Investigating the effect of risk and ambiguity aversion on the social cost of carbon

Dissertation for MSc in Environmental Change and Management

Candidate No: 31721

3 September, 2004

(14,745 words)

Acknowledgements

The thesis is done as part of a project to investigate the social cost of carbon for DEFRA. I would like to thank Tom Downing at the Stockholm Environment Institute for giving me the opportunity to participate in this project. Sincere thanks to Cameron Hepburn who introduced me to this interesting area of research and his support and guidance could not have been more helpful. Thanks to Richard Tol and Chris Hope for their invaluable help in explaining FUND and PAGE. Last but not least, thanks to David Anthoff, Jiehan Guo, Megan Ceronsky, housemates and friends in Hong Kong for their fantastic help during the whole process.

Except where otherwise stated and acknowledged I certify that this Dissertation is my sole and unaided work.

Abstract

The magnitude and probabilities of global warming consequences involve both *risk* and *ambiguity*. Consequences of global warming are *risky* because climate change may generate a variety of damage possibilities with different probabilities attached to them. Impacts of global warming are also *ambiguous* because the probabilities of the occurrences of events are imprecise. With *risk* and *ambiguity* surrounding a universal challenge of global warming, this thesis aims to give a realistic account of *risk* and *ambiguity aversion* in the estimation of the social cost of carbon (SCC) to reflect the level of *risk* and *ambiguity* society is willing to take based on our current knowledge.

This thesis studied the effect of *risk* and *ambiguity aversion* under different climate sensitivity, marine methane hydrate destabilisation and emission scenarios. It is found that in taking uncertainties of climate sensitivity into account, a risk premium of 0.8-23% of the expected SCC needs to be added to the social cost of carbon. Considering uncertainties in marine methane hydrate destabilisation, the SCC should increase by a risk premium of 0.1-6.4%. The uncertainties in emission scenarios also give a similar range of risk premium of 0.5-6.4%. When climate sensitivity, marine methane hydrate destabilisation and emission scenarios are taken into consideration altogether, it is shown that risk premium ranges from 1.4% to 22% and ambiguity premium varies between 2% and 34% of the SCC given our ranges of relative risk aversion and absolute ambiguity aversion.

Table of Content

Acknowledgements 2

Abstract 3

Abbreviations, Acronyms, & Chemical Formulae 5
List of Tables 6
List of Figures 7

Chapter 1 - Introduction 8
1.1 Background 8
1.2 Aim and Methodology 9

Chapter 2 - Literature Review 11
2.1 Decision Theories under Risk 11
2.2 Decision Theories under Ambiguity 16
2.3 Numerical Estimates of Risk and Ambiguity Premiums 21

Chapter 3 - Methodology 24
3.1 Introduction of FUND and PAGE2002 24
3.2 Sources of Uncertainties 25
3.2.1 Climate Sensitivity 25
3.2.2 Catastrophic Event- Marine Methane Hydrate Destabilisation 27
3.2.3 Emission Scenarios 29
3.3 Analytical Framework 30
3.3.1 Risk Premium Calculation 30
3.3.2 Ambiguity Premium Calculation 33
3.4 Meta-Analysis 36

Chapter 4 – Results and Discussion 37
4.1 Climate Sensitivity 37
4.1.1 Results in FUND Original, FUND A2 and PAGE A2 37
4.1.2 Regional Analysis 45
4.2 Marine Methane Hydrate Dissociation 48
4.2.1 Results in FUND A2 and PAGE A2 under CS2 48
4.2.2 Results in PAGE A2 under CS3 50
4.2.3 Results in PAGE A2 under Different Climate Sensitivity Scenarios 52
4.3 Emission Scenarios 54
4.3.1 Results in FUND under Different Emission Scenarios 54
4.3.2 Results in FUND under Different Climate Sensitivity and Methane Release Scenarios 56
4.3.3 Results in FUND with a Different Initial Wealth Level 57
4.4 Application of Empirical Risk and Ambiguity Premiums 57
4.5 Meta-Analysis 58

