Whither Climate Change Policy: Waiting to act or Abating Now?

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We present a two period model that examines trade-offs between acting now by precaution versus waiting to learn more. In our analysis, climate change has three types of consequences (rise in mean temperatures which leads to discomfort, increase in frequency of extreme weather events, and an increase in the risk of a climate catastrophe). We assume that the pre-emptive abatement leads to cleaner technology in second period, which is justified by the Porter Hypothesis; while assuming *status quo* for the state of technology in the waiting to learn more approach. This difference between these two approaches bears on each of these consequences by affecting the incremental increase to greenhouse gases' stock from consumption. A numerical illustration shows that procastrination on abatement can only be justified with a higher discount factor or a lower susceptibility to current extreme weather events. On the other hand, we find that the location of catastrophic threshold is irrelevant for climate change policy. However, to minimize the pain from climate change, the key lies in developing greener technologies.

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I. Introduction

With the risk of a catastrophic event triggered by the accumulation of a stock pollutant, is it better to abate emissions now and invest in abatement technology or should we instead wait and invest in gaining better scientific knowledge? This question synthesizes one of the key dilemma facing policy makers as stock effects, learning, and uncertainty lead to a tension between instituting control and delaying action to address global warming. Policy makers face similar trade-offs with a number of other environmental problems, including hazardous wastes, acid rain, species extinction, or pesticide accumulation, for example (Kolstad, 1996).

The basic science of climate change is now better understood and is supported by empirical evidence, but the magnitude of various potential changes in the climate is still hotly debated. Three effects of climate change are often mentioned. The first one is rising mean temperatures that has ramifications on humans, as well as on entire ecosystems. The most recent assessment by the UN Intergovernmental Panel on Climate Change (IPCC) reported that mean global temperature may increase between 1.5 and 6 degrees celsius over the 21st century (IPCC, 2001). The second consequence of climate change is a potential increase in extreme weather events that are likely to cause heavy damages. Indeed, rainfall patterns are likely to be affected and events such as tornadoes or droughts will likely become more common and more severe. The third, and even more worrisome, impact of climate change would be the occurrence of a catastrophic event, such as a change in ocean currents, which would trigger a very rapid climate shift. IPCC classifies its findings based on how confident it is in them, and these probability rankings are generally assumed to correspond to Bayesian subjective probabilities, so they give rise to different interpretations and hence different responses.

Policy makers are scrambling for ways to tackle climate change as some of its effects are starting to become apparent. In the last five years, the following events took place:

- 2002: dramatic floods on the Elbe in Germany and neighboring countries.
- 2003: a summer heat wave in Europe with over 35,000 fatalities.
- 2004: highest losses to-date from hurricanes in the North Atlantic in a single season; highest recorded number of tropical cyclones with landfall in Japan in a single year; first tropical cyclone in the South Atlantic with landfall in Brazil.
- 2005: highest number of tropical cyclones (27) and hurricanes (15) in a single season in the North Atlantic; strongest hurricane ever recorded in the North Atlantic (Wilma, 882 hPa central pressure), fourth strongest (Rita) and sixth strongest (Katrina) in a single season; the most northerly and easterly hurricane ever (Vince), which formed in October near Madeira; and the first tropical storm ever (Delta) to reach the Canary Islands (Munich Re).[1]

As the public has become more aware of the potential devastation that could be caused by climate change, a number of policies aiming to curb anthropogenic emissions of greenhouse gases have been put in place. For example, under the Kyoto Protocol, which came into force in February 2005, member states of the European Union, Russia & Japan have agreed to cut their CO_2 emissions below 1990 levels by 2008. As a result, these countries are investing in abatement technology and they are experimenting with emission trading schemes. By contrast, the United States has adopted a different approach. Instead of cutting emissions now, it has

[1] Munich Re website www.munichre.com

chosen to invest in climate change research so as to try to resolve remaining areas of uncertainty about damages from climate change and improve the state of technology. [2]

In the economics literature, the US is often characterized as a society with a high level of impatience (a high discount rate) and a high level of risk tolerance (a low index of relative risk aversion (IRRA)), while Europe & Japan are placed at the other end of the spectrum (Heal & Kristrom, 2002). Hence when we observe the nature of the problem along with responses from various countries, there is an apparent *paradox*, with the present-oriented and less risk-averse United States appearing to dread the risk of catastrophic uncertainty more (investing in scientific research but not abating GHGs), while the opposite holds for the European Union (signing and ratifying the Kyoto Protocol). The literature proposes two potential explanations: first, a slight increase in mean temperatures may actually benefit the U.S. (Mendelsohn et al, 1994; Schlenker et al, 2005); and second, abatement costs for the U.S. are very high (Goulder & Pizer, 2006). In our analysis, we find that waiting for additional information is consistent with a high discount rate and a low susceptibility to weather events.

The United States has refused to sign the Kyoto protocol, as it does not agree to any form of mandatory abatement of greenhouse gases (GHG) emissions. In contrast, the state of California has recently ratified a proposal for a mandatory cut in GHG emissions. These cuts in California aim to reduce emissions of state by 25 percent by 2020.[3] Officially, the U.S. is following a 'learn then act' strategy, which was analyzed by Kolstad (2002). From the year 2004 to 2006, the U.S. federal government has spent around 5 to 5.5 billion dollars per year on climate change (2 billions dollars every year on scientific research and about 3 billion dollars as

[2] http://www.climatescience.gov/

[3] http://news.bbc.co.uk/2/hi/business/5387198.stm

investment in climate change technology).[4] There has been an increase in international assistance programs that help developing countries to improve energy efficiencies. The striking feature of US climate change expenditure is the tremendous increase in energy tax incentive proposals recently. These proposals give tax savings to renewable energy projects; these incentives are to promote the deployment of energy efficient technologies at home.

By contrast, the EU approach is markedly different. It is based on the Precautionary Principle (PP), which says that, where there are threats of serious and irreversible damage, a lack of scientific certainty shall not be used as an excuse for postponing cost-effective measures to prevent environmental degradation.[5] The EU has invoked the precautionary principle for genetically modified (GM) crops and mad cow disease (BSE) (Gollier et al, 2003). Under the Kyoto agreement, the EU will reduce its greenhouse gases emissions to less than 1990 levels in a first phase (2008-2012); discussions have already started for emission targets for the next phase. As European companies have to follow the deadlines set under the Kyoto Protocol, a sudden push towards investing in abatement technology is expected.

The EU document on climate change advocates tax breaks, subsidizing research, and disseminating information on green technologies for member countries.[6] The EU's R&D program in 2002 to 2006 allocates roughly 2 billion euros to research that directly or indirectly deals with climate change, complimenting 1.2 billion euro being spent on nuclear research.

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[4] These figures are from the fiscal year 2006 report to congress on federal climate change expenditures. In the current year climate change research is funded by 1.892 billion dollars while the research in technology is marked for about 2.865 billion dollars. A lion share of the budget in climate change technology goes to Department of Energy.
http://www.whitehouse.gov/omb/legislative/fy06_climate_change_rpt.pdf#search=%22fiscal%20year%202006%20report%20to%20congress%20on%20federal%20climate%20change%20expenditures.%22

[5] From the United Nations summit in 1992, on Environment and Development.

http://www.unep.org/Documents.multilingual/Default.asp?DocumentID=78&ArticleID=1163

[6] http://europa.eu.int/comm/environment/etap/implementing.htm

These grants complement the financial resources that the 25 Member States commit nationally to climate change-related R&D. Also, it is proposed to increase EU funding for climate-relevant research approximately three-fold from 2007 onwards.[7] The International Energy Agency (IEA) forecasts that over 1 trillion dollars will be invested in non-hydro renewable technologies worldwide by 2030.[8]

In this paper, we consider a two period model with two policy decisions; the first alternative is investing in scientific research to warn us of catastrophic danger and the second is to start abating and investing in abatement technology. We compare these two approaches to explore under what conditions one approach is better than other. Calling the first alternative the 'American approach' is an obvious simplification as the US is also investing in renewable technologies and many US states are considering voluntary reductions. Conversely, we cannot call the second alternative the 'European approach' as the EU is also investing in scientific research. However for the sake of simplicity, we call the 'learn then act' approach as 'American' and the 'act preventively' approach as 'European'.

In the next section we review the literature pertinent to the problem posed. In Section III, we develop and discuss a two period model to inculcate all the features of a stock pollutant problem. We then report a numerical illustration based on the model for the case of climate change in Section IV, Section V introduces an incomplete two-period dynamic model and the last section concludes and suggests future research.

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[7] Source is EU's document on action on climate change.
http://ec.europa.eu/environment/climat/pdf/rd_stimulate_techn.pdf
[8] The Economist, Dec 8th 2005

II. Literature Review

In the economics literature, we have not found any analytical or numerical model that incorporates irreversibility, stock effect, research in science and abatement technology, threshold for catastrophic damage, magnitude of catastrophic damage, discounting factor for long term, precautionary and pre-emptive abatement and damage from current extreme weather events. These issues are in our opinion, characteristic of climate change. We discuss the following papers that deal with some of these concepts in isolation.

