Scientific Uncertainty and Climate Change Policy

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0.1 Introduction

The United Nation's Framework Convention for Climate Change is inherently built on the precautionary principle, arguing for action before the science is fully understood. The convention states that "the lack of full scientific certainty should not be used as an excuse to postpone action." A swift reduction of emissions is supported by numerous environmental groups to prevent possible severe consequences of climate change, while expectedly business groups are arguing for a more cautious approach. In arguing against the Kyoto protocols, the Bush government's position is that "robust scientific research is needed to better understand the climate issue." Bush government officials have gone as far as to argue "there is no such thing as the precautionary principle." (OMB quote John Graham, OMB, in a speech to the Heritage Foundation http://www.whitehouse.gov/omb/inforeg/speeches/031020graham.html).

Opponents of emissions reductions stress the need for flexibility. U.S. President Bush himself has argued that there is a cost to imposing regulations to reduce greenhouse gases (GHGs) now before more is known about climate change (Office of the President, 2001). This statement has been echoed by industry: "Climate change presents a long-term, uncertain, serious global risk...Addressing climate change requires balancing long-term uncertain risks against society's essential and growing demand for energy" (Exxon Mobil). Exxon and others have argued that strict emissions caps and regulation will limit economic growth and therefore the ability to respond more appropriately in the future (International Chamber of Commerce). Ironically, some of these groups have also helped fund research to argue that there is no scientific consensus on global climate change (e.g. Exxon Mobil, Environmental Defence Fund, 2005) while arguing that science can and will provide answers to climate change in the future. This paper asks whether it makes sense to act now before the effects of climate change are known or wait until we have more information about possible damage? Is there an economic model that would explain these two disparate positions?

The one area of consensus is that there is uncertainty about the nature and degree of damage threatened by climate change. "Because there is considerable uncertainty in current understanding of how the climate system varies naturally and reacts to emissions of greenhouse gases and aerosols, current estimates of the magnitude of future warming should be regarded as tentative and subject to future adjustments (either upward or downward)," (U.S. National Academy of Sciences, 2001, p.1). "The latest IPCC assessment is that doubling CO_2 levels will warm the world by anything from 1.4 to 5.8°C. In other words, this predicts a rise in global temperature from pre-industrial levels of around 14.8 °C to between 16.2 and 20.6°C. Even at the low end, this is probably the biggest fluctuation in temperature that has occurred in the history of human civilization. But uncertainties within the IPCC models remain, and the skeptics charge that they are so great that this conclusion is not worth the paper it is written on... Sceptics who pounce on such great uncertainties should remember, however, that they cut both ways. Indeed, new research based on thousands of different climate simulation models run using spare computing capacity of idling PCs suggest that doubling CO_2 levels could increase by as much as 11°C (Nature, vol 434, p. 403)," (New Scientist 2005).

The question remains as to what degree that uncertainty will be resolved before the effects of climate change are felt. Decision-makers not only do not know the full effect of climate change now, they may be unlikely to receive full information in the foreseeable future. In this paper, we explore the effect of the quality of information on early investment. Specifically, we ask how the schedule and among of mitigation varies with the quality of the forthcoming information. Unlike much of the past literature on decision-making under uncertainty, we do not rely on irreversibility, and instead rely on smoothing. This approach allows us to add on an option value if desired, but we do not need it to get interesting results. The paper proceeds as follows in the next section we discuss the past literature on decision-making under uncertainty as it pertains to climate change. In section 3 we develop the model and first order conditions. In section 4, we present a graphical illustration of our results, and we end with conclusions.

0.2 Background

Those arguing to allow the economy 'flexibility' to take advantage of future information are effectively making an option-value argument: there is a sunk cost associated with acting today, and we will know more tomorrow, so there is a value to waiting. However, there is also a potential cost to waiting: increasing environmental damage, such as the melting of polar ice caps, which may be irreversible. Environmental goods that face permanent damage can be thought of as having an environmental option value (called a quasi-option value). The concept of a "quasi" option value was developed in 1974 by Arrow and Fisher who noted that if there was a degree of irreversibility to an environmental action, and more information is expected in the next period, for example updated information regarding the costs of the environmental action, then there is an added benefit to preserving the environment in the short run.

Applying the concept of (regular) option value to non-market goods, Zhao and Kling (2000, 2001) develop a number of predictions about how willingness to pay (WTP) for an environmental externality will vary with information and reversibility: (1) WTP will increase if individuals expect that less information can be gathered about a good in the future. Thus, if expected information about climate change was likely to improve, individuals will be willing to spend less today to counteract the effects of global warming. (2) WTP will increase if individuals expect that the investment is more easily reversible. Therefore, policies that decrease the emission of GHGs that involve fundamental (irreversible) restructuring of the economy will be less acceptable than those that involve investments that are not sunk. For example, the population may be less willing to accept the phasing out of gasoline driven cars than an increased tax on gasoline and they may be more willing to invest in soil carbon sinks (which are inherently a short-term solution) to investing in alternative fuel research, where the costs are sunk. (3) WTP will increase if individuals are more certain about a good's value. In other words, the more certain the benefits of the policy action, the more individuals are willing to support it. (4) WTP for a good today will increase with an increasing discount rate. In our case, since the object of interest is an investment which involves foregoing income today, the willingness to support a policy that will reduce the current economy will decrease the higher the individual's discount rate.

Although Zhao and Kling do not consider the idea that there is also a quasi-option value that will increase the value of policy action today, some intuition can be gained from applying their results can also to the quasi-option value. Assume for the moment that all investment in mitigation can be recouped, however (some portion of) environmental damage from climate change is irreversible. In this case, one might conclude (1) support for policy action will decrease if one expects less information about the costs of climate change in the future. To understand the intuition behind this result, consider that the value of flexibility increases with expected information, and mitigation today increases flexibility. (2) Presumably, support for mitigation will increase with the irreversibility of climate change. (3) The more certain the costs of climate change, the less wiling the public will be to invest to reduce it today. The intuition here is similar to that used in point (1) – the greater the certainty, the lower the value of flexibility. The last point remains unchanged – a higher discount rate will still decrease expenditure today.