Chapter 5 – Limitations and Future Development 59

Chapter 6 – Conclusion 61

References 63

Abbreviations, Acronyms, & Chemical Formulae

AP	Ambiguity Premium
˚C	degrees Celsius
CAAA	Coefficient of absolute ambiguity aversion
CBA	Cost benefit analysis
CH_4	Methane
CO_2	Carbon dioxide
CRRA	Coefficient of relative risk aversion
CS	Climate Sensitivity
DICE	Dynamic Integrated model of Climate and the Economy
FUND	Climate Framework for Uncertainty, Negotiation and Distribution
GDP	Gross Domestic Product
IA	Integrated Assessment
IPCC	Intergovernmental Panel on Climate Change
MR	Methane Release
PAGE	Policy Analysis for the Greenhouse Effect
Pdf	Probability density function
RICE	Regional Dynamic Integrated model of Climate and the Economy
RP	Risk Premium
SCC	Social Cost of Carbon
SRES	Special Report on Emission Scenarios
SWLU	Subjectively Weighted Linear Utility
TAR	Third Assessment Report
THC	Thermohaline Circulation
VNM	Von Neumann and Morgenstern

List of Tables

Table 2.1	Existing Estimates of CRRA……………………………………………………………	13
Table 2.2	Estimates of Risk and Ambiguity Premiums from Insurers Surveys…………………...	22
Table 2.3	Consumer Risk and Ambiguity Premiums at Different Probability Levels…………….	22
Table 3.1	Estimates of Climate Sensitivities……………………………………………………	26
Table 3.2	Climate Sensitivity Scenarios………………………………………………………...	27
Table 3.3	Methane Release Scenarios…………………………………………………………..	28
Table 4.1	Mean SCC in the 4 Climate Sensitivity Scenarios……………………………………...	39
Table 4.2	Risk Premium due to Uncertainties in Climate Sensitivity in PAGE A2………………	40
Table 4.3	Risk Premium due to Uncertainties in Climate Sensitivity in FUND A2………………	40
Table 4.4	Expected Wealth and Expected Utility in PAGE A2	42
Table 4.5	Expected Utility and Expected Phi in PAGE A2……………………………………….	43
Table 4.6	Comparison of Ambiguity Premium for PAGE A2 Results……………………………	44
Table 4.7	Regional Analysis for FUND A2 Results……………………………………............	46
Table 4.8	Regional Analysis for PAGE A2 Results……………………………………............	47
Table 4.9	Subjective Probabilities Applied to Methane Release Scenarios under CS2…………...	50
Table 4.10	Risk and Ambiguity Premiums under Methane Release and Climate Sensitivity Scenarios in FUND A2…………………………………...……………………….	50
Table 4.11	Risk and Ambiguity Premiums under Methane Release and Climate Sensitivity Scenarios in PAGE A2…………………………………....................................	50
Table 4.12	Subjective Probabilities Applied to Methane Release Scenarios under CS3…………...	51
Table 4.13	Risk and Ambiguity Premiums under Methane Release Scenarios and CS3 in PAGE A2………………………………...………………………………………..........	51
Table 4.14	Subjective Probabilities Applied to Climate Sensitivity and Methane Release Scenarios…………………………………...………………………………………	52
Table 4.15	Risk and Ambiguity Premiums for both Climate Sensitivity and Methane Release Scenarios n PAGE A2………………………………...	52
Table 4.16	Risk and Ambiguity Premiums under Different Emission Scenarios in FUND………...	55
Table 4.17	Risk and Ambiguity Premiums under Climate Sensitivity, Methane Release and Emission Scenarios in FUND………………………………...............................	56
Table 4.18	Risk and Ambiguity Premiums Assuming Utility Drops to Minimum at a SCC of $1000………………………………....……………………………………......	57
Table 4.19	Risk and Ambiguity Premiums for Meta-Analysis……………………………………...	58