Climate change poses an interesting problem for economists (see, for example, surveys papers by Heal & Kristrom, 2002; and Goulder & Pizer, 2006). For an analysis of appropriate discounting factor to be used for climate change, see Portney & Weyant (2000).

Irreversibility, stock effect and the resolution of uncertainty

Learning in the presence of irreversibility, (here the stock of greenhouse gases) can lead to either more or less of the irreversible development activity depending on the shape of the marginal cost function. If this function is concave, Epstein (1980) showed that learning leads to less of the irreversible activity; the result is reversed if the marginal cost curve is convex. Unfortunately, strict concavity or convexity is overly restrictive for representing climate change (Ulph & Ulph, 1997). Furthermore, Epstein's result does not address the conditions under which learning has no effect (that is cases with and without learning leading to the same level of activity in the first period), or what determines whether the magnitude of a divergence is large or small (Leach, 2004). Thus, although the convexity or concavity of the marginal cost function determines the direction of learning effects, the shape of the probability distribution also affects it over uncertain abatement costs and damage costs.

If an action is irreversible, the possibility of acquiring better information in the future should lead to a lower level of commitment today. The irreversibility effect may not hold for all cases of climate change, and there is little empirical support for such an effect (see Ulph & Ulph, 1997; Kansuntisukmongkol, 2004). The above results hold in an expected utility framework. If we use the maxmin criteria, however, Lange (2003) shows that the irreversibility effect holds only if the value of learning is negative.

There is a clear dilemma between acting now or waiting until the arrival of more information when irreversibility is present. The first source of irreversibility lies in the fact that emissions are strictly positive, so the carbon stock in the atmosphere can only be reduced through slow natural decay. The second source of irreversibility is capital devoted to abatement. If a regulator learns about the level of damages from temperature changes, and can adapt policies over time, an easily reversible policy such as a tax is preferred to a level of abatement capital, which is non-reversible in the short run (Kolstad, 1996; also Kelly & Kolstad, 1999). Two interpretations are possible for the irreversibility related to investments in abatement capital. The first one is to measure irreversibility by the durability of capital; the second one is to define investment in abatement capital as irreversible if that capital cannot be used in other production sectors as in growth theory models. The consequences of irreversibility of abatement investment depend on which of these definitions is adopted (see Fisher & Narain, 2002).

Since climate change is characterized by uncertainty (about damages, future preferences, economic growth, and future abatement costs because of innovation) and irreversibility (relative to the GHG stock and capital for abatement), it is natural to seek using tools from of the theory of real options. In this context, for example, an option is associated with the flexibility to postpone investing in greenhouse gas abatement. Such an analysis is complicated by the presence of different types of uncertainty (scientific uncertainty, impact uncertainty and policy uncertainty). In general, a policy response can take two forms: mitigation, actions that reduce the flow of GHG into the atmosphere and hence change the probability distribution over future climate states, and adaptation, which characterizes actions that reduce the damages associated with a given climate state (for an extended discussion see Heal & Kristrom, 2002). Pindyck (2002) discusses optimal policies under economic and ecological uncertainty separately. Saphores (2004) examines a similar problem in a continuous time framework; his results suggest that environmental uncertainty is model dependent.

Precautionary Principle

To address uncertainty about some key parameters, a number of countries in the European Union have invoked the Precautionary principle. The debate between 'learn then act' and 'act then learn' has been outlined earlier. The balance between these two approaches depends on the shape of the utility function and in particular on whether or not society shows prudence. Prudence is equivalent to a positive third derivative of the utility function: a prudent person increases her savings in the face of an increase in the risk associated with future revenues (Gollier et al 2000, 2003; Henry & Henry, 2002). An early resolution of uncertainty reduces the initial saving of prudent consumers if either their utility function exhibits HARA, or if the rate of pure preference for the present equals the risk free rate. (Eeckhoudt et al, 2003). It has been suggested that applying the precautionary principle may not be optimal for climate change as it could lead to even higher emissions in the first period with rank dependent utility functions (Bargiacchi, 2002).

Numerical Approaches

There have also been attempts to model climate change in a general equilibrium framework. Several papers examine how long it could take to resolve uncertainty; results range from couple of decades (Kelly & Kolstad, 1999) to thousands of years (Leach, 2004). In fact, uncertainty about the magnitude of climate impacts is far less critical than uncertainty about the timing of their arrival (see Dumas & Duong, 2004 for a greater exposition). In a two-period model, the effect of learning on the first period consumption depends on cross-period interactions (Webster, 2000 using the MIT integrated global system model). Growth models with climate change have incorporated uncertain damage thresholds (see Kelly et al, 2004); these uncertain thresholds have been studied by Mastrandea & Schneider (2004).

International nature of the climate change problem

Since global warming is clearly an international problem, a number of papers have also focused on interactions between countries. For example, Ulph & Maddison (1997) find that the value of information increases with higher correlation of damages among two symmetrical countries both ways, when they co-operate and when they do not co-operate. Preliminary results (IPCC, 2001) show that poor countries will be affected more and don't have the resources to combat climate change, while the onus of climate change research and abatement falls on rich countries (see, for example, Baker, 2004; for a similar argument).

We believe with our integrated approach, we can strive to answer the big picture questions about climate change policy. That is, under what conditions it is optimal to procrastinate any action on climate change. Although the research till date asks the general questions about resolution of uncertainty and precautionary action, this paper tailors these concepts for the unique case of climate change by accounting for both current extreme weather events and a future catastrophe. We also take into account the technology changes being brought about by mandatory regulation as expressed in the Porter Hypothesis.[9]

III. A Two period Model

In this section, we outline the features of a two period model to compare 'learn then act' and 'acting preventively' approach, to deal with a stock pollutant in the presence of a catastrophic risk. Period 1 is now and period 2 is in the future. We assume that period 2 starts when the stock doubles from its natural level after full consumption in the first period.[10] We also assume that when the stock of pollutant doubles, catastrophic risk becomes credible.[11] A two period model is a convenient starting point for our analysis; it will be expanded in future to an infinite horizon model.

The utility function in period $i \in \{1,2\}$ is denoted by $U(c_i, s_i)$. It depends on the consumption of a composite good c_i and the level of a stock pollutant s_i. For climate change, the inclusion of s_i in the utility function is suggested in Heal and Kristrom (2002). The stock pollutant is a side effect of consumption, for example, using a motor vehicle for transportation adds to our utility, while the emissions generated by that vehicle add to the greenhouse stock, reducing our utility. We assume that

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[9] According to the Porter Hypothesis strict environmental regulations can induce efficiency and encourage innovations that help improve commercial competitiveness.

[10] Full consumption in period i signifies total indulgence of that period's income into consumption, signifying nil abatement in period *i.*

[11] We assume that unless the stock reaches twice its natural level, there is no risk of catastrophic damage.

$$\frac{\partial U}{\partial c_i} > 0,\ \frac{\partial U}{\partial s_i} < 0,\ \text{and}\ \frac{\partial^2 U}{\partial c_i^2} < 0. \tag{1}$$

Here $\frac{\partial U}{\partial c_i}$ decreases with increase in consumption (assuming diminishing marginal utility of consumption), while the discomfort due to stock pollutant increases with the level of its stock. We also assume

$$U(0, s_i) = -\infty \tag{2}$$

to ensure non-zero consumption in either periods.

We consider a social planner whose goal is to maximize the present value of expected utility across the two periods by choosing the consumption of the aggregate good c_i (control variable), which in turn impacts the level of the stock pollutant s_i (state variable). For simplicity, we normalize income in period 1 to unity, while income in the second period is equal to G (G>1) to reflect exogenous productivity growth. Income can either be consumed or invested in abatement:

$$\begin{cases} c_1 + a_1 = 1, \\ c_2 + a_2 = G. \end{cases} \tag{3}$$

The stock depends on the previous period's stock and also on additions in this period, which are related to state of technology and consumption. α_i, where $\alpha_i > 0$, is the contribution to the stock of pollutant per unit of consumption in period i. The state equations are then

$$\begin{cases} s_1 = s_0 + \alpha_1 (1 - a_1) c_1, \\ s_2 = s_1 + \alpha_2 (G - a_2) c_2. \end{cases} \tag{4}$$

We assume that $\alpha_1 \geq \alpha_2$, to reflect that the state of technology in the second period will not be worse than the first period.

We model catastrophic damage as a step function, with an uncertain threshold S. As shown on Figure 1, utility is not affected as long as the stock of pollutant remains below S, but as soon as this threshold is crossed, there is a discrete loss of utility *D*. We assume full knowledge of catastrophic damage *D*.