But what if one has both option value and quasi-option value at once? Kolstad (1996a) compares conflicting option values exploring the effect of a sunk investment versus stock externalities, where the stock externalities act as the sunk costs of not abating now. How does the prospect of better second-period information about the consequences of the externality affect the desired level of first-period investment in abatement capital? Kolstad allows the rate of learning to vary while the degree of investment irreversibility and the decay rate of GHGs are fixed. He finds which effect dominates depends on the relative magnitudes of the decay and depreciation rates and on expectations about damages. Using a multi-period simulation of GHGs based on the DICE model (Nordhaus 1994), Kolstad (1996b) finds that the optimal level of investment is affected by the capital stock irreversibility while emissions irreversibility has no impact. In his parameterization, the non-negativity restriction on emissions is never binding. Too little investment in emission control in the early periods can be compensated by a bit more investment in later periods, but there is no scenario in which it would be optimal to emit negatively in the future to correct over-emission today.

Ulph and Ulph (1997) also explore climate change and irreversibility. They develop a two period model and show that a sufficient condition for first-period emissions with learning to be less than first-period emissions without learning is that the non-negative restriction on emissions be binding in the no-learning case. In other words, for the government to cut its emissions today, there has to be some restriction that does not allow the decision-maker to push too much of its mitigation efforts into the second period, and that restriction must be binding. Using a similar framework, Fisher and Narain (2003) assume that the decision-maker will learn whether a climate event has occurred, and whether the damage associated with that event is high or low, where the risk is a function of the stock of GHGs. Again, they model the “sunk” aspect of the climate change by assuming a non-negativity constraint on emissions. They then consider how the level of first-period investment in abatement varies with the irreversibility of the investment, and with the degradability of the stock of GHGs. As one would intuit, the more sunk the investment, the lower the investment in the first period. The higher the irreversibility of GHGs, the higher the investment in the first period. Quantitatively, they find the effect of capital irreversibility is much stronger than either the effect of emissions irreversibility or of endogenous risk.

Our contribution is developing a model that does not use option value to explore the effects of uncertainty on climate mitigation, and instead relies on smoothing, which we argue is less restrictive. Further, unlike other models, we consider the revelation of the quality of information to come, not just the information itself. The model can then easily compare the incentives for smoothing potential costs of damage and the costs of mitigation.

0.3 Model

As noted above, recent predictions of temperature increases due to climate change range from 2 to 11 °C (Nature). Given that some degree of climate change is generally accepted, we make the assumption that even a good outcome implies some damage. Consider a temperature increase of 2 °C to imply a "good" outcome and 11 °C to represent a "bad" outcome. The government can respond to this threat by investing in mitigation, such as altering their economy to emit fewer GHGs. Altering the economy is assumed to be expensive, for example, setting up system of hydrogen fuel stations is costly. The more the economy is altered in a single period, the higher the immediate costs.

Assume that in period 0 a country can invest in damage mitigation, m_0. In period 1, a country receives information about the degree of the damage, and can invest again in mitigation, m_1. In period 2, the country experiences the damage. Damage is the function of a stochastic variable K and the amount spent on mitigation $D = D(K - m_0 + m_1)$, where damage is either minor i.e. "good" (G), or "bad" (B), where $B > G$.

Traditional option value requires irreversibility. In terms of irreversibility of mitigation, there would have to be a situation where one would want negative mitigation in the second period. For example, if damage in the good state is zero, $D|G = 0$ and the damage function can never be negative, i.e. $D \geq 0$, if mitigation in the initial period is positive (and cost of mitigation is positive), the government would like to reverse that mitigation in the following period, i.e. $m_1 < 0$. One simple way of modeling option value is to constrain mitigation in period 1 to be non-negative, i.e. $m_1 \geq 0$. On the other hand, quasi option value can be modeled as limits on the quantity of mitigation in any one period.

If climate change results in irreversible damage, that can be thought of as there being no level of mitigation that can address that damage, i.e. $m \leq X$. However, we find that we can achieve similar results without the use of option value, although it could easily be added in.

If both restrictions are in place, the results are ambiguous, and become a question that will be given by assumptions of the model (such as in Kolstad 1996b) or empirics. Given that our basic assumption is that damage will be greater than zero, we do not need to place restrictions on the level of mitigation. For example, one the infrastructure for hydrogen vehicles is created, we assume that the government will not regret making that investment. Similarly, we do not need to limit on the amount of mitigation in any one period. The amount of mitigation the government may desire to undertake in any one period may be very expensive, but we assume if the government will exists, the government could mitigate that much.

Instead of these assumptions of set limits, we assume that there are incentives for smoothing. By imposing curvature on the damage and mitigation cost functions, the government has an incentive to mitigate the same amount in both periods, and to limit the spread between the damage in both possible states. Thus, we assume that both costs and damages are increasing at an increasing rate. Thus, we assume

(1) $C', C'' > 0$, and $C''' \geq 0$.

(2) $D', D'' > 0$ and $D''' \geq 0$.

Instead of assuming that a decision-maker will know the truth in the next period, this model takes into account the quality of anticipated information. Assume a government wants to decide how much to invest in GHG mitigation today, but expects some information as to the effect of climate change tomorrow. In period 0, a country has to choose the amount of investment in GHG mitigation, m_0 with no information about whether the damage it will face will be good or bad. However, it knows in the following period it will receive some information about the future damage, but that information will be of a certain quality, denoted as α, ranging from no information ($\alpha = \frac{1}{4}$) to full information (at $\alpha = 0$). Thus α can be thought of as a parameter of ambiguity. Regardless of the quality of information, the true probability of receiving a good or bad outcome is $\frac{1}{2}$. We ask how the mitigation schedule and total mitigation changes with the quality of information.