List of Figures

Fig. 2.1	Utility Function…………………………………..………………………………..	11
Fig. 2.2	VNM Utility Function- Risk Aversion…………………………………….................	12
Fig. 2.3	VNM Utility Function- Risk Seeking……………………………………...................	12
Fig. 3.1	Iso-elastic Function with a CRRA of 0.8……………………………………...............	31
Fig. 3.2	Iso-elastic Function with a CRRA of 1.8……………………………………...............	31
Fig. 3.3	Estimation of Risk Premium from an Iso-elastic Function………………………………	33
Fig. 3.4	A Graphical Representation of an Ambiguity Function Φ………………………………	34
Fig. 4.1	The SCC under Different Climate Sensitivity Scenarios in FUND Original……………	37
Fig. 4.2	The SCC under Different Climate Sensitivity Scenarios in PAGE A2………………….	38
Fig. 4.3	The SCC under Different Climate Sensitivity Scenarios in FUND A2………………….	39
Fig. 4.4	Risk Premium Comparison with Different CRRA………………………………………	41
Fig. 4.5	Iso-elastic Function with a CRRA of 0.8……………………………………...............	42
Fig. 4.6	Phi Function with a CRRA of 0.8 and CAAA of 2……………………………………..	43
Fig. 4.7	Phi Function with a CRRA of 0.8 and CAAA of 2……………………………………..	44
Fig. 4.8	Phi Function with a CRRA of 1.8 and CAAA of 2……………………………………..	44
Fig. 4.9	Methane Release Scenarios under CS2 in FUND A2……………………………………	48
Fig. 4.10	Methane Release Scenarios under CS2 in PAGE A2……………………………………	49
Fig. 4.11	Methane Release Scenarios under CS3 in PAGE A2……………………………………	51
Fig. 4.12	The SCC under both Climate Sensitivity and Methane Release Scenarios in PAGE A2..	52
Fig. 4.13	The SCC under Different Emission Scenarios with CS2 in FUND……………………..	54
Fig. 4.14	The SCC under Climate Sensitivity and Methane Release Scenarios in FUND A2 and FUND B1…………………………………...………………………………………	56

Chapter 1 - Introduction

1.1 Background

Global warming has been widely recognised as one of the greatest environmental challenges in today's world. Its impacts are wide ranging – sea level rise, extreme weather effects, loss of habitat, changes in mortality rate, etc. Anthropogenic carbon emissions are considered the direct cause of global warming. (IPCC, 2001; Stott and Kettleborough, 2002) One of the ways to reduce global warming impacts is to mitigate carbon dioxide emissions. However, mitigation is costly. Cost benefit analysis (CBA) is one of the methods frequently used by economists and governments to decide the right level of mitigation for proper resource allocation in the economy.

The social cost of carbon (SCC) refers to the present value of the cost of the physical impacts of climate change to society by emitting carbon dioxide, expressed in terms of damages per tonne of carbon. (Clarkson and Deyes, 2002) The SCC will be helpful for policy analysis tools such as the CBA as it is used to balance the benefits from avoided damages and the costs involved in mitigating carbon emissions. The result is reaching an optimal level of carbon emission level whereby the marginal benefit of such emission equals the marginal cost of mitigation. (Pearce, 2003)

Estimating the SCC is challenging because the impacts of carbon dioxide emissions not only consist of market impacts that are readily expressed in monetary terms but also non-market impacts for which market based prices do not exist. Market impacts include changes to agriculture, forestry, coastal resources, etc. Non-market impacts include changes in wildlife habitat, human health effects such as heat stress, vector borne diseases, diseases triggered by water pollution, etc. and amenity values of weather.

Global warming impacts have enormous uncertainties stemming from the currently limited knowledge of the science, timing and economic impacts of climate change. Future emissions paths are also uncertain as they are driven by population growth, productivity growth and energy efficiency developments. It is very hard to predict when these uncertainties can be resolved. A number of models have been built to estimate the SCC such as DICE, RICE, PAGE and FUND (Nordhaus and Boyer, 2000; Plambeck and Hope, 1996; Link and Tol, 2004). These models are integrated assessment (IA) models that have a basic structure with a climate component as well as an economic component. They all rely on imperfectly understood geophysical processes such as the climatic reaction to changing greenhouse gas concentrations, the response of other climatic conditions such as extreme weather events to changes in global mean temperature, or the correlations of different climatic conditions. (Nordhaus, 1994; Tol, 1995) The magnitude of damage costs caused by climate change impacts is also uncertain. (Tol, 1995)

Uncertainties surrounding global climate change require us to make choices between *risky* and *ambiguous* alternatives for our future. The alternatives are *risky* because several different outcomes may result from the same action — global warming may generate a myriad of different outcomes with a variety of damage possibilities with different probabilities attached to them. The consequences of global warming are also *ambiguous* because the probabilities of the occurrences of events are imprecise.[1] Global warming is universal as everyone is exposed to the risks from different impacts of it. The society as a whole cannot rely on the insurance market to manage the risks as risk pooling fails when risks are not diversifiable. Moreover, global warming effects are also cumulative. Unlike many risks that are independent in different time periods, global warming risks in one period affect the risk exposure in the next. For example, if the society takes the risk of global warming and continuously increase the carbon dioxide emissions, the increasing concentration of carbon dioxide in the atmosphere will expose the society to greater global warming risks in the future. Moreover, many global warming impacts such as species extinction, life-loss, the shutdown of thermohaline circulation, etc. are irreversible. Because of these unique characteristics of global warming risks and its universal nature, managing global warming risks requires different strategies. If it is accepted that individuals have the right to a stable climate, the society as a whole should not be taking excessive climate change risks to infringe such rights. It is therefore essential to incorporate risk and ambiguity premiums in the estimation of the SCC at least to the extent to enable compensation to those who are risk or ambiguity averse but forced to face such risks because of the action of others.