Insert Figure 1 here

The threshold *S* is modeled as a random variable with the following support. Let s_N be the natural level of the stock and let s_0 $(s_0 > s_N)$ denote the starting stock in period 1. We assume that we have a risk of catastrophe when the stock doubles its natural level and the likelihood of catastrophe increases with further increase in stock. We suppose that, with total consumption of income in both periods and with an unchanged technology, the stock exceeds the stock threshold value. We also assume certainty of catastrophic damage with tripling of the stock pollutant above its natural level. So we consider $2s_N < S < 3s_N$, and $s_0 + \alpha_1 + \alpha_1 G^2 > S$. Although these assumptions may seem arbitrary, they can be justified for the case of climate change, as discussed in the next section.

Insert Figure 2 here

In Figure 2, the triangle shows the cumulative density function (cdf) for the random variable S. For simplicity, we assume a probability distribution with a linear density that increases with increase in stocks. The density function of *S* then needs to equal

$$f(s) = \frac{2(s - 2s_N)}{(s_N)^2} \qquad (5)$$

in order to have $\int_{2s_N}^{3s_N} f(s)ds = 1$.

Let ρ $(0 < \rho \leq 1)$ denote the discount factor to discount the second period utility. We shall now discuss the two strategies 'learn then act' and 'act preventively' as motivated in the introduction.

III.1 Learn then Act

In this strategy the social planner chooses not to abate at all in the first period but instead awaits the fruits of scientific research. In the second period, she knows the location of S with certainty. We assume that the social planner spends a small fraction β of her first period's income for scientific research. We also assume that α_1 characterizes the abatement technology in the second period, which remains the same from the first period. Not abating in the first period leads to a higher stock and hence a higher risk of catastrophe; however, it entails higher utility due to higher consumption than the 'act preventively' approach. In the second period, depending on the results of research, if the threshold S is low, we speculate that this strategy has less leeway and higher inertia in cutting emissions compared to the 'act preventively' approach. The social planner's problem can then be described as

$$\underset{c_2}{Max}\, V_1 \equiv U(1-\beta, s_1) + \rho\{\max_{0<\{c_2\}\leq G}[\, U(c_2, s_2) - DI(s_2 \geq S)]\} \qquad (6)$$

subject to

$$\begin{cases} s_1 = s_0 + \alpha_1(1-\beta)^2, \; s_2 = s_1 + \alpha_1 c_2^2, \\ c_1 = 1-\beta, a_1 = \beta \text{ and } c_2 + a_2 = G. \end{cases} \tag{7}$$

At the start of second period the social planner knows the exact location of threshold *S*, so c_2 will be chosen optimally according to the results of scientific research. We denote by $\pi_R(c_2)$ the utility in the second period without catastrophic damage.

$$\pi_R(c_2) \equiv U(c_2, s_0 + \alpha_1(1-\beta)^2 + \alpha_1 c_2^2) \tag{8}$$

Combining $\pi_R(c_2)$ with catastrophic damage, the second period optimization can be written

$$\max_{0< c_2 \le G} \pi(c_2) \equiv \max_{0< c_2 \le G} [\pi_R(c_2) - DI(s_2 \ge S)] \tag{9}$$

We first look at the case $s_2 \le S$ that is when we don't reach the threshold for catastrophic damage. We can check that $\pi_R(c_2)$ is concave.[12] Also, we note that Fisher and Narian (2002) also use a utility function that is concave in consumption.

In that scenario we choose c_2 such that

$$\frac{\partial \pi_R}{\partial c_2} = \frac{\partial U}{\partial c_2} + \frac{\partial U}{\partial s_2} 2\alpha_1 c_2 = 0 \tag{10}$$

Suppose c_{2o} solves the above. This means the optimum consumption is such that marginal utility of consumption is equal to the marginal disutility from the stock.

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[12] Hessian $H = \begin{pmatrix} \frac{\partial^2 U}{\partial c_2^2} & \frac{\partial^2 U}{\partial s_2 \partial c_2} \\ \frac{\partial^2 U}{\partial c_2 \partial s_2} & \frac{\partial^2 U}{\partial s_2^2} \end{pmatrix}$, here we have $\frac{\partial^2 U}{\partial s_2^2} = \frac{1}{4\alpha_1^2 c_2^2} \frac{\partial^2 U}{\partial c_2^2}$ using the state equation (4), $\frac{\partial^2 U}{\partial c_2 \partial s_2} = \frac{\partial^2 U}{\partial s_2 \partial c_2} = \frac{1}{2\alpha_1 c_2} \frac{\partial^2 U}{\partial c_2^2}$ by Young's theorem and the state equation (4), also $\frac{\partial^2 U}{\partial c_2^2} < 0$ from (1). Hence H is negative semidefinite.

For the case $s_2 > S$, we consider the following approach. Let us denote by c_{2T}, the corresponding consumption for the threshold stock S. From (4), $S = s_0 + \alpha_1(1-\beta)^2 + \alpha_1 c_{2T}^2$, so isolating c_{2T} leads to

$$c_{2T} \equiv \sqrt{\frac{S - s_0 - \alpha_1(1-\beta)^2}{\alpha_1}} \tag{11}$$

Our analysis will be based on comparing c_{2o} to c_{2T}, due to the presence of the discontinuity caused by catastrophic damage. Here we need to consider two cases

1. $c_{2o} \le c_{2T}$

In this case, c_{2o} is the solution and the stock does not reach its threshold value.

2. $c_{2o} > c_{2T}$

This is the more interesting case; we need to consider three sub-cases.

2.1 If $U(c_{2o}, s_0 + \alpha_1(1-\beta)^2 + \alpha_1 {c_{2o}}^2) - D > U(c_{2T}, S)$ then it is optimal to consume more than the threshold consumption, even though it triggers a catastrophe. Hence the consumption is c_{2o}.

2.2 If $U(c_{2o}, s_0 + \alpha_1(1-\beta)^2 + \alpha_1 {c_{2o}}^2) - D < U(c_{2T}, S)$ then it is optimal to avoid catastrophe and the consumption is c_{2T}.

2.3 If $U(c_{2o}, s_0 + \alpha_1(1-\beta)^2 + \alpha_1 {c_{2o}}^2) - D = U(c_{2T}, S)$ then we can have either consumption c_{2O} or c_{2T}.

It is interesting to note that, if the threshold is low, there is more willingness to consume more than the threshold level of consumption, even though these actions lead to catastrophic damages, but this willingness decreases with increases in magnitude of damages *D*. These are interior solutions, but we also check for corner solutions. The assumption $U(0,s)=-\infty$ ensures that $c_2 \neq 0$ .If $c_{2_o} < G$ then the treatment is the same as above. For $c_{2_o} > G$, we also have $c_{2T} < G$ by our assumptions on *S*. Then we have to compare $U(G, s_0 + \alpha_1(1-\beta)^2 + \alpha_2 G^2) - D$ with $U(c_{2T}, S)$ to see if the social planner wants to consume the total income and face the damages of a catastrophe or if she will consume up to the threshold values of consumption and hence avoid any catastrophe. By this strategy, the social planner has the exact location of *S* in the second period, but she is at a greater risk with high stock levels after the first period. Also not abating in the first period will lead to a higher inertia for emission cuts in the second period, if they are needed. One example of this inertia is the stolid state of technology across the periods for this approach.

III.2 Act Preventively

With this approach, the social planner chooses to have a mandatory, ad-hoc abatement in the first period and acts according to her expectations of catastrophic damage in the second period. Due to the mandatory cut in emissions, industries will conduct research to find cleaner technologies, and also the social planner subsidizes and supports R&D in clean technologies, so that $\alpha_1 > \alpha_2$. There will be a growth of new industry that revolves around innovations in abatement technology.[13] Hence we can safely assume cleaner technology in the second period.

The social planner chooses to cut the consumption by a certain fraction δ out of the total income. We have $c_1 = 1-\delta$ and $a_1 = \delta$. We consider the following system

$$V_2 = U(1-\delta, s_1) + \rho E\{\max_{0<\{c_2\}\leq G}[\,U(c_2, s_2) - DI(s_2 \geq S)]\} \qquad (12)$$

[13] The Economist Jun 8th 2006.

subject to

$$\begin{cases} s_1 = s_0 + \alpha_1(1-\delta)^2 \text{ and } s_2 = s_1 + \alpha_2 c_2^2 \\ c_1 = 1\text{-}\delta, a_1 = \delta \text{ and } c_2 + a_2 = G \end{cases} \tag{13}$$

In this case consumption in the second period should equal to $c_{2o}{}^*$ that is defined as a solution of $\frac{\partial U}{\partial c_{2o}} = -2\frac{\partial U}{\partial s_2}\alpha_2 c_{2o}$ or G, whichever is smaller. We consider the other case where $s_2 > 2s_N$.

The expected catastrophic damage using (5) is $\int_{2s_N}^{s_2} 2D\frac{[S-2s_N]}{[s_N]^2}dS = \frac{Ds_2^2}{s_N^2} - 4\frac{Ds_2}{s_N} + 4D$.

