouse gases caused by human activities will bring about abrupt changes in atmosphere, ocean, or biosphere. Examples include the "runaway" greenhouse effect, in which climate change triggers massive releases of greenhouse gases, a shutdown of the thermohaline circulation, and the disintegration of the West Antarctic Ice Sheet (WAIS), the topic of this paper. Although the process of disintegration is slow at a human time-scale, once it has been set in motion, there is no way of stopping the WAIS from disintegrating entirely. A WAIS collapse would lead to a sea level rise of 5-6 metre, but probably not faster than within the course of one century. A 5 metre sea level rise would have drastic impacts. This paper analyses how the risk of a WAIS collapse influences the optimal control of carbon dioxide emissions.

Besides the uncertainty about the collapse of the WAIS, we also consider the uncertainty about the damage costs. Uncertainty interacts with irreversibility, another key feature of climate change decision-making. On the one hand, carbon dioxide emission reduction is a sunk cost to society. Sunk costs create an opportunity cost of adopting a policy now rather than waiting for more information about the impacts of warming and their economic consequences. On the other hand, part of the atmospheric stock of carbon dioxide is not degradable. Emissions have irreversible impacts on the atmosphere, and climate change may well have further irreversible impacts. Adopting an abatement policy now rather than later has a sunk benefit, because the society is better protected from irreversible environmental damages. These opportunity costs (benefits) bias traditional cost-benefit analysis against (in favour) of policy adoption. We investigate which bias is stronger.

In this paper, we limit the response options of decision makers to either doing nothing (or rather, waiting for more information about the future) or adopting an environmental policy (i.e. reducing emissions / building dikes such that the probability of having another catastrophe is equal to zero). We do not distinguish between reducing emissions and building dikes. We focus on this second question by taking into account irreversibilities under uncertainties, which modify the traditional cost-benefit analysis. We then assume that the reduction quantity is already known, and that there is an international cooperation in order to reduce emissions: the model is global and deals with one decision maker who faces international social costs of warming.

To do so, we use a Real Options model, introduced by Arrow and Fisher (1974) and Henry (1974). They show that there is a premium or option value on policies to maintain flexibility. We follow Pindyck (2000, 2002) and Saphores (2004): irreversibility and environmental uncertainty can strongly influence the timing of environmental policy. This policy aims to minimize social costs in the presence of continuous and catastrophic damages. In the set-up of Pindyck (2000, 2002; see also Dixit and Pindyck, 1994; and Yin and Newman, 1996), the probability of a disaster only strenghens the discount rate. They show that, if environmental uncertainty increases, an investment in emission reduction should be delayed because of sunk costs. In contrast, Saphores (2004) shows that acting earlier to reduce GHGs emissions may be optimal in order to avoid long-term damages due to the GHGs accumulation (i.e., sunk benefits).

We choose here to consider this kind of problem by focusing on the report of IPCC (2001), which highlighted that the extreme weather events have increased in severity and frequency during the twentieth century as the atmospheric GHGs concentration has gone up. So our aim is to determine what to decide (i.e. when to adopt an environmental policy as well as how much GHGs emissions reductions should be optimal) according to what has already happened. Baranzini *et al.* (2003) include the possibility of *exogenous* climatic shocks into a Real Options model. However, the probability and magnitude of catastrophes are based on agents' behaviour, i.e. catastrophic risk is *endogenous* in this area. In Tsur and Zemel (1996) and Fisher and Narain (2003), the possibly catastrophic impacts depend on atmospheric gases concentration, which in turn depend on emissions and emission control. They also distinguished two kinds of catastrophes (high damage and low damage). In this paper, we add that the probability of a catastrophe depends on the occurrence of catastrophes in previous periods. In this manner, we simulate that an extreme climate scenario, in our case the collapse of the West-Antarctic Ice Sheet, would manifest itself through a series of floods that would increase in frequency (and intensity) but still be random.

As in Werey (2000), who studies endogenous probabilities of failures of water hubs, we combine Real Options and Operational Research approaches. We compare over one hundred years social costs when a policy is adopted (and then no catastrophe occurs anymore) and when nothing is done (and then the society has to cope with possible disasters that could increase these social costs). We adopt the policy when social costs are minimized.

Other papers on catastrophic risks of climate change include Gjerde *et al.* (1999) and Keller *et al.* (2004). These papers ignore stochasticity. In return, the representation of emission reduction is more sophisticated than what is possible here.

In Section 2 we present the model, hypotheses and data retained. We state results and the sensitivity analysis in Section 3. We conclude in Section 4.

2. The model and data

2.1. The model

Cost-benefit analysis is a standard framework to evaluate environmental policies, although by no means the only contender. Our cost-benefit model incorporates three essential characteristics of the investment problem:

- Irreversibilities: On the one hand, costs of an environmental policy are sunk for the society; on the other hand, benefits due to an immediate adoption of the policy are sunk as well.
- Uncertainties over future outcomes: The evolution of the ecosystem is uncertain; the evolution of GHGs concentration depends on the implementation or not of the environmental policy; frequency and magnitude of disasters are uncertain; social costs of climatic changes are unknown.

- Delay: The adoption on policy can be delayed.

The model aims to adopt a GHGs abatement policy at the optimal time, i.e. when the social costs are minimized (Pindyck 2000, 2002). This decision is unique and is not compounded of a series of sequential investment decisions. In contrast to Werey (2000), we fix a terminal boundary. The policy has to be adopted no later than year 100.

The information structure of the problem is as follows. There is uncertainty on social costs and on the probabilities and magnitudes of damages, variables that depend on the temperature and so on the concentration of greenhouse gases.

Let $M(t)$ denote the stock of environmental pollutants.[1] According to Nordhaus (1994),[2] the present stock of pollutant $M(t)$ evolves as:

(1) $$M(t) = M(0) + \beta E(t) + (1-\alpha)\left[M(t-1) - M(0)\right]$$

where $M(0)$ = 596.4 billions tons of CO_2 is the initial stock of CO_2; $M(t\text{-}1)$ is the stock of CO_2 at the previous period; $E(t)$ is emissions of CO_2; β is the marginal atmospheric retention ratio; α is the natural rate at which the stock of CO_2 dissipates over time.