1.2 Aim and Methodology

The purpose of this thesis is to study how risk and ambiguity aversion affect the social cost of carbon. The hypothesis tested is that incorporating risk and ambiguity premiums will increase the estimates of the SCC. The method employed to achieve this purpose is the analysis of uncertainties in the SCC as generated by integrated assessment models and the application of decision theories under uncertainty to estimate risk and ambiguity premiums for the SCC. Previously, decision theories under risk have been applied to estimate the external cost of a nuclear accident (Eeckhoudt et. al., 2000). This thesis makes a step further to include ambiguity in the analysis.

[1] A more detailed explanation and analysis of the concepts of risk and ambiguity is provided in sections 2.1 and 2.2.

The structure of the thesis is as follows: Chapter 2 will establish how risk and ambiguity attitudes should be applied to global warming challenges. Existing literature on risk and ambiguity aversion both in theories and experimental studies will be reviewed. Chapter 3 will introduce the IA models, FUND and PAGE, used in this thesis, describe the climate sensitivity, marine methane hydrate destabilisation and different emission scenarios that are being used in the 2 IA models and explain in detail the methods for computing the risk and ambiguity premiums. Chapter 4 will discuss the results of how SCC is affected by the different scenarios and analyse the risk premium and ambiguity premium effects. Chapter 5 will discuss the limitations of the study and the future research directions. Chapter 6 will conclude.

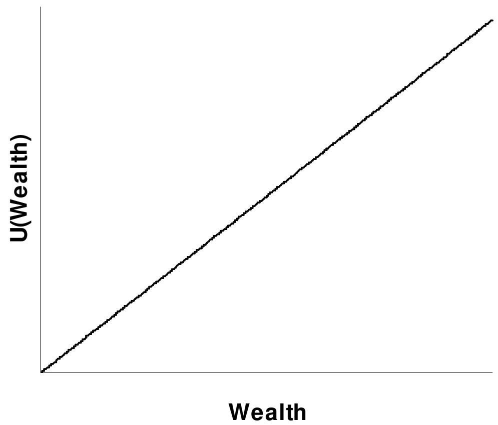
Chapter 2 - Literature Review

This chapter will review the decision theories and models that capture risk and ambiguity aversion behaviours. The literature of decision theories under uncertainty is vast. The theories introduced here only represent some of the major ones developed. Empirical estimates of coefficient of relative risk aversion, risk and ambiguity premiums will also be gathered.

2.1 Decision Theories under Risk

Risk refers to the uncertainty of outcomes when the probabilities of events are known. When making decision under risk, one is concerned not only the different outcomes but also the probability of each outcome happening. In 1728, Nicholas Bernoulli illustrated that individuals consider more than just expected value. (Machina, 1987) Gabriel Cramer and Daniel Bernoulli argued that a gain of $200 was not necessarily worth twice as much as a gain of $100 and suggested a utility function where utility is a numeric measure of a person's happiness at different levels of wealth and people are assumed to make choices so as to maximize their utility. (Machina, 1987 and Varian, 1999) A utility function of wealth is positively sloped as shown in Fig 2.1 below and it implies that utility increases with increase of wealth level.