Assuming expected utility maximizing behavior for the second period, we get

$$\max_{0<\{c_2\}\le G} E[U(c_2, s_2) - DI(s_2 \ge S)] \tag{14}$$

Taking the FOC, we have

$$\frac{\partial U}{\partial c_2} + 2\alpha_2 c_2 \frac{\partial U}{\partial s_2} - 2\alpha_2 c_2 [\frac{2D(s_1 + \alpha_1 c_2^2)}{s_N{}^2} - \frac{4D}{s_N}] = 0 \tag{15}$$

Suppose c_2^* solves this equation. Then we have,

$$\frac{\partial U}{\partial c_2{}^*} = 2\alpha_2 c_2{}^* [\frac{2D(s_1 + \alpha_1 c_2^2)}{s_N{}^2} - \frac{4D}{s_N} - \frac{\partial U}{\partial s_2}] \tag{16}$$

This means the optimum consumption is such that marginal utility of consumption is equal to the sum of marginal disutility from the stock and the expected damage from catastrophe.

It should be kept in mind that for the first period the consumption is cut by a fraction δ. Due to this cut, consumption in first period is less than the first period consumption for the 'learn then act' strategy. We are not sure about the optimal value of δ, however, for the case of climate change dealt in the next section, we find that δ has a bound defined on the state of technologies and economic growth in the two periods, as outlined in (18).

We now need to compare the total utility functions V_1 and V_2 for both cases. If we just compare the consumption values in both periods for both approaches, 'learn then act' is superior in the first period due to higher consumption. However, comparing consumption approach ignores the effect of stock build-up. For climate change, scientists emphasize the consequences of a stock effect at least as much as the looming dangers of a catastrophic event. The Economist reported that the year 2004 was laced with the worst extreme events ever seen and year 2005 is going to be worse.[14] The prophecy came true with Munich Re reporting 2005 as the worst year in weather related losses; $83 billion was the damage due to tropical cyclones alone.[15]

IV. A numerical illustration for the case of Climate Change

In this section, we illustrate numerically the model described above to gain insights in the policy issues regarding climate change. With the sophistication of back of envelope calculations, this illustration gives a rationale for the difference between the 'learn then act' and 'act preventively' approaches.

[14] The Economist September 30th 2004.

[15] www.munichre.com

The doubling of greenhouse gases from their pre-industrial age natural levels is expected to occur before the next century at the current emission rate.[16] Hence we assume the period 2 to be median 50 years from now. We define the utility function (c.f. section III)

$$U(c_i, s_i) = \ln c_i - \phi s_i^2 \tag{17}$$

Here ϕ signifies the regional sensitivity of the increased stock. It is reasonable to assume this functional form for utility, given our assumptions about diminishing marginal utility of consumption. We also assume that the damage from extreme weather-related events ϕ increases faster than the stock of GHG. This assumption makes sense given the latest IPCC report that states, with an increasing concentration of GHG, extreme events will become more frequent. In contrast to our assumption that makes catastrophic damages D a constant, ϕ can vary for different regions. In IPCC (2001), various models show increased sensitivity for tropical regions that is some areas are more prone to extreme events such as droughts or tornadoes, which are exacerbated by climate change.

IPCC (2001) reports that the pre-industrial age concentration of carbon dioxide (CO_2) was 280 parts per million (ppm), the concentration of stock now is about 370 ppm and with the doubling of stock, generally expected in this century it shall be around 560 ppm. The doubling of the CO_2 stock from its natural level can lead to an increase of average global temperature by $1.4 - 5.8^0$ degree Celsius at the turn of next century. The European Union in 2005 states that the

[16] *Science* News July 1, 2005, http://www.sciencemag.org/cgi/content/full/309/5731/100

current stock of GHG is 425 ppm CO_2 equivalent.[17] Latest news reports about the fourth IPCC report, which is expected next year, suggest a range of $2-4.5^0$ degree Celsius.[18]

Mastrandea & Schneider (2004) argue from a Monte Carlo simulation that with the doubling of stock from its natural level, 39% of scenarios cross the catastrophic threshold of 3.5^0 degree Celsius. According to Schneider, 3.5^0 degree Celsius is a conservative estimate for a threshold to trigger 'dangerous' impacts.[19] By contrast, the European Union believes that the threshold is at 2^0 degree Celsius. The IPCC (2001) reports that the mean global temperature has increased by $0.6^0-0.9^0$ degree Celsius (over the last century) and even if we stop the emissions right now it shall lead to about 0.6^0 degree Celsius further increases in temperature. This is due to the buildup of the stock of CO_2, even though it is not enough to trigger catastrophic damage. It is worthy to keep in mind that we are far from an ice age by $5\text{-}10^0$ degrees Celsius.[20] We ignore GHG stock and temperature interactions in our analysis.

We can have a rough estimate of the value of α_1 from (4). The stock of greenhouse gases doubles at the start the second period with the assumption of total consumption of income in the first period. Hence $560 = 425 + \alpha_1(1)^2$, so $\alpha_1 = 135\,ppm$. In the 'learn then act' approach, the parameter of spending on climate science is β ($\beta \sim 0.001-0.01$), this estimate is made from the

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[17] http://europa.eu.int/rapid/pressReleasesAction.do?reference=MEMO/05/42&format=HTML&aged=0&language=en&guiLanguage=en

[18] http://news.bbc.co.uk/2/hi/science/nature/4761804.stm

[19] http://stephenschneider.stanford.edu/Climate/Climate_Impacts/CliImpFrameset.html

[20] http://www.agiweb.org/gap/legis106/climate_hearings.html

figures of scientific budgets of the US.[21] In the 'act preventively' case, the social planner chooses to cut the consumption by a fraction δ ($\delta \sim 0.01 - 0.03$).[22] These figures for δ are calculated from the estimates of costs of implementing the Kyoto protocol. Income in the second period G is expected to be about 5 times the current income, assuming a realistic 3-3.5% growth rate over the next 50 years.[23]

In the 'act preventively' case, how can 'acting preventively' escape climate change catastrophe? By acting preventively, we can escape catastrophe only if the GHG stock, even with total consumption of income in the second period, is less than the twice the natural level of stock, which is assumed to be the lower bound of the catastrophic threshold S.[24] Asking this question is important, as the agenda of the European Union is to stop the growth of the stock of greenhouse gases before a catastrophe strikes.

$$1.5s_N + \alpha_1(1-\delta)^2 + \alpha_2 G^2 < 2s_N \Rightarrow \alpha_1(1-\delta)^2 + \alpha_2 G^2 < .5s_N \qquad (18)$$

We assumed that with total consumption of income (no abatement) in the second period, the stock reaches twice its natural level. So we have, $1.5s_N + \alpha_1 = 2s_N$ leads to $\alpha_1 = 0.5s_N$. Inserting this into (18) gives $\alpha_2 G^2 < \alpha_1[1-(1-\delta)^2]$, which leads to $\delta > 1 - \sqrt{1 - \frac{\alpha_2}{\alpha_1} G^2}$. To

[21] http://www.usgcrp.gov/

[22] http://www.oecd.org/dataoecd/38/53/1923159.pdf

[23] http://www.imf.org/external/pubs/ft/weo/2004/01/chp1pdf/fig1-1.pdf The growth rate for the world's gdp has been 3-3.5% from 1970-2003. We assume the same rate of growth for the next 50 years as IMF found for the last 30 years.

[24] This means that due to the policies in the first period, even with full consumption (no abatement) in the second period, the stock does not reach catastrophic levels.

understand these conditions we have to see that $1-\frac{\alpha_2}{\alpha_1}G^2$ should be positive, i.e. $\frac{\alpha_1}{\alpha_2} > G^2$. Hence, as a pre-requisite, the rate of de-carbonization over the two periods should be faster than the square of economic growth.

From the assumptions and numerical values outlined earlier, we construct Table 1 listing relevant parameters with the range of values explored.

Insert Table 1 here

We use these values to arrive at the consumption, stock and utility level for both approaches in the first period. *Ceteris paribus*, consuming more in the first period for the 'learn then act' approach leads to a higher first period utility and a marginally higher greenhouse stock. The real difference is in the resultant state of technologies in the second period; with 'learn then act' approach the level of technology remains the same across periods. From our assumption of mandatory abatement, per-unit emissions drop by half for the 'act preventively' case. This is not unreasonable, given the recent interest of industry in greener technologies due to the implementation of Kyoto protocol.[25] With the help of the above-mentioned assumptions and parameters, we construct the following scenarios to compare the two approaches.[26]

- Median case (to avoid calling this scenario as 'average'): We choose average values of all the parameters for this scenario and illustrate the results in Figure 3. We find that the 'act preventively' approach has a higher combined utility at its optimal consumption than the 'learn then act' approach. It is interesting to notice in the 'learn then act' case, it is

[25] The Economist, Jan 8th 2006.