Assume that the more favorable, or 'high' the information, the better the probability of a good outcome. Specifically, with full information, if one observes 'high' information, the probability of experiencing a good outcome is one. On the other hand, if there is no information, there is an equal probability of experiencing a good and a bad outcome regardless of whether the information observed is high or low. Assume the following probabilities are associated with the quality of information, α:

Conditional probability:

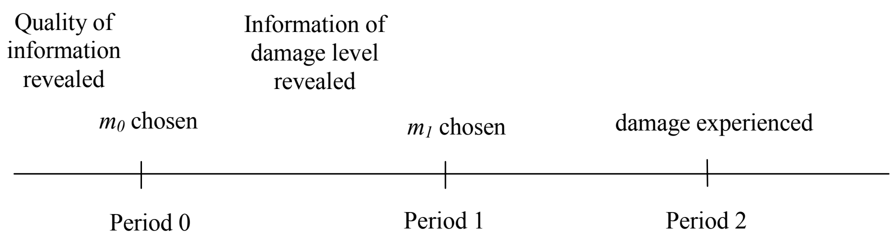

Figure 1: Time Line

		Damage	
		Bad	Good
Information	High	2α	$1-2\alpha$
	Low	$1-2\alpha$	2α

Unconditional probability

		Damage	
		Bad	Good
Information	High	α	$\frac{1}{2}-\alpha$
	Low	$\frac{1}{2}-\alpha$	α

where $0 < \alpha < \frac{1}{4}$, $\alpha = \frac{1}{4}$ implies there is no information, $\alpha = 0$ implies there is full information

Assuming the government chooses m_0 based on its expected mitigation in period 1, we can solve the two period choices simultaneously (note that we assume that the government is risk-neutral). Thus, the government chooses mitigation in period 0, m_0, and the mitigation conditional on the information in period 1, be it high (m_1^H) or low, (m_1^L) to minimize expected welfare loss. Welfare loss can come both from the damage,$D(m)$ and the cost of mitigation $C(m)$.Further, assume that mitigation tomorrow may not be as useful as mitigation today - specifically think of the government reducing the flow of GHGs, so that mitigation tomorrow implies the stock of GHGs has increased by the additional emissions in period 0. This stock effect is represented by δ, where $0 < \delta \leq 1$. Also assume that the government has a discount factor, β, where $0 < \beta \leq 1$ The government's objective function is then to chose its levels of mitigation to minimize the welfare loss, i.e. the damage times the probability of a good and bad outcome with high and low information (equation 3).

(3) $$Min_{m_0,m_1^H,m_1^L}\, E(-W) = \left(\tfrac{1}{2}-\alpha\right)\beta^2 D\left(G-\delta m_1^H - m_0\right) + \alpha\beta^2 D\left(B-\delta m_1^H - m_0\right) + \alpha\beta^2 D\left(G-\delta m_1^L - m_0\right) + \left(\tfrac{1}{2}-\alpha\right)\beta^2 D\left(G-\delta m_1^L - m_0\right) + \tfrac{1}{2}\beta C\left(m_1^H\right) + \tfrac{1}{2}\beta C\left(m_1^L\right) + C\left(m_0\right).$$

The fist order conditions are:

(4) $\frac{dE(-W)}{dm_i^H} : -\left(\frac{1}{2}-\alpha\right) D'_{GH} - \alpha D'_{BH} + \frac{1}{2\beta\delta} C'_H = 0$

(5) $\frac{dE(-W)}{dm_i^L} - \alpha D'_{GL} - \left(\frac{1}{2}-\alpha\right) D_{BL} + \frac{1}{2\beta\delta} C'_L = 0$

(6) $\frac{dE(-W)}{dm_0} - \left(\frac{1}{2}-\alpha\right) D'_{GH} - \alpha D'_{BH} - \alpha D'_{GL} - \left(\frac{1}{2}-\alpha\right) D_{BL} + \frac{1}{\beta^2} C'_0 = 0$

To determine how the government's choice of mitigation schedule changes with the quality of information, we totally differentiate *w.r.t.* the three endogenous variables, m_0, m_1^H, m_1^L and the endogenous variable, α.

(4') $dm_1^H \left[\delta\beta^2 \left(\frac{1}{2}-\alpha\right) D''_{GH} + \delta\beta^2 \alpha D''_{BH} + \frac{1}{2\delta} C''_H\right]$
$+dm_0 \left[\beta^2 \left(\frac{1}{2}-\alpha\right) D''_{GH} + \alpha\beta^2 D''_{BH}\right] - d\alpha \left[\beta^2 D'_{BH} - \beta^2 D'_{GH}\right] = 0$

(5') $dm_1^L \left[\delta\beta^2 \alpha D''_{GL} + \delta\beta^2 \left(\frac{1}{2}-\alpha\right) D''_{BL} + \frac{1}{2\delta} C''_L\right]$
$+dm_0 \left[\alpha\beta^2 D''_{GL} + \left(\frac{1}{2}-\alpha\right) \beta^2 D''_{BL}\right] - d\alpha \left[-\beta^2 \left(D'_{BL} - D'_{GL}\right)\right] = 0$