Fig. 2.1 Utility Function



Risk attitudes can be illustrated by using utility functions to analyse a gamble with 2 possible outcomes, x_1 and x_2, and their corresponding probabilities p_1 and p_2. Von Neumann and Morgenstern (VNM) developed an expected utility theorem to evaluate gambles using expected utility $EU = \Sigma U(x_i)p_i$ (Von

Neumann and Morgenstern, 1944). The VNM utility function not only ranks the preferences of outcomes by their utility values, but also measures the strength of preferences over outcomes. Consider the following VNM utility functions:

Fig. 2.2 VNM Utility function- Risk Aversion

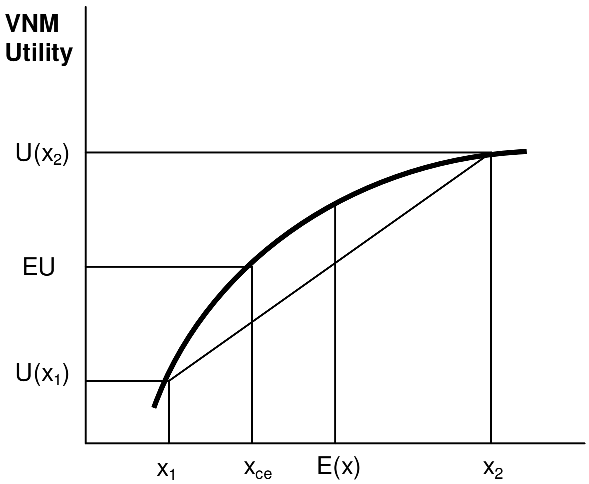
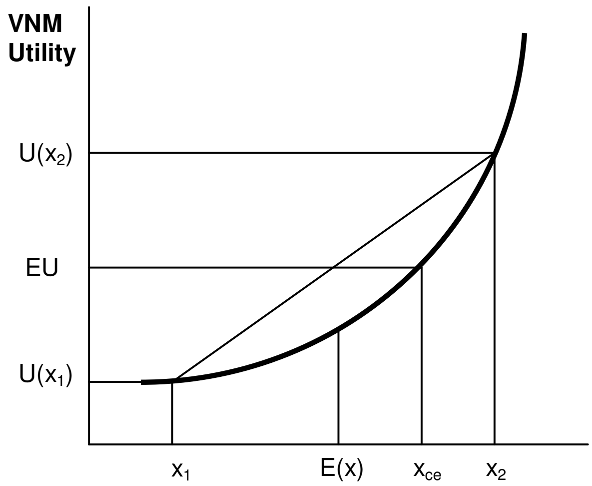


Fig. 2.3 VNM Utility Function- Risk Seeking



Figures 2.2 and 2.3 compare a gamble between outcomes x_1 and x_2 with probabilities p_1 and p_2 respectively, and the mean of the gamble E(x). In figure 2.2, as wealth level increases, the utility level increases by a smaller and smaller amount (diminishing marginal utility) as depicted by the decreasing slope. The expected value of the gamble is $E(x) = x_1*p_1 + x_2*p_2$ and the expected utility is $EU = U(x_1)*p_1 + U(x_2)*p_2$. Such a gamble gives a utility EU instead of U(E(x)) and is equivalent to a sure payoff of x_{ce} at utility level EU. x_{ce} is therefore called the certainty equivalent of the gamble. A person with such a utility function is *risk averse* because the value of the gamble to him is only x_{ce}, an amount that is less than the gamble's expected value E(x). He needs to be compensated for taking the risk of unsure payoffs in the gamble by a risk premium of $E(x)-x_{ce}$. Applying this type of utility function to a *risk averse* individual facing global warming risk, if his current wealth is x_2 with a probability p_2 of keeping such wealth and there is a probability of p_1 that his wealth decreases to x_1 because of climate change impacts, a risk premium of $E(x)-x_{ce}$ is required for him to take the risk.

In contrast, a person having the utility function as in figure 2.3 is *risk seeking* as he values the gamble at a higher valuation than its expected value, $x_{ce}>E(x)$, i.e. he is willing to pay x_{ce} to participate in such a gamble. If a person is risk neutral, his utility function will be linear and his willingness to pay for a gamble will be the same as the expected value of the gamble.

Risk aversion can be represented by a utility function concave in shape (having a decreasing slope, i.e. negative second derivative) as in Fig. 2.2. The more concave the utility function is, the more risk averse an agent is. Arrow (1965) and Pratt (1964) introduced measures of risk aversion:

- Coefficient of Absolute Risk Aversion = $-\dfrac{u''(w)}{u'(w)}$
- Coefficient of Relative Risk Aversion = $-\dfrac{u''(w)w}{u'(w)}$

The interpretation of absolute risk aversion is that an agent's risk aversion attitudes change with his wealth level. If an agent has a constant absolute risk aversion, the risk premium he is willing to pay for gambles with the same absolute risk exposure is constant. If an agent's absolute risk aversion decreases (increases) with wealth, it implies that as he becomes wealthier, he will be willing to pay less (more) risk premium for a fixed risk.