[26] This approach of considering scenarios is adopted from IPCC.

optimal to abate around 26 percent of its total income in the second period. Another interesting observation is that the threshold point for the 'learn then act' approach occurs much earlier than the 'act preventively' approach, given dirtier technology in period two for the former. The sudden dip in value functions is observed due to the discontinuity from catastrophe, it occurs at the point when the stock reaches its threshold level. A careful study of the value functions reveals that it is optimal to consume more than the threshold amount therefore triggering a catastrophe, even though the damage in magnitude is equal to half the utility from total consumption of income in the second period. The value functions become flatter after the discontinuity from the catastrophe; that might be due to a decreasing marginal utility from increasing consumption and an increasing load of extreme weather events.

Insert Figure 3 here

The following scenarios are based on varying one parameter from the median scenario.

- Varying regional sensitivity to extreme events: Both value functions decrease with an increase in regional sensitivity ϕ (please refer to Figure 4). We also find that if ϕ is greater than 6.3E-09, then it is optimal to pursue 'act preventively' approach. Hence 'learn then act' can only be justified as an optimal policy for regions where a slight warming can actually be beneficial, even though there is a looming danger of catastrophe that equally affects the earth.[27]

[27] http://www.grida.no/climate/ipcc_tar/wg2/index.htm

Insert Figure 4 here

- Varying discount factor ρ: In this case, we vary the discount factor ρ from 0 to 10 percent, and all other parameters remain at their median scenario values. We find that the 'learn then act' approach does better than the 'act preventively' approach, if the long-term discount factor exceeds 6.45%. Hence this finding corroborates higher discount factor for environmental risks speculated for the American society, as mentioned in Heal & Kristrom (2002). This is shown in Figure 5 in the appendix.

Insert Figure 5 here

- Varying catastrophic damage *D*: Only with very high catastrophic damages (with the value of damages greater than 70 percent of utility from second period income), it is optimal to consume up to threshold level of consumption. A caveat to this assertion is that the social planners do not know the exact value of *D* in either approaches of our model. In Figure 6, we plot the optimal value functions and the second period consumption for both approaches versus the catastrophic damage *D*.

Insert Figure 6 here

- Varying catastrophic threshold *S*: Every other parameter except catastrophic threshold S remains the same from the median case. Here the catastrophic threshold varies from 560 ppm to 720 ppm, which is two to three times the natural stock of GHGs. We can conclude that the threshold for catastrophic damage is immaterial for climate change policy in our model. Hence it is not optimal to wait for scientific information to arrive before deciding on any serious action for tackling climate change. This is illustrated in Figure 7.

Insert Figure 7 here

- Sensitivity analysis on cost of information β and cost of abatement δ: On varying the cost of information and cost of abatement in the first period, we find that it changes the stock and utility for the first period, but qualitative results for value functions from the median case remain the same.

V. A dynamic two-period model

In this section, we retain the notation of the static case discussed earlier in the paper. As before, there are two time periods, $i \in (1,2)$. We assume the income in the first period is 1 as numeraire and the second period income equals to $G > 1$. This income in either period can either be

a) consumed leading to stock emissions as the side-effect; c_i,

b) used in abatement effort to reduce the emissions; a_i or

c) used in investment for research in technology; i_i. This is only an option for period 1, as we just have two periods. Hence we have,

$$c_1 + a_1 + i_1 = 1 \qquad (19)$$

$$c_2 + a_2 = G \qquad (20)$$

We know the initial stock of pollutant is equal to s_0. Due to the consumption in either period, we have positive additions to the stock; hence the trajectory of stock is given by

$$s_i = \pi s_{i-1} + \alpha_1 g(a_i) c_i,\ 0 < \pi < 1 \tag{21}$$

We assume $c_i > 0, a_i > 0 \ \&\ i_1 \geq 0$ and π is the natural rate of decay of the stock pollutant. Here the function $g(a_i)$ is the abatement function and the function α_i reflects the state of technology. We also have,

$$g(0) = 1, g(\infty) = 0, g' < 0 \ \&\ g'' > 0$$

Hence we assume $g(a_i)$ to be convex decreasing. We consider $\alpha_2 = h(i_1)$, that is, the state of technology in period two depends on the investment in the first period. We also assume that it is convex decreasing, where,

$$h(0) = \alpha_1, h(\infty) = 0, h' < 0 \text{ and } h'' > 0 .$$

The utility in either period is defined by $U \equiv U(c_i, s_i)$. We also assume that,

$$U'(c_i) > 0, U''(c_i) < 0, U(c_i = 0) = -\infty, U'(s_i) < 0 \ \&\ U''(s_i) < 0 .$$

Here $\frac{\partial U}{\partial c_i}$ decreases with increase in consumption (assuming diminishing marginal utility of consumption), while the discomfort due to stock pollutant increases with the level of stock. Hence the problem is actually budget allocation, that is, how much should we invest in technology and how much should we abate in the first period and how much should we consume and abate in the second period. Due to the presence of damages from stock that necessitates abatement, full consumption in any period is not an option, neither is zero consumption. The problem is to maximize the present sum of discounted utilities over the two periods, that is,

$$
\begin{aligned}
&V = \max_{c_1, a_1} \; U(c_1, s_1) + \rho \max_{c_2} \; U(c_2, s_2) \\
&\text{where } c_1 + a_1 + i_1 = 1 \\
&c_2 + a_2 = G \qquad (22) \\
&s_1 = s_0 + \alpha_1 c_1 g(a_1) \\
&s_2 = s_1 + \alpha_2 c_2 g(a_2)
\end{aligned}
$$

Here ρ is the discount factor, where $0 < \rho < 1$.

To incorporate the risk of catastrophe in this model, we discuss two cases,

- At the optimum, the catastrophic event does occur. In this case, we have analysis similar to that on pages 16-17. That is, we have similar conditions under which it is optimal to stop consuming before catastrophe strikes or to assimilate the catastrophe. If *S* is the threshold for stocks and *D* is the damage from catastrophe.

$$U(c_{2o}, s_{2o}) - D <> U(c_{2T}, S) \qquad (23)$$

Further analysis is similar to the one attempted earlier in the paper for the static case.

- At the optimum, the catastrophic event does not occur, so we have the following analysis.

For the second period problem, the lagrangian is:

$$\Im_2 = U(c_2, s_2) + \lambda_2 (s_2 - s_1 - \alpha_2 c_2 g(a_2)) + \mu_2 (G - c_2 - a_2). \qquad (24)$$

The first order necessary conditions for an interior solution can be written as

$$\frac{\partial \Im_2}{\partial c_2} = \frac{\partial U}{\partial c_2} - \lambda_2 \alpha_2 g(a_2) - \mu_2 = 0 \qquad (25)$$

$$\frac{\partial \Im_2}{\partial a_2} = -\lambda_2 \alpha_2 c_2 \frac{\partial g}{\partial a_2} - \mu_2 = 0 \qquad (26)$$

$$\frac{\partial \Im_2}{\partial \lambda_2} = s_2 - s_1 - \alpha_2 c_2 g(a_2) = 0 \qquad (27)$$

$$\frac{\partial \Im_2}{\partial \mu_2} = G - c_2 - a_2 = 0 \tag{28}$$

We can interpret the lagrange multiplier λ_2 as the marginal effect of varying second period stock s_2 on the lagrangian function $\Im_2$ at the solution of problem. Similarly, the multiplier μ_2 is the marginal effect of varying second period income G on the lagrangian function $\Im_2$ at the solution of problem. We can simplify expressions (25) and (26) to get

$$\frac{\partial U}{\partial c_2} = \lambda_2 \alpha_2 (g(a_2) - c_2 \frac{\partial g}{\partial a_2}) \tag{29}$$

We continue this exercise for the first period case,[28]

$$\Im_1 = U(c_1, s_1) + V_1(s_1) + \lambda_1(s_1 - s_0 - \alpha_1 c_1 g(a_1)) + \mu_1(1 - c_1 - a_1) \tag{30}$$

We should also have from first order conditions,

$$\frac{\partial \Im_1}{\partial c_1} = \frac{\partial U}{\partial c_1} - \lambda_1 \alpha_1 g(a_1) - \mu_1 = 0 \tag{31}$$

$$\frac{\partial \Im_1}{\partial a_1} = -\lambda_1 \alpha_1 c_1 \frac{\partial g}{\partial a_1} - \mu_1 = 0 \tag{32}$$

$$\frac{\partial \Im_1}{\partial \lambda_1} = s_1 - s_0 - \alpha_1 c_1 g(a_1) = 0 \tag{33}$$

$$\frac{\partial \Im_1}{\partial \mu_1} = 1 - c_1 - a_1 = 0 \tag{34}$$

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[28] We can use FOC in (25)-(26) to find out the expressions for $\lambda_2 = \dfrac{\frac{\partial U}{\partial c_2}}{\alpha_2 (g(a_2) - c_2 \frac{\partial g}{\partial a_2})}$ and

$\mu_2 = \dfrac{c_2 \frac{\partial U}{\partial c_2} \frac{\partial g}{\partial a_2}}{(g(a_2) - c_2 \frac{\partial g}{\partial a_2})}$.