(6') $dm_1^H \left[\delta\beta^2 \left(\frac{1}{2}-\alpha\right) D''_{GH} + \delta\beta^2 \alpha D''_{BH}\right] + dm_1^L \left[\delta\beta^2 \alpha D''_{GL} + \delta\beta^2 \left(\frac{1}{2}-\alpha\right) D''_{BL}\right]$
$+dm_0 \left[\left(\frac{1}{2}-\alpha\right) \beta^2 D''_{GH} + \alpha\beta^2 D''_{BH} + \alpha\beta^2 D''_{GL} + \beta^2 \left(\frac{1}{2}-\alpha\right) D''_{BL} + \frac{1}{\beta^2} C''_0\right] -$
$d\alpha \left[\beta^2 \left(D'_{BH} - D'_{GH}\right) - \beta^2 \left(D'_{BL} - D'_{GL}\right)\right] = 0$

The above can be re-written in matrix form as:

$$\begin{bmatrix} \delta\beta^2 A''_H + \frac{1}{2\delta} C''_H & 0 & \beta^2 A''_H \\ 0 & \delta\beta^2 A''_L + \frac{1}{2\delta} C''_L & \beta^2 A''_L \\ \delta\beta^2 A''_H & \delta\beta^2 A''_L & \beta^2 \left(A''_H + A''_L\right) + \frac{1}{\beta^2} C''_0 \end{bmatrix} \begin{bmatrix} dm_1^H \\ dm_1^L \\ dm_0 \end{bmatrix} =$$
$$\begin{bmatrix} \beta^2 N_H \\ -\beta^2 N_L \\ \beta^2 \left(N_H - N_L\right) \end{bmatrix} d\alpha$$

where A''_H and A''_L are the weighted average of the change in the marginal damage function when the information is high and low respectively. Thus, A''_H is the change in the expected marginal damage caused by increase in mitigation, when information is high. Similarly, N_H and N_L are the difference in the marginal damage during the bad and good state when the information is high and low respectively. Figures 2 and 3 illustrate the marginal damage associated with various levels of outcome and mitigation. The weighted average of the change in marginal damage, A''_H and A''_L and the change in marginal damage N_H and N_L are illustrated at full and no information. Since initially the government does not know whether the information indicates a good or bad outcome, m_0 is constant given the quality of information. At full information, A''_L is the slope of the marginal damage function at $B - m_0 - m_1^L$ since the government knows for certain that the damage will be bad, and mitigates appropriately. Likewise, if the information is high, the government knows the damage will be good, and will mitigate less in the first period. Thus, A''_H is the slope of the marginal damage function at $G - m_0 - m_1^H$. N_H is simply the difference in marginal damage at a bad and good outcome when the government chooses its mitigation given high information and therefore expecting to see a good outcome, and

N_L is the difference in marginal damage between good and bad states when the government mitigates expecting to see a bad outcome. Note that, as long as there is some information, $N_H > N_L$, thus the difference in marginal damage between a good and bad outcome is larger with high information than with low information. Since, on average, the government will mitigate less with a revelation of high information, and mitigation matters more the greater the damage, an unexpected bad outcome will be much worse than a relatively expected one, while the damage of an unexpected good outcome will only be a bit better than if the government had planned based on the expectation of a good outcome. The other thing to note is that if marginal damage is increasing at an increasing rate (i.e. $D''' > 0$) and there is some information, the slope of the marginal damage function will be higher with low information than with high information, thus $A''_L > A''_H$. The intuition goes as follows: as the information is low, the probability of a bad outcome is higher than the probability of a good outcome. As long as mitigation is not costless, the government will not increase their mitigation to completely offset the increased probability of a bad outcome, implying that the expected outcome with low information, even given the increased mitigation, will still be worse than if the information indicates that a good outcome is more likely.

As information quality deteriorates, the choice of mitigation in period one with high information will converge to that with low information, until, when the information is content-free, the two levels of mitigation will be the same. This scenario is illustrated in figure 3. As the levels of mitigation converge, so do the difference in marginal damages and the slopes of marginal damage: $N_H = N_L$, and $A''_H = A''_L$.

Proposition 1 *Mitigation in the first period will increase with better information ($\frac{dm_0}{d\alpha} < 0$) iff the ratio of the absolute value of the elasticity of marginal benefit to marginal cost is higher with high information than with low information.*

Using Cramer's rule, we can now calculate how the first period mitigation varies with the amount of information. Solving for $\frac{dm_0}{d\alpha}$:

$$\frac{dm_0}{d\alpha} = \frac{\left(\delta\beta^2 A''_H + \frac{1}{2\delta}C''_H\right)\left(\delta\beta^2 A''_L + \frac{1}{2\delta}C''_L\right)\beta^2(N_H - N_L) + \left(\delta\beta^2 A''_H + \frac{1}{2\delta}C''_H\right)\left(\delta\beta^2 A''_L\right)\beta^2 N_L - \left(\delta\beta^2 A''_L + \frac{1}{2\delta}C''_L\right)\left(\delta\beta^2 A''_H\right)\beta^2 N_H}{SOC}$$

$$(5) \quad \frac{dm_0}{d\alpha} = \frac{\beta^2 N_L\left(\delta\beta^2 A''_L + \frac{1}{2\delta}C''_L\right)C''_H\left(\frac{N_H}{N_L} - \frac{2\delta^2\beta^2\frac{A''_H}{C''_H}+1}{2\delta^2\beta^2\frac{A''_L}{C''_L}+1}\right)}{2\delta(SOC)}$$

Since A''_L, C''_L and C''_H are all positive (given our assumptions on $D(\cdot)$ and $C(\cdot)$ above), we know the sign of the first portion of the numerator, $\beta^2 N_L\left(\delta\beta^2 A''_L + \frac{1}{2\delta}C''_L\right)C''_H > 0$. Thus the sign of $\frac{dm_0}{d\alpha}$ depends on the sign of the last term in brackets: $\frac{N_H}{N_L} - \frac{2\delta^2\beta^2\frac{A''_H}{C''_H}+1}{2\delta^2\beta^2\frac{A''_L}{C''_L}+1}$.The first term is the ratio of the