Relative risk aversion concerns with risk in proportion to wealth. If an agent has a constant relative risk aversion, for the same risk in proportion to his wealth, his risk premium in proportion to his wealth is constant. For example, an agent who faces a gamble valued y% of his wealth has a risk premium of z% of his wealth. If he has constant relative risk aversion, his risk premium is the same z% of his wealth for any other gambles which risk the same y% of his wealth.

In the context of global warming, risk aversion might be best represented by constant relative risk aversion. Since all countries with different wealth levels are affected by climate change, it is unrealistic to assume that people in poorer countries evaluate the absolute size of climate change risk irrespective to their wealth level and in the same way as people in rich countries. Relative risk aversion can better reflect people's aversion to risk according to the relative size of the risk to them. Constant relative risk aversion is assumed because the purpose of this thesis is to measure different risk premium resulting from different possibilities of risk exposure in climate change, but not how wealth level affects risk aversion attitudes.

The coefficient of relative risk aversion (CRRA) estimates in existing literature vary significantly across different contexts and models. As shown in Table 2.1, CRRA estimated from insurance and consumption are a lot lower than those estimated from financial economics. CRRA might be different under different context. While none of the estimates directly reflect the CRRA in long term global warming impacts, the range of CRRA given below provides a useful guidance on the plausible magnitude of CRRA in global warming applications.

Table 2.1: Existing Estimates of CRRA

CRRA Estimate	Type of Estimate	Source
1	Theoretical explanation	Arrow (1971)
0.7 – 15.8	Gamble on lifetime income	Barsky et. al. (1997)
1.2-1.8	Property/ liability insurance in the US	Szpiro (1986)
Median: 0.888 Mean: 3.735	Life insurance	Halek and Eisenhauer (2001)
2.35, 3.09	Consumer Expenditures	Weber (1970)
1.3-1.8	Consumer Expenditures	Weber (1975) referenced in Halek and Eisenhauer (2001)
Nondurable consumption: 2.44-5.26 Durable goods consumption: 1.79-3.21	Consumption Spending	Mankiw (1985)
0.68-0.97	Consumption data and stock return	Hansen and Singleton (1982)
0.16-4.11	Consumption data and stock return	Hansen and Singleton (1983)
well in excess of 1 probably in excess of 2	Demand for risky assets	Friend and Blume (1975)
2.6-21.2	Human capital and stock return	Campbell (1996)
2-4 if only financial assets, e.g. bonds and shares are considered as household wealth. 10-15 if all assets e.g. real estate, financial assets are considered as household wealth;	Risky asset holdings of Swedish households	Palsson (1996)

7.88 – 47.6 (average 36.04)	Risk and return relationships for UK investors at different wealth ranges	Blake (1996)
12.1	Stock ownership	Barsky et. al. (1997)
9.7 – 15 (around 12)	Risk and return of equity as the ultimate impact of a return on consumption	Parker and Julliard (2003)
26.3	Financial economics	Mankiw and Zeldes (1991)

The utility function in the expected utility model measures utilities of final states of wealth rather than gains and losses and its concave shape ensures both aversion to risks whether over gains or losses. Kahneman and Tversky (1979) had some of the major critiques to these assumptions. Through various experiments, they observed that individuals did not integrate a sure bonus with risky payoffs when making their decisions. As a result they concluded that utility is affected by change of wealth rather than final asset positions. However, the sure bonus could also be viewed as a positive change of wealth rather than the actual wealth endowment. Experiments that truly use the final states of wealth to analyse risk attitudes are lacking. Due to the insufficient evidence to prove that utility is dependent on changes of wealth rather than on wealth, the analysis used in this thesis will be based on wealth.

The expected utility model also assumed risk aversion at all probability levels. However, experiments done by Tversky and Kahneman (1992) observed that there are risk seeking behaviours for low probability gains and high probability losses and risk aversion for high probability gains and low probability losses. This pattern is also observed in other studies (Hogarth and Einhorn, 1990; Kahn and Sarin, 1988). It is worth pointing out that the risk seeking behaviours in high probability loss cases do not impact our analysis on risk aversion in the damage cost of global warming. The analysis this thesis is conducting is done on an assumption that there are sufficient numbers of people who are risk averse at all probabilities with respect to global warming and that their rights for a stable climate need to be protected.