World GDP grows over time at a rate of 2% per year. We express social costs, damages and investment costs in percentage of GDP. Emissions $E(t)$ increase over time if no policy is implemented:

(2a) $$E(t) = (1+\delta)E(t-1)$$

with δ=0.5% or 1% per year. That is, carbon efficiency improves by 1.0% or 1.5% per year.

When the policy is adopted at time t^*, emissions $E(t)$ are reduced by 0.1% or 1.1%. Then they begin to grow again but at a lower rate than in the baseline

(2b) $E(t^*) = (1-\eta)E(t^*-1)$ with $\eta \in [0.1\%;1.1\%]$

(2c) $E(t+1) = (1+\gamma)E(t)$ for $t > t^*$, with $\gamma < \delta$ and γ=0.1%.

The costs K of 1% emission reduction are equal to 0.02% GDP (Tol, forthcoming).

The climate system is characterized by a multi-layer system comprising the atmosphere, the mixed layer of oceans and the deep oceans. Nordhaus (1994) expresses the temperature evolution of atmosphere and upper oceans by the following equation:

(3a) $$T(t) = T(t-1) + \sigma_1\left[f(t) - \lambda T(t-1)\right] - \sigma_2\left[T(t-1) - T_{LO}(t-1)\right]$$

where $\sigma_1 = 1/R_1$ with R_1 the thermal capacity of atmosphere and upper oceans; $\sigma_2 = R_2/\tau_2$ with R_2 the thermal capacity of deep oceans and $1/\tau_2$ the transfer rate from the upper layer to the lower layer; λ is the climate feedback parameter;

T_{LO} is the temperature of the deep ocean:

(3b) $$T_{LO}(t) = T_{LO}(t-1) + \sigma_3\left[T(t-1) - T_{LO}(t-1)\right]$$

[1] Note that we use "stock" and "concentration" interchangeably; the two are not the same, but there is a one-to-one relationship between them. In the model, we use the stock.

[2] We ignore later, more complicated models of carbon cycle and climate (e.g., Nordhaus and Boyer, 2000). We only take carbon dioxide into account.

with $\sigma_3 = 1/\tau_2$.

The radiative forcing due to carbon dioxide (relative to 1990) follows

(4) $$f(t) = \frac{\mu}{\ln 2} \ln\left(\frac{M(t)}{M(0)}\right)$$ with $\mu = 0.99$.

The social costs of warming depend on the temperature (cf. Fischer and Narain, 2003). Climate change brings damages. There are three potential states of nature in each year: no catastrophe, mild catastrophe and bad catastrophe.

Without a catastrophe, damage costs depend on temperature:

(5) $$C(t) = cT^2$$

The parameter *c* is set such that a warming of 3°C implies damages equal to 1% of GDP, which roughly corresponds to the values found in the survey by Smith *et al.* (2001). If a mild (bad) catastrophe occurs, the parameter c is multiplied by 3 (11), for that year. Note that the damage cost convexity can be interpreted as the risk aversion of society against disasters.

The risk of catastrophic damages is endogenous, in the sense that the probability of the damages occurring depends on the stock of GHGs, which is endogenous in our model. Following Fisher and Narain (2003), the probability of the occurrence of a catastrophe is:

(6) $$p(t)=(2/(1+e^{-b(t)M(t)}))-1$$

The present probability, i.e. for $M(0)$, of a disaster equals 1%. The probability rises to 5% for $2M(0)$. So, $b(t)$ evolves over time as

(7) $$b(t) = b(t-1) + b(t-1)\frac{M(t)-M(t-1)}{M(t-1)} \frac{\log\frac{0.5}{1.5} - 2\log\frac{0.9}{1.1}}{2\log\frac{0.9}{1.1}}$$

If $p(t)$ is the probability to have a disaster at time t, $p(t)k(N(t))$ is the probability that this is a bad disaster, where:

(8) $$k(N(t)) = q + 0.8N(t) \text{ with } k(N(t)) \in [0;1],$$

The probability of a bad catastrophe increase linearly with the number of bad catastrophes in the past ($N(t)$, with $0 \le N(t) \le t$). This is because, once the WAIS starts to collapse, chances are it will continue. However, a really bad flood may also just be a freak event. A WAIS collapse would manifest itself by bad floods becoming ever more common, but the first bad floods are not necessarily a sign that the WAIS is collapsing. Note that $\left(1-k(N(t))\right)$ is the conditional probability of a mild catastrophe.

2.2. Solution

The decision tree has 100 periods, but we present the two periods case for illustration in Figure 1. The squares represent decision nodes (adopting a policy P or not NP), and circles represent stochastic nodes (the occurrence of catastrophes D or not ND).

After adopting a policy, emissions, concentrations and temperatures evolve differently. $C_P(t)$ and $C_P(t+1)$ denote the social costs involved by a policy adopted at time t. $C_{NP,P}(t+1)$ are social costs when the policy is only adopted at time $(t+1)$, $C_{NP}(t)$ and $C_{NP}(t+1)$ are social costs when the policy is not adopted. Note that investment costs K are made at the beginning of the period, so they have to be discounted by the discount rate r.

Social costs of damages depend on the number of disasters that have already occurred and that modify the probability of having high damages (which involve social costs D_h, whereas D_l denotes social costs due to mild damages). So, social damages after the occurrence of one catastrophe at time t equal

$$D_D(t) = k(t,1)D_h(t) + \left[1 - k(t,1)\right]D_l(t) \tag{9}$$

(The equation is the same at time t+1 when nothing happens at the time t.) The social damages after the occurrence of a second catastrophe at time (t+1) when a disaster has already arrived at time t equal

$$D_{DD}(t+1) = k(t+1,2)D_h(t+1) + \left[1 - k(t+1,2)\right]D_l(t+1) \tag{10}$$

The optimal strategy minimizes expected net present total costs. It is computed using the algorithm of averaging-out-and-folding-back (cf. Appendices A and B). We begin by choosing the better solution at nodes 2 and 3 (evaluated at time t=0), which is the one that minimizes social costs occurred in period (t+1) and after. At node 2

$$\min Node2 = \min\left\{\begin{array}{l} K\left(\frac{1}{1+r}\right)^{t} + C_{NP,P}(t+1)\left(\frac{1}{1+r}\right)^{t+1} + \ldots; \\ \left[p(t+1)\left(C_{NP}(t+1) + D_{DD}(t+1)\right) + (1-p(t+1))C_{NP}(t+1)\right]\left(\frac{1}{1+r}\right)^{t+1} + \ldots \end{array}\right\} \tag{11}$$