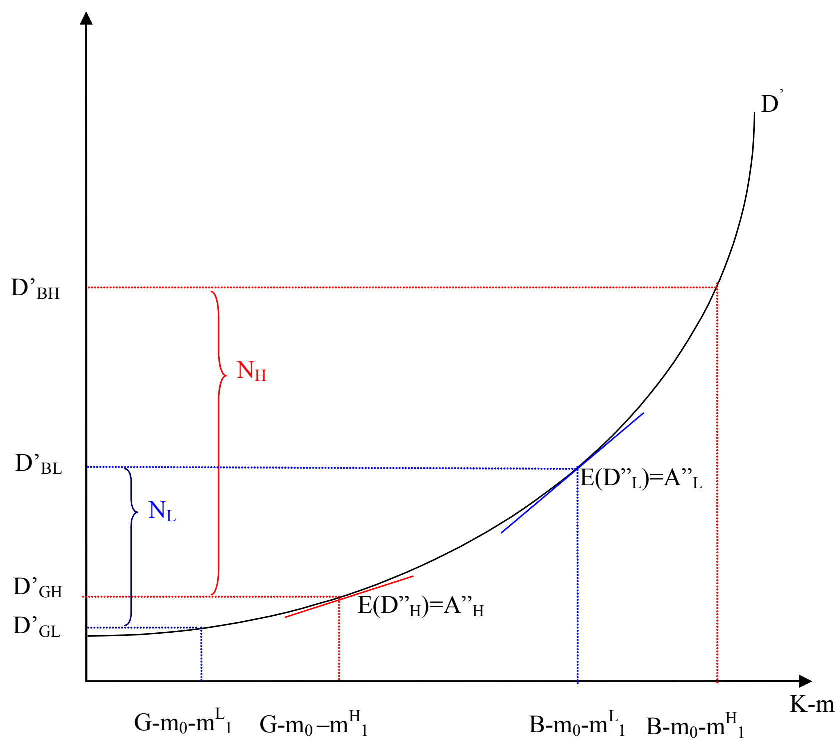

Figure 2: Marginal damage and mitigation with full information

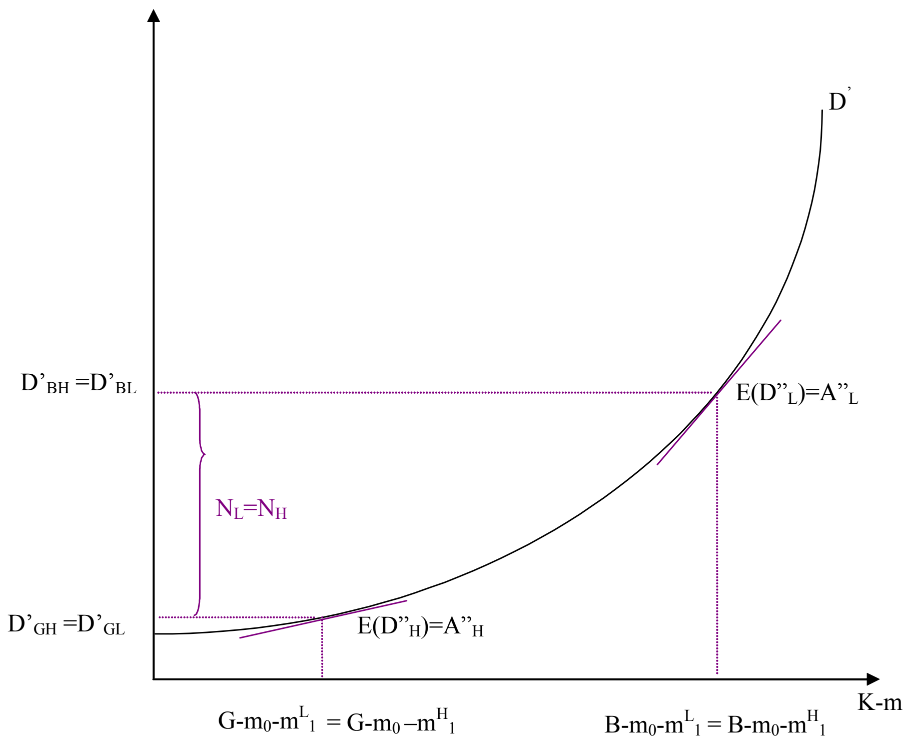

Figure 3: Marginal damage and mitigation with no information

difference in marginal damage in the two states with high and low information. If $D''' > 0$, the difference in marginal damage will be greater with high information than low, implying the first term will be larger than 1. Likewise, if $D''' > 0$, the the expected marginal damage is greater if the information is low than when it is high, thus $A_L" > A_H"$. If $C''' = 0$, $C''_H = C''_L$, and $A_L" > A_H"$ the second term is clearly less than one, implying that the mitigation in period 0 decreases with an increase in information quality, $\frac{dm_0}{d\alpha} > 0$.If $C''' \leq 0$, the sign is unambiguously positive. However, if $C''' > 0$, $C_L" > C_H"$ which may offset the difference in $A_L"$ and $A_H"$. For the derivative to be negative however, the relative increase in marginal costs must be greater than the relative expected marginal damage, implying $C''' > D'''$. Thus, the curvature of the cost function must be positive and greater than the curvature of the damage function. In short, if the ratio of the change in marginal damage to marginal cost is much higher in the bad state than in the good state, the term may be negative, implying that a decrease in information (thus, moving to less than perfect information) will result in less mitigation initially. This can be thought of the marginal cost of mitigation in the bad state increasing much more over the good state compared to the marginal damage. One could envision this happening if, with information that the damage is likely bad, the mitigation needed in the first period is unacceptably high. For example, imagine a scenario where a small increase in expected damage implied that all inhabitants of coastal regions have to be evacuated, and coastal cities need to be rebuilt inland.