There are many factors in decision making such as subjective beliefs, ambiguity, non-linearity in utility, etc. that are not represented in the expected utility model. The model clearly cannot explain all preference choices. In the analysis of global warming risks with imprecise probabilities, it is important to also analyse them using decision theories under ambiguity.

2.2 Decision Theories under Ambiguity

The analysis of preference in the expected utility model is limited to risky prospects with objective probabilities such as ones in a gamble where the probability of an outcome can be accurately determined. However, real world decisions involve uncertain prospects such as investments in the stock market, climate change, insurance, etc. the outcomes of which have uncertain probabilities. Ellsberg (1961), using his famous 3-colour urn example, examined choices where the uncertainty cannot be completely captured by probabilities. The 3-colour urn contains 30 red balls, 60 black and yellow balls in unknown proportion (as shown below). The example goes like this: A ball will be drawn at random from the urn and there are 4 options. Option I is “a bet on Red” where the payoff is $100 if a red ball is drawn and $0 if a black or yellow ball is drawn. Option III is “a bet on Red or Yellow”.

No. of balls	30	60	
Option	Red	Black	Yellow
I	$100	$0	$0
II	$0	$100	$0
III	$100	$0	$100
IV	$0	$100	$100

Most people prefer I to II and at the same time IV to III. Such preferences violate the subjective probability theory[2] postulated by Savage (1954). If I is preferred to II, it implies that you believe the urn has less than 30 black balls (therefore more than 30 yellow balls). Preferring IV to III thus contradicts with your expectation of more than ⅔ chance of getting a red or yellow ball in III. This example showed that it is impossible to infer probabilities from people’s choices. People might not actually put any subjective probabilities to ambiguous situations or even if they have subjective probabilities of black and yellow balls, they are not confident to use them in their decision-making. People’s decision in situations where there is a lack of information on the probabilities of different states (red, black and yellow in this case) might not be relying on subjective probabilities as predicted in subjective expected utility analysis. Moreover, empirical evidence also suggests that decisions are influenced by how much people know about the probability of states (Becker & Brownson, 1964; Slovic & Tversky, 1974; MacCrimmon &

[2] Subjective expected utility, SEU, is defined as $SEU = \sum_{s} p(s)u(x(s))$, where p(s) is the subjective probability of the states and u(x(s)) is the utility of payoff x in each state. An act with a larger SEU is preferred to one with a smaller SEU.

Larson, 1979; Einhorn & Hogarth, 1986; Kahn & Sarin, 1988; Curley & Yates, 1989). People's preference for options I and IV can be characterised as behaviour under ambiguity aversion because they prefer options where probabilities of winning are clearly defined.

Ambiguity has been described in a number of ways, e.g. ambiguous probabilities, second order probabilities, ambiguity arising from expert disagreement, etc (Camerer, 1999; Camerer and Weber, 1992). Einhorn and Hogarth (1986) defined ambiguity as an intermediate state between ignorance (having no information to rule out any probability distribution possibilities) and risk (having one defined probability distribution). For the purposes of this thesis, ambiguity refers to the uncertainty associated with specifying a probability distribution that is appropriate in a given situation due to the lack of knowledge. Ambiguity aversion then refers to the preference for choices that has a unique probability distribution than choices with unknown probabilities or sets of possible probabilities.

Since the introduction of the famous Ellsberg's Paradox in 1961, a large number of decision theories have also been developed to explain behaviour under ambiguity. The basic analytical structure is as follows:

X = set of outcomes (consequences that the decision maker cares about)
S = set of states (states of nature which is beyond the control of the decision maker)
A = set of acts (options that the decision maker can choose)

In Ellsberg's 3-colour urn example, the payoffs are the set of outcomes, the colours of balls are the states and the options I-IV are the acts. In the global warming context, the payoffs are captured by the damage done by climate change, the functioning of the climate system itself constitutes the unknown states, and the acts are different emission scenarios and policy responses. A wide range of acts including consumption smoothing over time and different precautionary investments such as emission abatement, adaptation, knowledge investment through geophysical and social science research, are among our options (Nordhaus, 1994).