At node 3:

$$\min Node3 = \min\left\{\begin{array}{l} K\left(\frac{1}{1+r}\right)^{t} + C_{NP,P}(t+1)\left(\frac{1}{1+r}\right)^{t+1} + \ldots; \\ \left[p(t+1)\left(C_{NP}(t+1) + D_{D}(t+1)\right) + (1-p(t+1))C_{NP}(t+1)\right]\left(\frac{1}{1+r}\right)^{t+1} + \ldots \end{array}\right\} \tag{12}$$

Finally at node 1 (evaluated at time t=0), decision makers choose between implementing the policy or waiting at time t according to:

$$\min Node1 =$$

$$(13)\qquad \min\left\{\begin{array}{l} K\left(\frac{1}{1+r}\right)^{t-1} + C_P(t)\left(\frac{1}{1+r}\right)^{t} + C_P(t+1)\left(\frac{1}{1+r}\right)^{t+1} + ...; \\ p(t)\left[\left(C_{NP}(t) + D_D(t)\right)\left(\frac{1}{1+r}\right)^{t} + \min Node2\right] \\ +(1-p(t))\left[C_{NP}(t)\left(\frac{1}{1+r}\right)^{t} + \min Node3\right] \end{array}\right\}$$

Depending on the number of catastrophes that have already happened, we can deduce when it is optimal to choose to invest in an environmental policy: when the social costs of implementing a policy are inferior to the social costs of waiting.

We do not evaluate option values here. Option values represent the difference between results of one shot analysis (i.e. either investing right now or never, result evaluated by the Net Present Value) and a sequential decision framework. Decision for first period is affected by the prospect of future learning about climatic events. Option values are positive if more development proceeds with more complete information than without it. We know that in case of options to invest, option values are always positive even with risk aversion (cf. Pindyck, 2002). It is worth to take into account the occurrence of information to the future. See for example Schimmelpfennig (1995) who evaluates option values in a two periods framework of two possible choices.

2.3. Data and parameters

We calibrate our model on the basis of hypotheses and results obtained by Nordhaus (1994), Nordhaus and Boyer (2000), Tol (2002a,b) and Fisher and Narain (2003). See Table 1.

3. Results

Table 2 shows the optimal time of investment as a function of the number of catastrophes occurring. For comparison, Table 2 also displays the marginal, net present cost of waiting and policy implementation. Decision makers start choosing between implementation and waiting for further information at t=0. At the optimal time t^*, the costs of implementing an environmental policy are always lower than costs of waiting.

Costs fall if the number of catastrophes decreases, and implementing is postponed policy. If no catastrophe occurs, it is better to wait to time t=100. That is, catastrophes are the main reason for reducing greenhouse gas emissions in our model.

The optimal time to implement a policy is equal to 59 when 59 catastrophes have already occurred; to 58 when 57 or 56 catastrophes have already occurred; and to 59 when 56, 55 or 54 catastrophes have already occurred. This is due to the probability of having a catastrophe, which is a concave function between 0 and 1. When catastrophes are very numerous, the probability of having another one is very similar regardless of the exact number of previous catastrophes. Therefore, the costs of waiting can be lower than the costs of implementing a policy (which takes into account the capital costs). Decision makers can invest later (at $t^*=59$ instead 58).

However, generally, emission reduction is postponed to later periods if fewer catastrophes occur. The earliest time for abatement is after 58 years, which is relatively late. Therefore, emission reduction is not used to prevent a WAIS collapse, but only to reduce damages.

Table 3 contains the results of a sensitivity analysis. Emission reduction is implemented earlier if (1) the costs of emission abatement are lower and (2) the time horizon is shorter. If emissions grow faster, less catastrophes are needed to induce implementation.

Uncertainty gives rise to two different issues. One relates to risk aversion. The fact that one cannot undo past emission reduction or actively remove carbon from the atmosphere is irrelevant to the optimal regulatory strategy (Kolstad, 1996). One relates to uncertainty where that uncertainty is being resolved over time, i.e. information is being acquired over time. The literature on irreversibilities tells us that with learning, we should avoid decisions that restrict future options.

The results obtained with the assumption of risk aversion prove that an environmental policy involves two kinds of irreversibilities that work in opposite directions:

- Sunk costs associated with an environment regulation: policies aimed at reducing ecological damage impose sunk costs on society;
- Sunk benefits of avoided environmental degradation: environmental damage can be partially or totally irreversible. So adopting a policy now rather than waiting has a sunk benefit (a negative opportunity cost).When there is no GDP growth over time, implementation is earlier. A higher discount rate implies earlier implementation. Note that lower (or no) economic growth and a higher (consumption) discount rate are equivalent. A higher discount rate implies reduced care for the future. The higher preference for the present is equivalent to a lower value for the future, i.e. a lower value of waiting for more information. Finally, the option value decreases and decision makers invest earlier. Emission reduction is implemented earlier.

Table 3 also shows that, if there are no catastrophes or if the catastrophes are not serially correlated (that is, no WAIS collapse), emission reduction is postponed. That is, the possibility of a WAIS collapse increases optimal emission reduction.

Emission reduction is postponed too, if the policy intervention is adaptation (dike building) rather than mitigation (emission reduction). This is because mitigation would reduce the probability of catastrophes as well as non-catastrophic damages, whereas adaptation would reduce the damage due to catastrophes only.

Finally, Table 3 shows that the date of implementation is independent of the intensity of emission reduction. However, social costs decrease with higher emission reduction. The base case policy of Table 2 may be optimal in the timing, but not in the level of emission abatement.

4. Concluding remarks

We use a stylized model of the costs and benefits of emission reduction, with large and endogenous uncertainty, with irreversible emission reduction and irreversible climate change impacts, to assess the optimal timing of policy. This was done before. However, we introduce serial correlation into the stochastic process that generates catastrophes, increasing the irreversibility on the climate change impact side. In this manner, we approximate the effects of a possible collapse of the West-Antarctic Ice Sheet.

We confirm the findings of previous studies that catastrophic risks justify greenhouse gas emission reduction. We extend that result to show that catastrophic scenarios (here represented as serially correlated catastrophic risks) justify even greater emission reduction.