We can interpret the lagrange multiplier λ_1 as the marginal effect of varying first period stock s_1 on the lagrangian function $\Im_1$ at the solution of problem. Similarly, the multiplier μ_1 is the marginal effect of varying first period income on the lagrangian function $\Im_1$ at the solution of problem. From the manipulation of (31) and (32),[29] we get

$$\frac{\partial U}{\partial c_1} = \lambda_1 \alpha_1 (g(a_1) - c_1 \frac{\partial g}{\partial a_1}) \tag{35}$$

In future research, we propose to solve this model with a suitable functional form for utility and abatement.

VI. Conclusions

In this paper, we try to understand the two different approaches in climate change policy. This analysis justifies procrastination on stock abatement only in the case of high discount factor and low susceptibility to the current climate change, which is true for the United States (Heal & Kristrom, 2002). From our numerical illustration, the following conclusions emerge. First, except for extremely high catastrophic damages (a doomsday scenario), it is optimal to consume more than the threshold stock, even though such consumption will lead to catastrophic damages. Second, with both low and high thresholds for catastrophe, the 'learn then act' approach does worse than the 'act preventively' approach. Research into early warning systems for calamities like tsunamis are justified, but this rationale does not hold for climate change. [30] Hence the

[29] Similar to footnote 28, we can derive out the expressions for $\lambda_1 = \frac{\frac{\partial U}{\partial c_1}}{\alpha_1 (g(a_1) - c_1 \frac{\partial g}{\partial a_1})}$ and $\mu_1 = \frac{c_1 \frac{\partial U}{\partial c_1} \frac{\partial g}{\partial a_1}}{(g(a_1) - c_1 \frac{\partial g}{\partial a_1})}$.

[30] The Economist, Dec 28th 2004.

location of threshold for catastrophe is irrelevant for the climate change policy. This is because of the fact that we quote the scientific literature to assume that the threshold for catastrophe lies between 560-840 ppm (two to three times the natural level of GHG stock). Hence, except for the eventuality of miraculously low second period emissions technology, the second period stock will reach more than 2000 ppm in any other scenario. Therefore, value functions do not depend on the threshold values of stock. The decision to consume more than catastrophic amount is determined by the magnitude of catastrophic damage. Third, the adage 'one stitch in time saves nine' holds true in the most likely case (median scenario). In that scenario, the social planner in 'learn then act' approach has to cut consumption by about a quarter in the second period, when compared to the license for total consumption of income in the second period, due to a 2 percent abatement earlier for the 'act preventively' approach.[31] We concede that the above statement hinges on our assumption that abating now will later reduce the emissions per unit consumption by half. This assumption is also related to our fourth conclusion that abatement policies like the Kyoto protocol do not dent the stock of greenhouse gases to a great extent, but these policies can actually spur innovation in greener technology. [32,33] Greener technologies seem to be our best bet to reduce the pain from climate change.

We propose to extend this work in future in the following ways. First, we shall consider extending the present two-period dynamic model to include an infinite time horizon with multiple periods, while assuming an exogenous growth in income. Second, we shall introduce risk aversion in this analysis. We shall analyze a constant relative risk aversion (CRRA) utility

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[31] All these figures are fractions and percentages of the income.

[32] http://yaleglobal.yale.edu/display.article?id=5280

[33] The Economist, Dec 8th 2005.

function, from which we can derive (17) as a special case. This class of utility functions is a norm in empirical studies of behavior under uncertainty (Heal and Kristrom, 2002).

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Table 1: Numerical Values for the parameters used in the numerical exercise.

No.	*Symbol*	*Name*	*Units*	*Value*	*Explanation/Assumption*
1		Income in first period	dollars	1	Numeraire
2	G	Income in 2nd period	dollars	5	Assuming 3-3.5% growth rate for next 50 years (see footnote 19).
3	α_1	State of technology in period 1	ppm/square dollars	135	We assume doubling GHG concentration before the start of second period, with total consumption of income in the first period. $560 = 425 + \alpha_1 (1)^2$
4	α_2	State of technology in period 2	ppm/square dollars	0-135	We assume that $\alpha_1 \leq \alpha_2$, hence for 'learn then act' case $\alpha_2 = 135$ ppm, while we choose $\alpha_2 = 67.5$ ppm for the 'act preventively' case in our median scenario. That is we assume most probable reduction by half in the carbon intensity of consumption with 'act preventively' approach.
5	s_N	Natural stock of GHG	ppm	280	IPCC (2001) reports.
6	s_0	Present stock of GHG	ppm	425	EU memo mentioned in footnote (13).
7	S	Threshold for catastrophe	ppm	560 -840	Based on Mastrandea, M.D. & S.H. Schneider (2004) and our assumptions in the model. We take 700 ppm as a conservative average value.
8	D	Damage from	utils	1.609	ln(G=5) = 1.609. This is an abnormally high

		catastrophe			value for damage from catastrophe, in average case we choose D = 0.8045, which is still very high.
9	ρ	Discounting factor	none (expressed in percentage)	0.01-10%	Portney, P.R. & J.P. Weyant eds (1999), for the median scenario we take a value of 3%. Government agencies in US use a rate from 3-7% for long-term projects.[34]
10	β	Cost of information for learn then act case	dollars	0.001-0.01	Assuming US GDP to be 10 trillion dollars, with figures from footnote (2) and investment in science.
11	δ	Cost of voluntary abatement	dollars	0.01-0.03	OECD projections about the Kyoto Protocol.[35]
12	ϕ	Regional sensitivity to happening climate change	utils/square ppm	0-0.000000055	Annual costs of hurricanes and extreme events in the United States put at approximately 100 billion dollars for the year 2005. For example, the insured losses from tropical cyclones in North America were 83 billion dollars in 2005 (Munich Re). Calibrating this value into the Utility equation.

[34] http://www.rff.org/rff/Documents/RFF-Resources-146-discount.pdf

[35] http://www.oecd.org/dataoecd/38/53/1923159.pdf

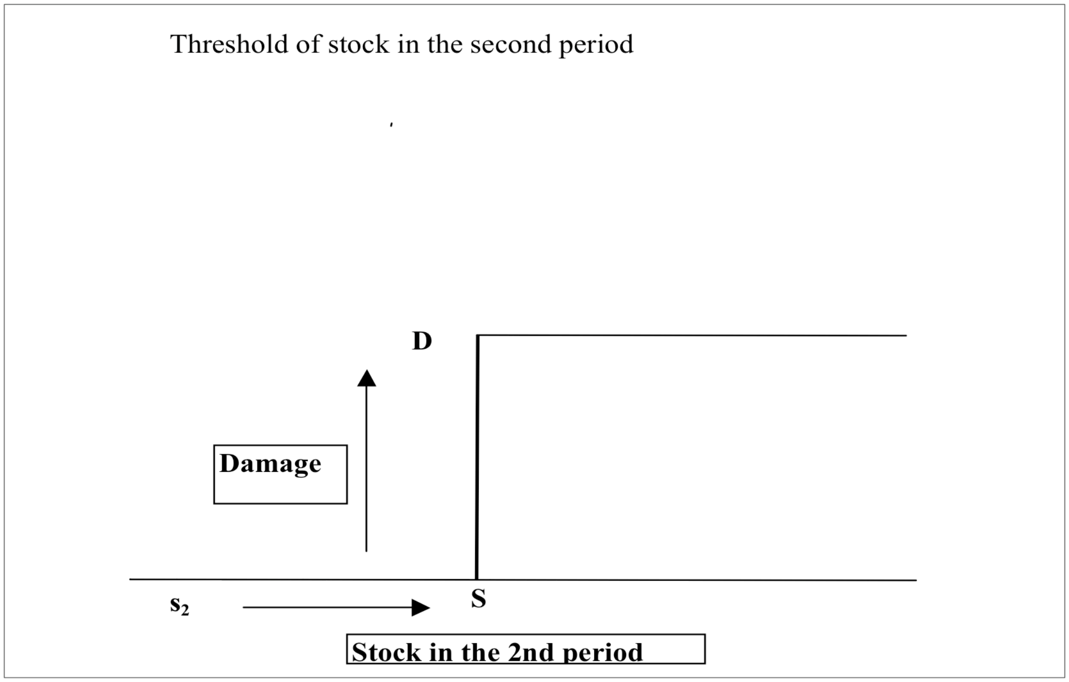


Figure 1: Catastrophic Damage as a function of second period stock s_2 with S as the threshold.

When the second period stock s_2 crosses the threshold *S*, there is a catastrophic loss D. Units of parameters are expressed in Table 1.