Since $N_H \geq N_L$ given assumption (2), for $\frac{dm_0}{d\alpha} < 0$, $\frac{2\delta^2\beta^2\frac{A''_H}{C''_H}+1}{2\delta^2\beta^2\frac{A''_L}{C''_L}+1} > 1$. For this ratio to be greater than one, the ratio in the slopes of the expected marginal benefit (or reduction in marginal damage) must be greater than the reduction $\frac{A''_H}{C''_H} > \frac{A''_L}{C''_L}$. Consider that -$A''_H\frac{m_1^H}{D'_H} = \frac{-\partial E(D'_H)}{\partial m}\frac{m_1^H}{D'_H} = \eta_H$. Since -$D'_H = C'_H$ at equilibrium, $\frac{A''_H}{C''_H}$ can be rewritten as $\frac{\eta_H}{\varepsilon_H}$ where η_H is the elasticity of marginal benefit and ε_H is the elasticity of marginal cost.

To see this result graphically, consider figure 4, where the choice of mitigation is illustrated under the two extremes - a situation with full information compared to that with no information. For simplicity, we assume that marginal cost is linear, and there is no stock effect or discount rate. Because of the incentive for smoothing, the government will want to equate expected marginal benefit (equal to negative expected marginal damage) and expected marginal cost across the two periods. With no information, the expected marginal damage in the second period will be mid-way between the marginal damage with a bad outcome and the marginal damage with a good outcome $E\left(D'|m_0,\alpha = \frac{1}{4}\right) = \frac{1}{2}D'(B - m_0 - m_1) + \frac{1}{2}D'(G - m_0 - m_1)$. Since in this case the government receives no new information in the first period (and there is no stock effect or discount rate), it will set mitigation equal across the two periods, $m_0 = m_1$. Thus, marginal cost will also be equal across both periods, equal to expected marginal damage $C'(m_0) = C'(m_1|m_0, \alpha = \frac{1}{4}) = E\left(D'|m_0,\alpha = \frac{1}{4}\right)$.

With full information, in the first period, the government knows whether

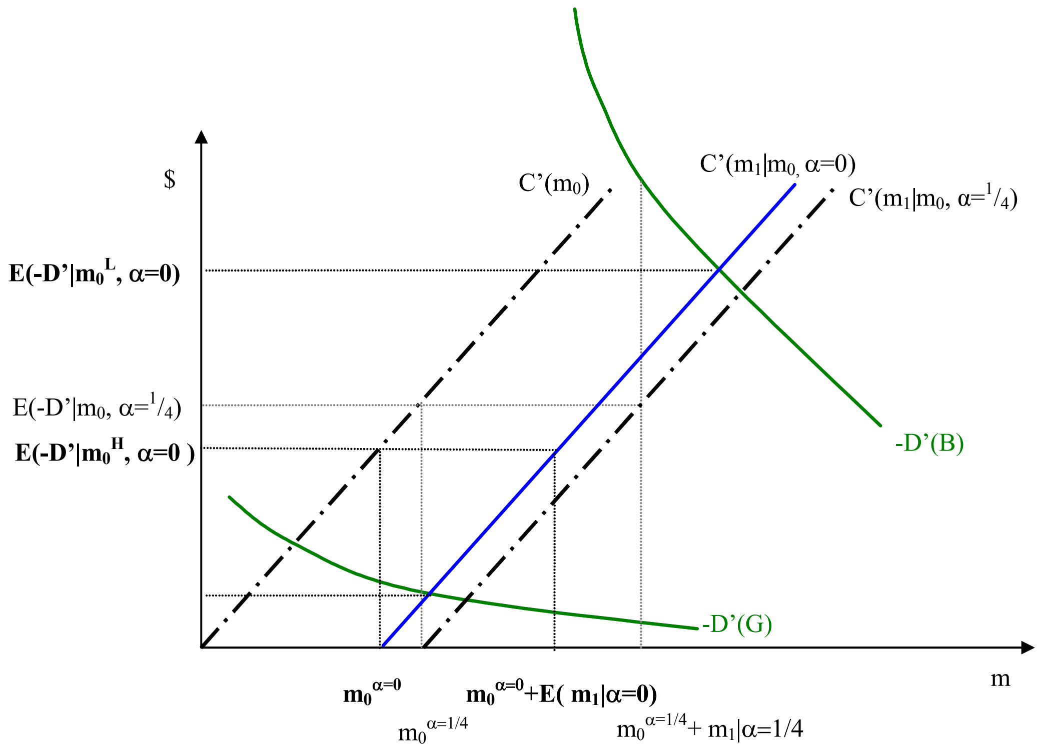

Figure 4: Mitigation choice in two periods with no and full information

the outcome will be good or bad with certainty, and can mitigate accordingly. If the information is low, indicating a bad outcome, the government will invest to the point where the marginal cost of mitigation equals the marginal damage of the bad outcome. Thus, it will set m_1^l where $D'(B - m_0 - m_1^l) = C'(m_1^l|m_0)$. Similarly, with high information indicating a good outcome, is will set m_1^h, where $D'(G - m_0 - m_1^h) = C'(m_1^h|m_0)$. In period 0, the expected marginal damage will be half-way between these two outcomes, $E\left(D'|m_{0,}\alpha = 0\right) = \frac{1}{2}D'(B - m_0 - m_1^l) + \frac{1}{2}D'(G - m_0 - m_1^h)$. The government will chose m_0 so that $E\left(D'|m_{0,}\alpha = 0\right) = C'(m_0)$ and will set $C'(m_0) = E(C'(m_1))$. Note that in this situation, where $C''' < D'''$, there is more mitigation in the initial period with no information than with full information.