The model used is highly stylised. One improvement would be to include technological progress. If endogenous and irreversible – both reasonable assumptions – the model dynamics would be more complicated still, and the results may differ. Other improvements include a better parameterisation of the model and a more realistic representation of the physical and economic processes. A greater intellectual challenge is to merge our approach, which emphasizes stochasticity, sunk costs and the timing of policy but has a static and discrete representation of emission reduction, with the alternative school of decision making under catastrophic risk (e.g., Keller *et al.*, 2004), which has dynamic and continuous emission reduction but downplays stochasticity, sunk costs and timing.

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Table 1. Parameters, values, and sources.

Parameters	Initial values	References
Atmospheric stock of greenhouse gases $M(0)$ (billions tons of CO2 equivalent)	785.3	Fisher-Narain (2003)
Initial atmospheric temperature $T(0)$ (Celsius degrees)	0.58	Fisher-Narain (2003)
Initial ocean temperature $T_{LO}(0)$ (Celsius degrees)	0.07	Fisher-Narain (2003)
Emissions	6.1587	Nordhaus-Boyer (2000)
Emissions growth rate, δ	0.005	This study
If an environmental policy is implemented Reduction rate η Then increase	 0.011 0.001	This study
Costs of a policy adoption K (% GDP) for 1% emissions reduction	0.02	Tol (forthcoming)
Social costs of pollution c (1% GDP when T=3)	0.001	Nordhaus (1994)
Damage costs		
h (10% GDP when T=3)	0.01	This study
l (2% GDP when T=3)	0.002	This study
Discount rate r (%)	5	This study
GNP growth rate, *gnp*	0.02	This study
Various parameters for gas concentration evolution		
a (between 0 and 1)	0.02	Nordhaus (1994)
β	0.9	Nordhaus (1994)
σ_1	0.1	Nordhaus (1994)
σ_2	0.1	Nordhaus (1994)
σ_3	0.1	Nordhaus (1994)
λ	0.1	Nordhaus (1994)
μ	0.99	Nordhaus (1994)
Initial parameters of probabilities of catastrophes		
Initial probability of a WAIS collapse	0.001	This study
Initial probability of a disaster, $p(0)$	0.1	This study
Initial probability that this disaster provokes a high-costly damage	0.1	This study

Table 2. Optimal time of investment.

Number of catastrophes already happened before implementing the policy		Optimal time t^* to invest in an environmental policy	Costs of implementing the policy at time t^*	Costs of waiting at time t^*
Number of no catastrophe	Number of catastrophes			
0	59	$t^*=59$	0.03524480	0.03663589
1-2	57-56	$t^*=58$	0.03626460	0.03683871
3-5	56-54	$t^*=59$	0.03524480	0.03663589
6-9	54-51	$t^*=60$	0.03423276	0.03561851
10-12	51-49	$t^*=61$	0.03322862	0.03460699
13-15	49-47	$t^*=62$	0.03223248	0.03360323
16-18	47-45	$t^*=63$	0.03124445	0.03260736
19-20	45-44	$t^*=64$	0.03026464	0.03161948
21-23	44-42	$t^*=65$	0.02929313	0.03063971
24-26	42-40	$t^*=66$	0.02833001	0.02966812
27-28	40-39	$t^*=67$	0.02737534	0.02870480
29-31	39-37	$t^*=68$	0.02642919	0.02774984
32-33	37-36	$t^*=69$	0.02549162	0.02680330
34-36	36-34	$t^*=70$	0.02456267	0.02586523
37-38	34-33	$t^*=71$	0.02364240	0.02493569
39-40	33-32	$t^*=72$	0.02273083	0.02401473
41-43	32-30	$t^*=73$	0.02182800	0.02310239
44-45	30-29	$t^*=74$	0.02093391	0.02219868
46-47	29-28	$t^*=75$	0.02004859	0.02130364
48-49	28-27	$t^*=76$	0.01917205	0.02041729
50-51	27-26	$t^*=77$	0.01830428	0.01953963
52-54	26-24	$t^*=78$	0.01744528	0.01867066
55-56	24-23	$t^*=79$	0.01659503	0.01781039
57-58	23-22	$t^*=80$	0.01575352	0.01695880
59-60	22-21	$t^*=81$	0.01492072	0.01611588
61-62	21-20	$t^*=82$	0.01409661	0.01528161
63-64	20-19	$t^*=83$	0.01328115	0.01445595
65-66	19-18	$t^*=84$	0.01247429	0.01363888
67-68	18-17	$t^*=85$	0.01167600	0.01283036
69-70	17-16	$t^*=86$	0.01088622	0.01203035
71-72	16-15	$t^*=87$	0.01010489	0.01123879
73-74	15-14	$t^*=88$	0.00933195	0.01045563
75-76	14-13	$t^*=89$	0.00856734	0.00968082
77-79	13-11	$t^*=90$	0.00781099	0.00891428
80	11	$t^*=91$	0.00706281	0.00815596
81-83	11-9	$t^*=92$	0.00632274	0.00740576
84	9	$t^*=93$	0.00559068	0.00666363
85-87	9-7	$t^*=94$	0.00486654	0.00592947
88-89	7-6	$t^*=95$	0.00415023	0.00520320
90-91	6-5	$t^*=96$	0.00344166	0.00448472
92-93	5-4	$t^*=97$	0.00274071	0.00377394

94-95	4-3	$t^*=98$	0.00204729	0.00307076
96-98	3-1	$t^*=99$	0.00136128	0.00243827

Table 3. Sensitivity analysis

Variations of parameters	**t^* compared to t^*=59**	**Value of implementing the policy at time t^***
Costs of capital K=0.001% (<) for 1% emission reduction	< t^*=58 for 0-2 no catastrophes and 58-56 catastrophes	<
Costs of capital K=0.01% (<) for 1% emission reduction	=	<
Costs of capital K=0.1% (>) for 1% emission reduction	=	>
Costs of capital K=1% (>) for 1% emission reduction	>	>
Risk neutrality	<	>
Discount rate r=4% (<)	>	>
Discount rate r=8% (>)	<	<
No GNP growth (<)	< t^*=46 for 0-3 no catastrophes and 46-43 catastrophes	< 0.01286666
GNP growth rate gnp=4% (>)	> t^*=70 for 0-6 no catastrophes and 70-64 catastrophes	> 0.12519976
No GNP growth and a lower discount rate (r=4%)	< t^*=52 for 0-2 no catastrophes and 52-50 catastrophes	< 0.02051516
No GNP growth and a higher discount rate (r=6%)	< t^*=40 for 0-1 no catastrophes and 40-39 catastrophes	< 0.00883048
T=95 (<)	< t^*=57 for 0-4 no catastrophes and 57-53 catastrophes	<
T=105 (>)	>	>
Emissions growth of		
0.6% (>)	= t^*=58 for 0-2 no catastrophes and 58-56 catastrophes	>
0.8%	= t^*=58 for 0-3 no catastrophes and 58-55 catastrophes	>
1%	= t^*=58 for 0-4 no catastrophes and	>