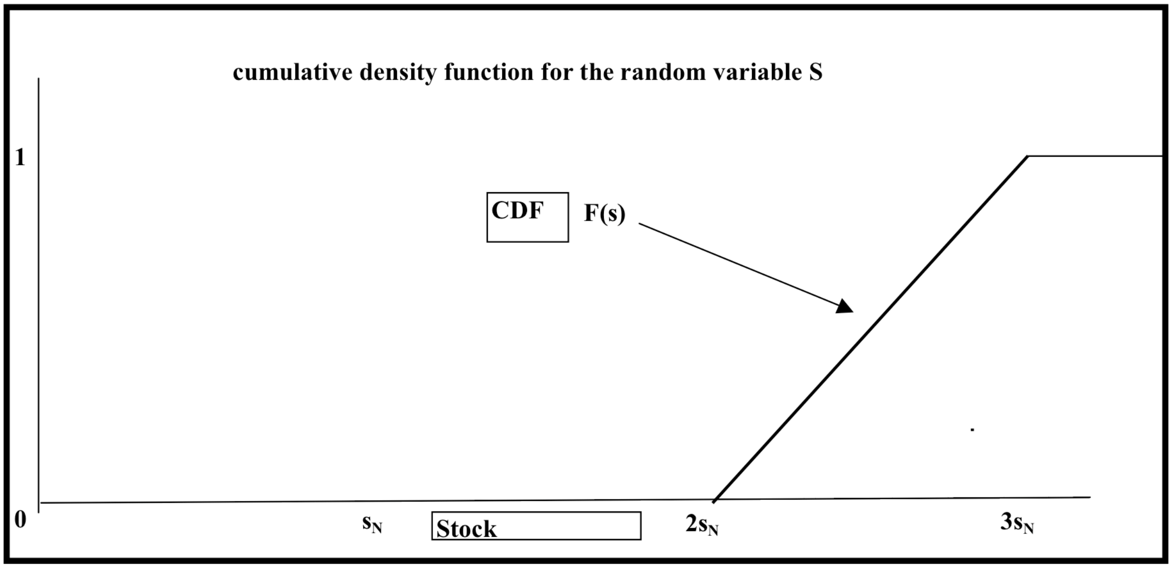


Figure 2: Cumulative Density function for the Threshold *S*.

Assuming linear increase in cumulative density function of *S*. That is, there is a greater risk of catastrophe when the stock reaches 780 ppm compared to when it is at 580 ppm. Units of parameters are expressed in Table 1.

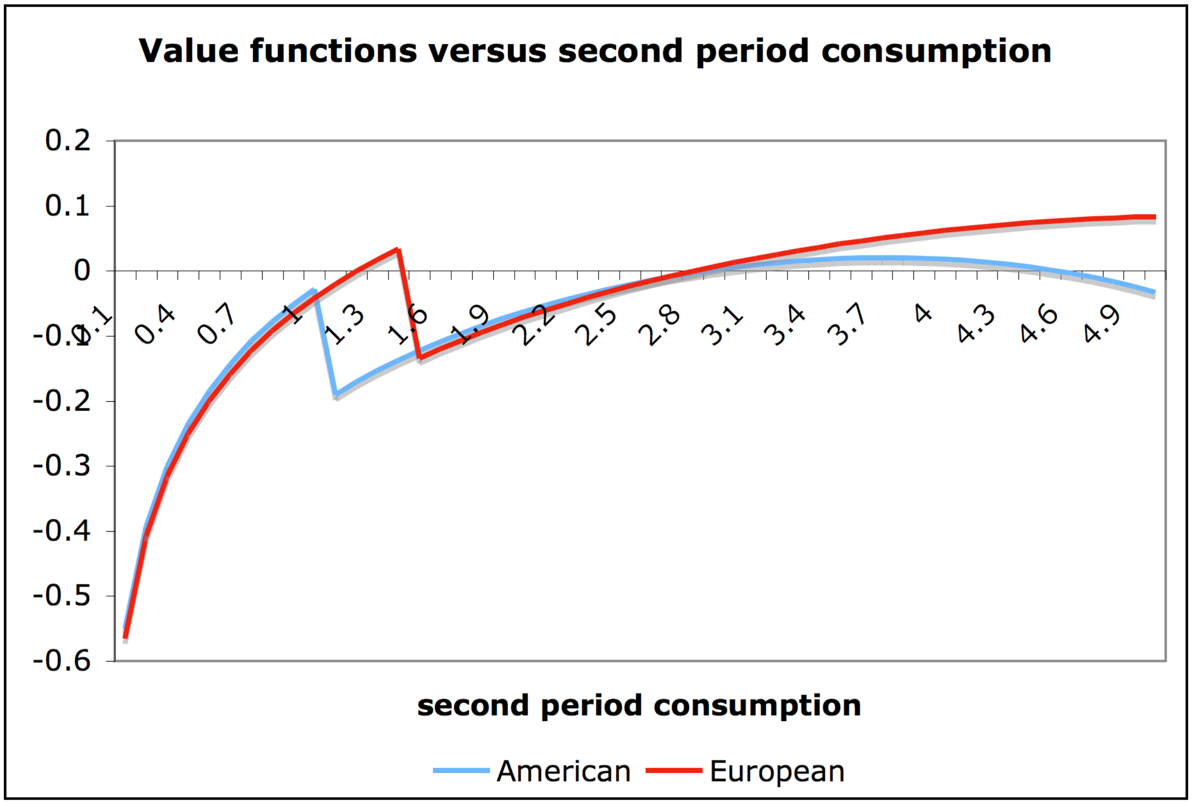


Figure 3: Value functions V_1 and V_2 in the median case versus second period consumption c_2.

This figure shows the value functions (6) and (12) versus second period consumption. It is interesting to see that for the 'act preventively' case, it is optimal to consume whole of income. In the 'learn then act' case, it is optimal to reduce consumption by about 25.56% (optimal c_2 = 3.722, income = 5, hence abatement required = 1.278). Units of parameters are expressed in Table 1.

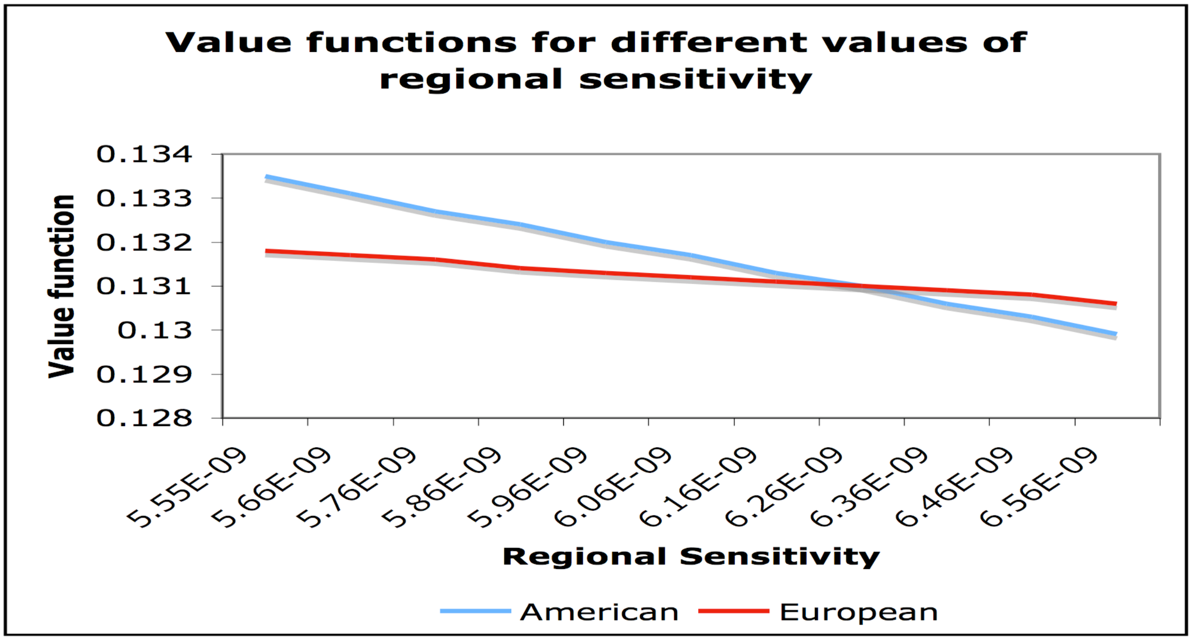


Figure 4: Value functions V_1 and V_2 versus regional sensitivity ϕ to current weather extremes.

In this case we find that if the regional sensitivity parameter ϕ is higher than 6.3E-09, the 'act preventively' approach does better. We can also see that the value functions for both approaches decrease with an increase in ϕ. It should be kept in mind that ϕ for current extreme weather events is about 9 times larger than the cutoff value 6.3E-09. Units of parameters are expressed in Table 1.