In summary, $\frac{dm_0}{d\alpha}$is most likely to be positive, implying that as information increases, one mitigates less in the first period. For the reverse to be true, i.e. $\frac{dm_0}{d\alpha} < 0$, C''' must be large relative to D''' and δ must be relatively large. In other words, the curvature of the cost function must be greater than the curvature of the damage function and the stock externality must be small. In

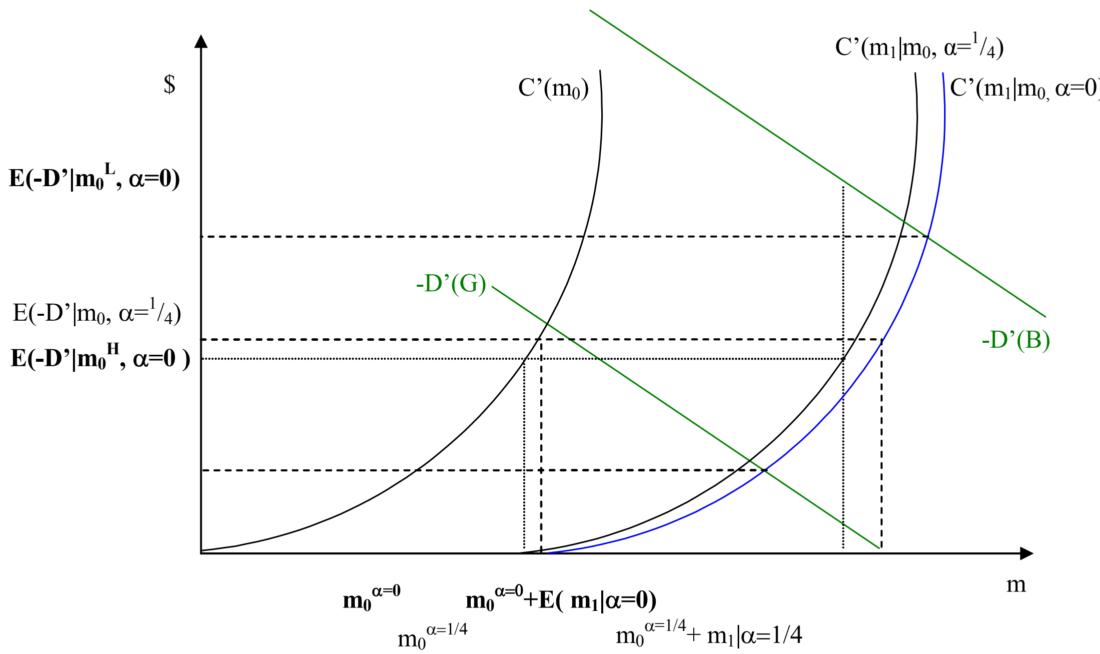

Figure 5: Mitigation choice in two periods with linear marginal damage and convex marginal cost.

general, as α is closer to 0 (i.e. there is closer to perfect information), $\frac{dm_0}{d\alpha}$ is more likely to be positive.

Proposition 2 ***Proposition 2:*** *The total mitigation will not decrease with a decrease in the quality of information.*

The proof of this proposition is in the appendix.

0.4 Conclusions

In this paper we ask about the effect of the quality of information on mitigation. We find that mitigation in the first period tends to increase when there is less information anticipated in the following period. This result is consistent with Zhao and Kling (2000). Since the government has the incentive to try to balance its expected expenditure over the two periods, and it can react more precisely with better information, the expected expenditure will be lower will better information. Therefore, its expenditure in the initial period will also be lower if the information is expected to be of good quality. Further, overall expenditure on mitigation will be lower with better information.

In summary, there is justification for both those who argue that we need to do more now (assuming that the information will not get better soon) and for those who anticipate better information around the corner and argue to wait. On the other hand, the model contradicts those corporations who both argue that there should be little investment in mitigation now by arguing that the science is too uncertain.

0.5 References

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0.6 Appendix: Proof of proposition 2.

To solve for the effect of the quality of information on total mitigation, we first need to solve for $\frac{dm_1^H}{d\alpha}$ and $\frac{dm_1^L}{d\alpha}$ To determine $\frac{dm_1^H}{d\alpha}$ we can once again use Cramer's rule:

$$\frac{dm_1^H}{d\alpha} = \frac{\begin{matrix} \beta^2 N_H & 0 & \beta^2 A_H'' \\ -\beta^2 N_L & \delta\beta^2 A_L'' + \frac{1}{2\delta}C_L'' & \beta^2 A_L'' \\ \beta^2 (N_H - N_L) & \delta\beta^2 A_L'' & \beta^2 (A_H'' + A_L'') + \frac{1}{\beta^2}C_0'' \end{matrix}}{SOC}$$
$$= \frac{\beta^2 N_H\left(\delta\beta^2 A_L''+\frac{1}{2\delta}C_L''\right)\left[\beta^2\left(A_H''+A_L''\right)+\frac{1}{\beta^2}C_0''\right]-\beta^2 N_L\delta\beta^2 A_L''\beta^2 A_H''-\beta^2(N_H-N_L)\left(\delta\beta^2 A_L''+\frac{1}{2\delta}C_L''\right)\beta^2 A_H''-\beta^2 N_H\delta\beta^4 A_L''^2}{SOC}$$
$$= \frac{\beta^2 N_H\left(\delta\beta^2 A_L''+\frac{1}{2\delta}C_L''\right)\left[\beta^2\left(A_H''+A_L''\right)+\frac{1}{\beta^2}C_0''\right]-\delta\beta^6 N_L A_L'' A_H''-\beta^4(N_H-N_L)\left(\delta\beta^2 A_L''+\frac{1}{2\delta}C_L''\right)A_H''-\delta\beta^6 N_H A_L''^2}{SOC}$$
$$= \left[\delta\beta^6 N_H A_L'' (A_H'' + A_L'') + \beta^4 N_H (A_H'' + A_L'') \left(\tfrac{1}{2\delta}C_L''\right) + \delta\beta^4 N_H A_L'' \left[\tfrac{1}{\beta^2}C_0''\right] + \tfrac{1}{2\delta}N_H C_0'' C_L'' - \delta\beta^6 N_L A_L'' A_H'' -\right.$$
$$= \left[\frac{\beta^4}{2\delta}C_L'' (N_H A_L'' + N_L A_H'') + N_H C_0'' \left(\delta\beta^2 A_L'' + \frac{1}{2\delta}C_L''\right)\right] \frac{1}{SOC} > 0$$