	58-54 catastrophes	
1.1%	= t^*=58 for 0 no catastrophes and 59 catastrophes	<
1.4%	= t^*=58 for 0 no catastrophes and 59 catastrophes	<
Emissions growth after policy		
0.0005 (<)	< t^*=58 for 0-2 no catastrophes and 58-56 catastrophes	<
0.002 (>)	=	>
0.005	= t^*=59 for 0-4 no catastrophes and 59-55 catastrophes	>
Catastrophes		
No catastrophe at all	> t^*=85 for 0-2 no catastrophes and 85-83 catastrophes	< 0.0116760
No slide of the WAIS: k(numb(t))=0, $\forall t$	> t^*=85 for 0-2 no catastrophes and 85-83 catastrophes	< 0.01171848
Only dikes*	> t^*=85 for 0-1 catastrophes and 85-84 catastrophes	< 0.01179251
Probability of a bad catastrophe q (k(1)=0.9 and k(2)=1)		
0.05 (<)	=	<
0.15 (>)	< t^*=58 for 0-2 no catastrophes and 58-56 catastrophes	<
Probability of a bad catastrophe q (k(1) and k(2) are adjusted)		
0.05 (<)(k(1)=0.85 and k(2)=1)	=	=
0.15 (>)(k(1)=0.95 and k(2)=1)	< t^*=58 for 0-2 no catastrophes and 58-56 catastrophes	>
Evolution of the probability of a bad catastrophe k(1) and k(2)		
k(1)=0.8 (<) and k(2)=1	=	=
k(1)=1 (>) and k(2)=1	= t^*=59 for 0-1 no catastrophes and	>

	59-58 catastrophes	
Emissions reduction of		
0.1% (<)	=	> 0.03526846
0.2%	=	> 0.03526610
0.3%	=	> 0.03526373
0.4%	=	> 0.03526137
0.5%	=	> 0.03525900
0.6%	=	> 0.03525664
0.7%	=	> 0.03525427
0.8%	=	> 0.03525190
0.9%	=	> 0.03524954
1.0%	=	> 0.03524717
1.2% (>)	=	< 0.03524243
1.3%	=	< 0.03524006

* Only building dikes means that there is neither emission reduction nor different growth path after implementing the policy. Note that here we conserve the same capital costs as for implementing a policy to reduce 1.1% of emissions.

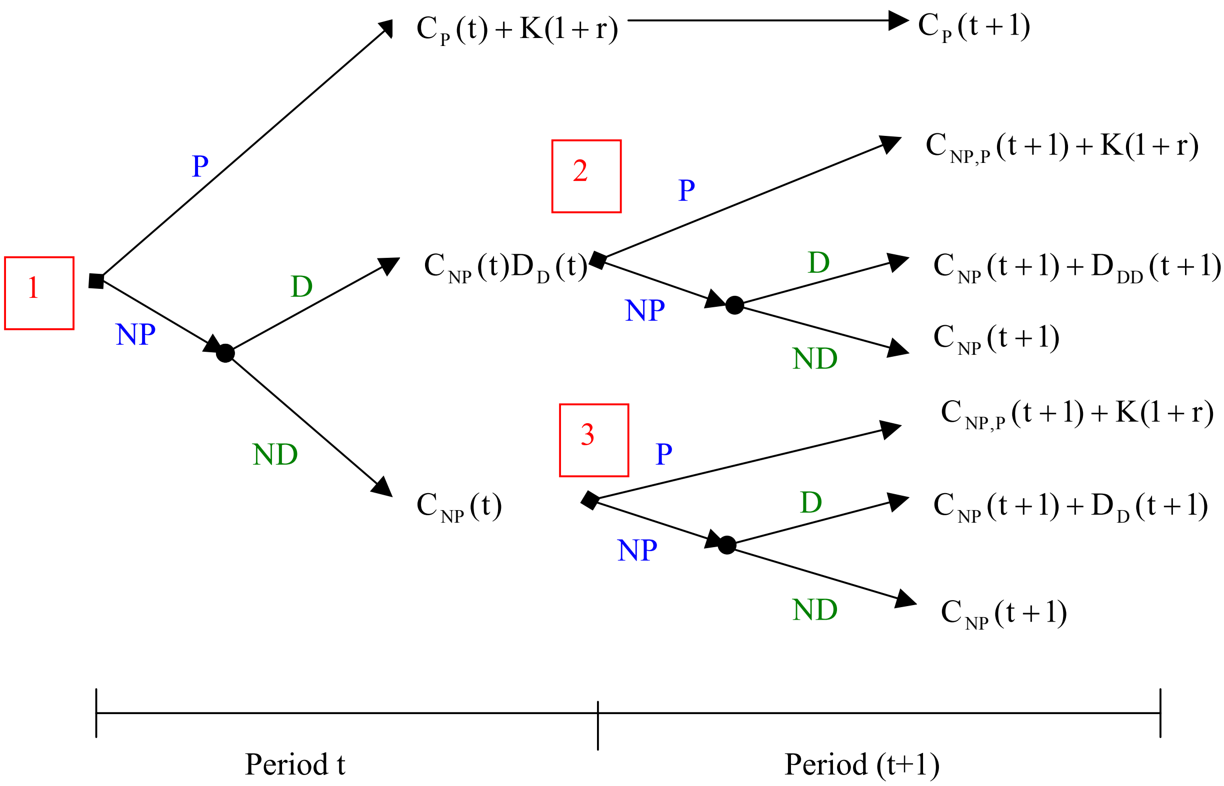

Figure 1. The sequential decision framework over two periods.