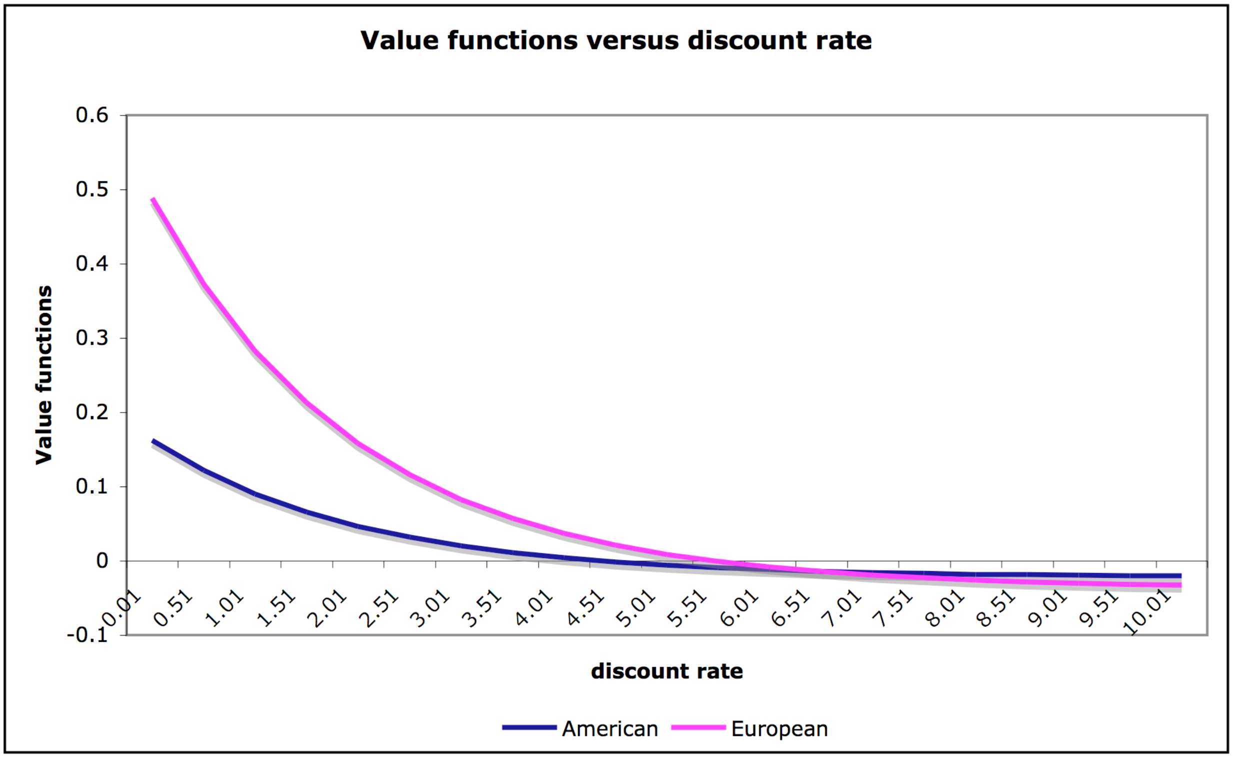
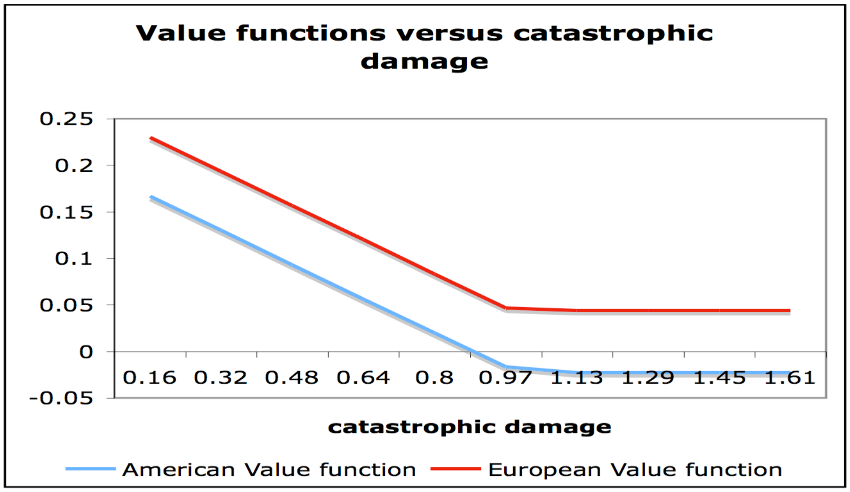


Figure 5: Value functions V_1 and V_2 versus the discount rate ρ.

We can observe that it is optimal to 'learn then act' if the discount rate is higher than 6.5%. Units of parameters are expressed in Table 1.



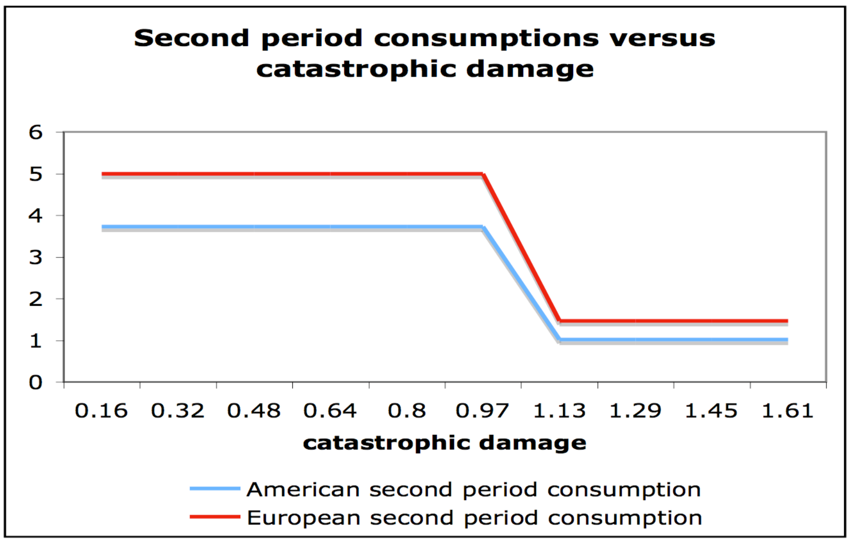


Figure 6: The case with varying catastrophic damages *D*.

We find that it is optimal to ignore any catastrophe, if the catastrophic damages are lower than 70% of utility from total consumption of income in the second period. Units of parameters are expressed in Table 1. We can also see that the value functions slightly decline with an increase in D.

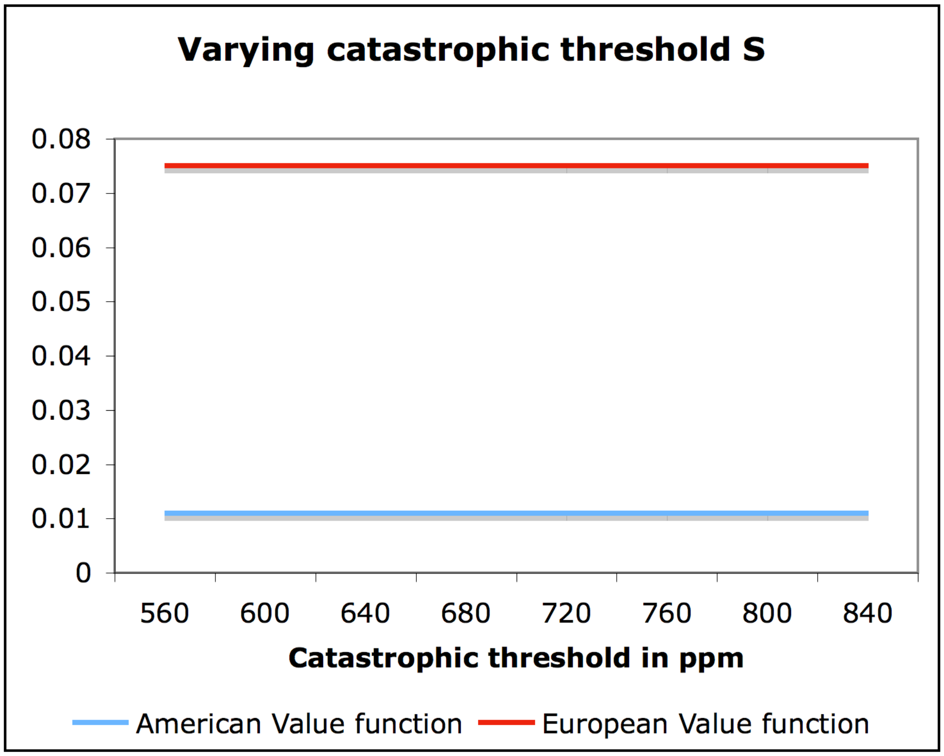


Figure 7: Value functions V_1 and V_2 **versus catastrophic threshold** S**.**

We can see that value functions are not affected by the location of catastrophic threshold with the median values of other parameters. Units of parameters are expressed in Table 1.