Similarly, to solve for $\frac{dm_1^L}{d\alpha}$:

$$\frac{dm_1^L}{d\alpha} = \frac{\begin{bmatrix} \delta\beta^2 A_H'' + \frac{1}{2\delta}C_H'' & \beta^2 N_H & \beta^2 A_H'' \\ 0 & -\beta^2 N_L & \beta^2 A_L'' \\ \delta\beta^2 A_H'' & \beta^2 (N_H - N_L) & \beta^2 (A_H'' + A_L'') + \frac{1}{\beta^2}C_0'' \end{bmatrix}}{SOC}$$

$$= \frac{-\left(\delta\beta^2 A_H''+\frac{1}{2\delta}C_H''\right)\beta^2 N_L\left(\beta^2\left(A_H''+A_L''\right)+\frac{1}{\beta^2}C_0''\right)+\delta\beta^6 N_H A_L'' A_H''+\delta\beta^6 A_H''^2 N_L-\left(\delta\beta^2 A_H''+\frac{1}{2\delta}C_H''\right)\beta^4 A_L''(N_H-N_L)}{SOC}$$
$$= \left[-\delta\beta^6 N_L A_H'' (A_H'' + A_L'') - \tfrac{1}{2\delta}\beta^4 C_H'' N_L (A_H'' + A_L'') - \delta\beta^2 A_H'' N_L C_0'' - \tfrac{1}{2\delta}C_H'' N_L C_0'' + \delta\beta^6 N_H A_L'' A_H'' + \delta\beta^6 \right.$$

$$= -\left[\frac{\beta^4}{2\delta}C_H'' (N_H A_L'' + N_L A_H'') - N_L C_0'' \left(\delta A_H'' + \frac{1}{2\beta^2\delta}C_H''\right)\right] \frac{1}{SOC}$$

Combining the above , we obtain, $\frac{dm}{d\alpha} = \frac{dm_0}{d\alpha} + \frac{1}{2}\left(\frac{dm_1^L}{d\alpha} + \frac{dm_1^H}{d\alpha}\right)$

$$= \{ \tfrac{\beta^2}{4\delta^2} (N_H - N_L) C''_H C''_L + \tfrac{\beta^4}{2} (N_H A''_L C''_H - N_L A''_H C''_L) - \tfrac{1}{2} \left[\tfrac{\beta^4}{2\delta} C''_H (N_H A''_L + N_L A''_H) - N_L C''_0 \left(\delta\beta^2 A''_H + \tfrac{1}{2\delta} C \right. \right.$$

$$+ \tfrac{1}{2} \left[\tfrac{\beta^4}{2\delta} C''_L (N_H A''_L + N_L A''_H) + N_H C''_0 \left(\delta\beta^2 A''_L + \tfrac{1}{2\delta} C''_L \right) \right] \} \tfrac{1}{SOC}$$

$$= \tfrac{\beta^2}{4\delta^2} (N_H - N_L) C''_H C''_L + \tfrac{\beta^4}{2} (N_H A''_L C''_H - N_L A''_H C''_L) + \tfrac{\beta^4}{4\delta} (N_H A''_L + N_L A''_H) (C''_L - C''_H) +$$
$$\tfrac{\delta\beta^2}{4} C''_0 (N_H A''_L - N_L A''_H) + \tfrac{1}{4\delta} C''_0 (N_H C''_L - N_L C''_H)$$

$$= \tfrac{\beta^2}{4\delta^2} (N_H - N_L) C''_H C''_L + \tfrac{\beta^4}{2} \left(1 - \tfrac{1}{2\delta}\right) (N_H A''_L C''_H - N_L A''_H C''_L) + \tfrac{\beta^4}{4\delta} (N_H A''_L C''_L - N_L A''_H C''_H) +$$
$$\tfrac{\delta\beta^2}{4} C''_0 (N_H A''_L - N_L A''_H) + \tfrac{1}{4\delta} C''_0 (N_H C''_L - N_L C''_H)$$

If $\frac{dm_0}{d\alpha} < 0$, $(N_H A''_L C''_H - N_L A''_H C''_L) < 0$ while all other terms are unambiguously positive. If $\delta > 0.5$, $\frac{\beta^4}{2}\left(1 - \frac{1}{2\delta}\right) \leq \frac{\beta^4}{4\delta}$ and, assuming $D''' \geq 0$ and $C''' \geq 0$, $N_L A''_H C''_L - N_H A''_L C''_H \leq N_H A''_L C''_L - N_L A''_H C''_H$. Thus, $\frac{dm}{d\alpha} \geq 0$. Note that even if $\delta < 0.5$, $(N_H A''_L C''_H - N_L A''_H C''_L) < (N_H A''_L C''_L - N_L A''_H C''_H)$, so that $\frac{dm}{d\alpha} \geq 0$.Further, note that, unlike $\frac{dm_0}{d\alpha}$, if $D''' = 0$ and $C''' > 0$, the term is still positive.