Appendix A: Model Code : Temporal variables for backward induction

```
set numb /0*99/;
parameter val(numb),val2(numb);
val(numb) = ord(numb);
val2(numb) = card(numb)-ord(numb)+1;

display val,val2;

file temp /timemap.gms/;
put  temp;

temp.nd = 0;
temp.nw = 0;
temp.tw = 0;
temp.lw = 0;

PUT 'SET ' /;
PUT ' TIME Forward looking time' /;
PUT '  /' /;
LOOP(numb,
 put @4 'time',val(numb),' Time period ',val(numb) /; );
PUT '  /' /;

PUT ' INVTIME backward looking time' /;
PUT '  /' /;
LOOP(numb,
 put @4 'invtime',val(numb),' Backward time period ',val(numb) /; );
PUT '  /' /;

PUT ' TIMEMAP(TIME,INVTIME)' /;
PUT '  /' /;
LOOP(numb,
 put @4 'time',val(numb),'.invtime',val2(numb) /; );
PUT '  /' /;
PUT ';' /;
```

Appendix B: Model code

```
$include timemap.gms

SETS
statevariable

/concentration,concentration_we,temperature,temperature_we,temperature_LOwe,tem
perature_LO,probability,proba_catast,modified_probability,discrete_growth,growth,p
ara_prob/
ecovariable
 /high_damage,low_damage,cumulated_costs,policy,implement,wait,min,gdp/
decision
 /reduce_emissions,do_nothing/
lastime(time)
numb_catastrophes
 /numb_catastrophes1*numb_catastrophes100/
;

SCALARS
absorption absorption factor (in a range of 0 to 1)
 /0.02/
beta
 /0.9/
nu
 /0.99/
sigma1
 /0.1/
sigma2
 /0.1/
lambda
 /0.1/
sigma3
 /0.1/
K PV of cost of policy adoption (0.02% GDP for 1% emission reduction)
 /0.00022/
social_cost social costs of pollution (1% GDP when T is equal to 3)
 /0.001/
h2 coeff of high damage (10% GDP when T is equal to 3)
 /0.01/
l2 coeff of low damage (2% GDP when T is equal to 3)
 /0.002/
discount_rate discount rate
 /0.05/
emission_0 emission rate
 /6.1587/
emission_growth emissions grow over time (0.5% or 1%)
 /0.005/
reduction_rate between 0.1% and 1.1%
 /0.011/
```

```
discrete_step
 /0.001/
concentration_0 value at time1 (billions tons of CO2 equivalent)
 /785.3/
temp_0 initial atmospheric temperature at time1 (Celsius degrees)
 /0.58/
temp_LO_0 initial non-atmospheric temperature at time1 (Celsius degrees)
 /0.07/
pop_growth
 /0.02/
;

PARAMETERS
f(time) in order to transform the gas concentration in temperature (without others
GHGs and aerosols eg DICE)
h(time) idem for equations without emission
x(time,statevariable) physical state indexes (gas concentration temperature damages
and probability of such damages)
y(time,ecovariable) social costs (due to pollution or catastrophe)
action(time,decision,numb_catastrophes)
z(time,ecovariable,numb_catastrophes) social costs according to the number of
catastrophes
x2(invtime, statevariable)
y2(invtime,ecovariable)
action2(invtime,decision,numb_catastrophes)
z2(invtime,ecovariable,numb_catastrophes)
timevalue(time) the time value (equal to 0 at time1)
invtimevalue(invtime)
numbvalue(numb_catastrophes) the number of catastrophes
report_decisions(time,decision,numb_catastrophes)
;

option decimals=8;

timevalue(time)=ord(time)-1;
invtimevalue(invtime)=card(invtime)-ord(invtime);
numbvalue(numb_catastrophes)=ord(numb_catastrophes)-1;

alias(time,timebis);

lastime(time) = no;
lastime(time) $ (timevalue(time) EQ card (time)-1) = yes;

x("time1","concentration")=concentration_0;
x("time1","temperature")=temp_0;
x("time1","temperature_LO")=temp_LO_0;
x("time1","modified_probability")= 0;
x("time1","discrete_growth")= 0;
x("time1","growth")= emission_0;
x("time1","para_prob")=-(log(0.9/1.1))/concentration_0;
```

```
x("time1","probability")= 2 / (1+exp(-
x("time1","para_prob")*x("time1","concentration"))) - 1;

x2("invtime100","concentration")=x("time1","concentration");
x2("invtime100","temperature")=x("time1","temperature");
x2("invtime100","temperature_LO")=x("time1","temperature_LO");
x2("invtime100","probability")= x("time1","probability");
x2("invtime100","modified_probability")= 0;
x2("invtime100","discrete_growth")= 0;
x2("invtime100","growth")= x("time1","growth");
x2("invtime100","para_prob")= x("time1","para_prob");

y(time,"gdp")=0;
y(time,"cumulated_costs")=0;
y(time,"high_damage")=0;
y(time,"low_damage")=0;
x(time,"concentration_we")=0;
x(time,"temperature_we")=0;
x(time,"temperature_LOwe")=0;


loop (timebis,
 y(timebis,"gdp") $ (timevalue(timebis) EQ timevalue("time1"))= 1;
 y(timebis,"gdp") $ (timevalue(timebis) GT timevalue("time1"))= y(timebis-
1,"gdp")*(1+pop_growth);
);

loop (timebis,
 x(timebis,"concentration_we") $ (timevalue(timebis) EQ timevalue("time1")) =
concentration_0;
 x(timebis,"discrete_growth") $ (timevalue(timebis) EQ timevalue("time1")) =
emission_0*(1-reduction_rate);
 x(timebis,"discrete_growth") $ (timevalue(timebis) GT timevalue("time1")  ) =
x(timebis-1,"discrete_growth")*(1+ discrete_step);
 x(timebis,"concentration_we") $ (timevalue(timebis) GT timevalue("time1")) = 596.4
+ beta * x(timebis,"discrete_growth") + (1-absorption) * (x(timebis-
1,"concentration_we")- 596.4);
 h(timebis) = nu*(log(x(timebis,"concentration_we")/596.4)/log(2));
 x(timebis,"temperature_we") $ (timevalue(timebis) EQ timevalue("time1"))
=temp_0;
 x(timebis,"temperature_we") $ (timevalue(timebis) GT timevalue("time1")) =
x(timebis-1,"temperature_we") + sigma1*(h(timebis)-lambda* x(timebis-
1,"temperature_we")-sigma2*(x(timebis-1,"temperature_we")-x(timebis-
1,"temperature_LOwe")));
 x(time,"temperature_LOwe") $ (timevalue(timebis) EQ timevalue("time1"))
=temp_LO_0;
 x(time,"temperature_LOwe") $ (timevalue(timebis) GT timevalue("time1")) =
x(timebis-1,"temperature_LOwe")+sigma3*(x(timebis-1,"temperature_we")-
x(timebis-1,"temperature_LOwe"));
```

```
 y(timebis,"cumulated_costs") $ (timevalue(timebis) EQ timevalue("time1")) =
K*y(timebis,"gdp") * (1/(1+discount_rate))**(timevalue("time1")) + (social_cost
*y(timebis,"gdp"))* (x(timebis,"temperature_we")**2) *
(1/(1+discount_rate))**(timevalue("time1")+1);
 y(timebis,"cumulated_costs") $ (timevalue(timebis) GT timevalue("time1")) =
y(timebis-1,"cumulated_costs") + (social_cost * y(timebis,"gdp"))*
(x(timebis,"temperature_we")**2) * (1/(1+discount_rate))**(timevalue(timebis)+1);
);

y("time1","policy") = sum(lastime,y(lastime,"cumulated_costs"));

action(time,decision,numb_catastrophes) = no;
action2(invtime,decision,numb_catastrophes) = no;

loop (timemap(time,invtime)
        $ (timevalue(time) GT 0),

 x(time,"growth") $ (timevalue(time) GT 0) = x(time-
1,"growth")*(1+emission_growth);
 x(time,"concentration") = 596.4 + beta * x(time,"growth") + (1-absorption) *
(x(time-1,"concentration")-596.4);
 f(time) = nu*(log(x(time,"concentration")/596.4)/log(2));
 x(time,"temperature") = x(time-1,"temperature") + sigma1*(f(time)-lambda* x(time-
1,"temperature")-sigma2*(x(time-1,"temperature")-x(time-1,"temperature_LO")));
 x(time,"temperature_LO") = x(time-1,"temperature_LO")+sigma3*(x(time-
1,"temperature")-x(time-1,"temperature_LO"));
 x(time,"para_prob") $ (timevalue(time) GT 0) = x(time-1,"para_prob")+ x(time-
1,"para_prob")*((x(time,"concentration")-x(time-1,"concentration"))/x(time-
1,"concentration"))* ((log (0.5/1.5) -2 * log (0.9/1.1) ) / (2*log (0.9/1.1) ) );
 x(time,"probability") = 2 / (1+exp(-x(time,"para_prob") * x(time,"concentration"))) -
1;
 y(time,"high_damage") = (h2*y(time,"gdp"))* (x(time,"temperature"))**2;
 y(time,"low_damage") = (l2*y(time,"gdp"))* (x(time,"temperature"))**2;
 y(time,"cumulated_costs")=0;
 x(time,"concentration_we")=0;

 loop (timebis
        $ (timevalue(timebis) GE timevalue(time)),

  x(timebis,"discrete_growth") $ (timevalue(timebis) EQ timevalue(time)) =
x(timebis,"growth")*(1-reduction_rate);
  x(timebis,"discrete_growth") $ (timevalue(timebis) GT timevalue(time) ) =
x(timebis-1,"discrete_growth")*(1+ discrete_step);
  x(timebis,"concentration_we") $ (timevalue(timebis) EQ timevalue(time)) = 596.4 +
beta * x(timebis,"discrete_growth") + (1-absorption) * (x(time-1,"concentration")-
596.4);
  x(timebis,"concentration_we") $ (timevalue(timebis) GT timevalue(time)) = 596.4 +
beta * x(timebis,"discrete_growth") + (1-absorption) * (x(time-
1,"concentration_we")- 596.4);
  h(timebis) = nu*(log(x(timebis,"concentration_we")/596.4)/log(2));
```

```
  x(timebis,"temperature_we") $ (timevalue(timebis) EQ timevalue(time)) =x(time-
1,"temperature");
  x(timebis,"temperature_we") $ (timevalue(timebis) GT timevalue(time)) =
x(timebis-1,"temperature_we") + sigma1*(h(timebis)-lambda* x(timebis-
1,"temperature_we")-sigma2*(x(timebis-1,"temperature_we")-x(timebis-
1,"temperature_LOwe")));
  x(time,"temperature_LOwe") $ (timevalue(timebis) EQ timevalue(time)) =x(time-
1,"temperature_LO");
  x(time,"temperature_LOwe") $ (timevalue(timebis) GT timevalue(time)) =
x(timebis-1,"temperature_LOwe")+sigma3*(x(timebis-1,"temperature_we")-
x(timebis-1,"temperature_LOwe"));
  y(timebis,"cumulated_costs") $ (timevalue(timebis) EQ timevalue(time)) =
K*y(timebis,"gdp") * (1/(1+discount_rate))**(timevalue(timebis)) +
(social_cost*y(timebis,"gdp")) * (x(timebis,"temperature_we")**2) *
(1/(1+discount_rate))**(timevalue(timebis)+1);
  y(timebis,"cumulated_costs") $ (timevalue(timebis) GT timevalue(time)) =
y(timebis-1,"cumulated_costs") + (social_cost*y(timebis,"gdp")) *
(x(timebis,"temperature_we")**2) * ((1/(1+discount_rate))**(timevalue(timebis)+1));
 );

 y(time,"policy") = sum(lastime,y(lastime,"cumulated_costs"));

);

loop (timemap(time,invtime),
 x2(invtime,"concentration")= x(time,"concentration");
 x2(invtime,"probability")=x(time,"probability");
 y2(invtime,"high_damage")=y(time,"high_damage");
 y2(invtime,"low_damage")=y(time,"low_damage");
 y2(invtime,"policy") =y(time,"policy");
 y2(invtime,"gdp")=y(time,"gdp")
);

loop (numb_catastrophes,
 action2("invtime1","reduce_emissions",numb_catastrophes) = yes;
 action2("invtime1","do_nothing",numb_catastrophes) = no;

action("time100","reduce_emissions",numb_catastrophes)=action2("invtime1","reduc
e_emissions",numb_catastrophes);

action("time100","do_nothing",numb_catastrophes)=action2("invtime1","do_nothing"
,numb_catastrophes);
);

loop (numb_catastrophes
   $(numbvalue(numb_catastrophes) GE 1),

 x2("invtime2","modified_probability") $ ((numbvalue(numb_catastrophes))  EQ 1) =
0.9;
```

```
 x2("invtime2","modified_probability") $ ((numbvalue(numb_catastrophes))  EQ 0) =
0.1;
 x2("invtime2","modified_probability") $ ( numbvalue(numb_catastrophes) GE 2) =
1;
 z2("invtime2","wait",numb_catastrophes-1) = (y2("invtime2","policy")+
social_cost*y2("invtime2","gdp")*(x2("invtime2","temperature")**2)*(1/(1+discount
_rate))**(invtimevalue("invtime2")+1))* (1-
x2("invtime2","probability"))+x2("invtime2","probability")*(y2("invtime2","policy")
+(x2("invtime2","modified_probability")*y2("invtime2","high_damage")+(1-
x2("invtime2","modified_probability"))*y2("invtime2","low_damage"))*(1/(1+discou
nt_rate))**(invtimevalue("invtime2")+1));
 z2("invtime2","implement",numb_catastrophes-1) = y2("invtime2","policy");
 z2("invtime2","min",numb_catastrophes-1) $ (
z2("invtime2","implement",numb_catastrophes-1) LE
z2("invtime2","wait",numb_catastrophes-1) ) =
z2("invtime2","implement",numb_catastrophes-1);
 z2("invtime2","min",numb_catastrophes-1) $ (
z2("invtime2","implement",numb_catastrophes-1) GT
z2("invtime2","wait",numb_catastrophes-1) ) =
z2("invtime2","wait",numb_catastrophes-1);
 action2("invtime2","reduce_emissions",numb_catastrophes-1) $(
z2("invtime2","implement",numb_catastrophes-1) LE
z2("invtime2","wait",numb_catastrophes-1) ) = yes;
 action2("invtime2","do_nothing",numb_catastrophes-1) $(
z2("invtime2","implement",numb_catastrophes-1) GT
z2("invtime2","wait",numb_catastrophes-1) ) = yes;
 action("time99","reduce_emissions",numb_catastrophes-1)$(
z2("invtime2","implement",numb_catastrophes-1) LE
z2("invtime2","wait",numb_catastrophes-1) ) = yes;
 action("time99","do_nothing",numb_catastrophes-1) $(
z2("invtime2","implement",numb_catastrophes-1) GT
z2("invtime2","wait",numb_catastrophes-1) ) = yes;
);

loop (timemap(time,invtime)
      $ (invtimevalue(invtime) LT invtimevalue("invtime2") ),

 loop (numb_catastrophes
       $(numbvalue(numb_catastrophes) LE (invtimevalue(invtime))),

  x2(invtime,"modified_probability") $ ((numbvalue(numb_catastrophes))  EQ 1) =
0.9;
  x2(invtime,"modified_probability") $ ((numbvalue(numb_catastrophes))  EQ 0) =
0.1;
  x2(invtime,"modified_probability") $ ( numbvalue(numb_catastrophes) GE 2) = 1;
  z2(invtime,"wait",numb_catastrophes) =
(social_cost*y2(invtime,"gdp")*x2(invtime,"temperature")**2*(1/(1+discount_rate))
**(invtimevalue(invtime)+1)+z2(invtime+1,"min",numb_catastrophes+1))*(1-
x2(invtime,"probability"))
```

```
            +
x2(invtime,"probability")*((x2(invtime,"modified_probability")*y2(invtime,"high_da
mage")+(1-
x2(invtime,"modified_probability"))*y2(invtime,"low_damage"))*(1/(1+discount_rat
e))**(invtimevalue(invtime)+1)+z2(invtime+1,"min",numb_catastrophes));
  z2(invtime,"implement",numb_catastrophes) = y2(invtime,"policy");
  z2(invtime,"min",numb_catastrophes) $ (
z2(invtime,"implement",numb_catastrophes) LE
z2(invtime,"wait",numb_catastrophes) ) =
z2(invtime,"implement",numb_catastrophes);
  z2(invtime,"min",numb_catastrophes) $ (
z2(invtime,"implement",numb_catastrophes) GT
z2(invtime,"wait",numb_catastrophes) ) = z2(invtime,"wait",numb_catastrophes);
  action2(invtime,"reduce_emissions",numb_catastrophes) $(
z2(invtime,"implement",numb_catastrophes) LE
z2(invtime,"wait",numb_catastrophes) ) = yes;
  action2(invtime,"do_nothing",numb_catastrophes) $(
z2(invtime,"implement",numb_catastrophes) GT
z2(invtime,"wait",numb_catastrophes) ) = yes;

action(time,"reduce_emissions",numb_catastrophes)=action2(invtime,"reduce_emissi
ons",numb_catastrophes);

action(time,"do_nothing",numb_catastrophes)=action2(invtime,"do_nothing",numb_c
atastrophes);
 );
);


report_decisions(time,decision,numb_catastrophes)=action(time,decision,numb_catast
rophes);
display z2;
display report_decisions;
```

Working Papers

Research Unit Sustainability and Global Change

Hamburg University and Centre for Marine and Atmospheric Science

Guillerminet, M.-L. and R.S.J. Tol (2005), *Decision making under catastrophic risk and learning: the case of the possible collapse of the West Antarctic Ice Sheet*, **FNU-79** (submitted)

Nicholls, R.J., R.S.J. Tol and A.T. Vafeidis (2005), *Global estimates of the impact of a collapse of the West Antarctic Ice Sheet: An application of FUND,* **FNU-78** (submitted)

Lonsdale, K., T.E. Downing, R.J. Nicholls, D. Parker, A.T. Vafeidis, R. Dawson and J.W. Hall (2005), *Plausible responses to the threat of rapid sea-level rise for the Thames Estuary,* **FNU-77** (submitted)

Poumadère, M., C. Mays, G. Pfeifle with A.T. Vafeidis (2005), *Worst Case Scenario and Stakeholder Group Decision: A 5-6 Meter Sea Level Rise in the Rhone Delta, France,* **FNU-76** (submitted)

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