Gilboa and Schmeidler (1989) and Gardenfors and Sahlin (1982) proposed very similar *maximin* decision criterion to explain the Ellsberg paradox. When a set of probability measures, i.e. a number of possible probability distributions, is used to represent one's knowledge on a particular state, the minimal expected utility of an act is computed and the act with the largest minimal expected utility is preferred. For example, in Ellsberg's 3-colour urn example, a bet on black has possible probability distributions of winning bounded by the range 0 to ⅔, i.e. the distributions can be (0 winning, ⅔ losing), (⅓ winning, ⅓ losing), etc. The minimum expected utility, u(0) from the first distribution is thus used for decision making. With this *maximin* decision criterion, ambiguity aversion is strong as it assumes maximum pessimism (Gollier et. al., 2001). Facing catastrophic scenarios, even if they are extremely unlikely to occur, people with maximum pessimism will do everything they can to avoid it. In a society, this might not be the socially optimal way of resources allocation.

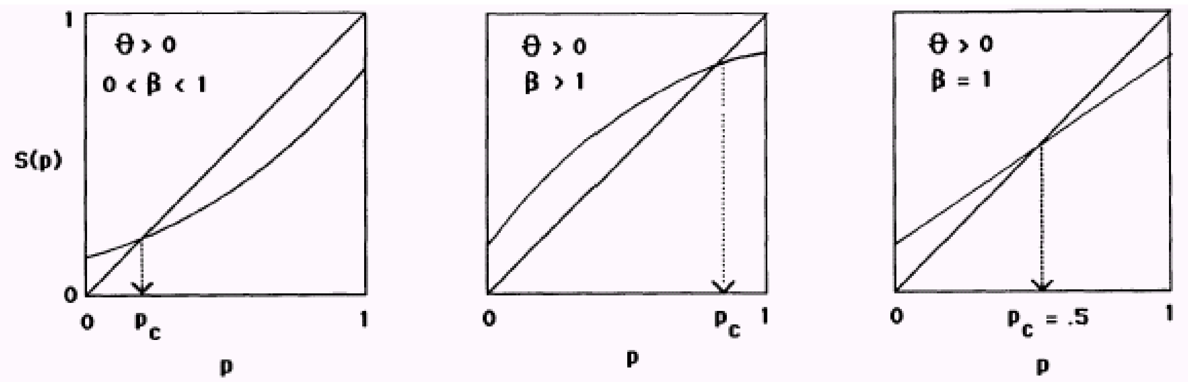
Some models do not assume sets of probabilities but adjust probabilities. Einhorn and Hogarth (1985) propose an anchoring-and-adjustment model in which an anchor probability is adjusted for ambiguity magnitude and attitude. Facing an ambiguous probability as in a bet of black of Ellsberg's ambiguous 3-colour urn, a decision maker chooses an anchor probability, p, within the possible range 0 to ⅔. Such anchor probability can come from a probability that is salient in memory, the best guess of experts, etc. For example, an anchor probability of 50% can be chosen and then adjusted for ambiguity. The overall judged probability is given by

$S(p)= p+\theta(1-p-p^{\beta})$ where p is the anchor probability

θ is the amount of perceived ambiguity ($0\leq \theta \leq 1$) and

β is the decision maker's attitude towards ambiguity.

With θ, the model is able to adjust for the amount of perceived ambiguity. For example, if there are 70 black and yellow balls in the ambiguous urn, the perceived ambiguity is larger as the probability range (0 to 0.7) is widened. β refers to the relative weighting of "imagined" probabilities that are higher and lower than the anchor and its value determines the overweighing and underweighing of different probability levels as shown in the following diagrams.



(adopted from Einhorn and Hogarth, 1986)

Using a β value greater than 1, ambiguity aversion attitudes (against loss) that overweigh probabilities especially in the low to moderate range can be represented. In such a case, less likely losses are overweighed in the decision making. By overweighing and underweighing probabilities, this model can explain people's ambiguity averse and ambiguity seeking attitudes at different probability levels as suggested in some experimental studies (Einhorn and Hogarth, 1986; Hogarth and Kunreuther1989).

Some models use an ambiguity function on the utility of consequences to reflect ambiguity attitudes. Hazen (1987) proposed a subjectively weighted linear utility (SWLU) model. The model supposes that subjective probabilities assigned to events (states) not only depend on the preference ranking of the associated payoffs but also on their sizes (Hazen and Lee, 1991). The subjective probability for event A is given by $\pi(A)\Psi(u(x_A))$. $\pi(A)$ is the subjective probability measure which depends on the preference ranking of event A. Ambiguity function Ψ depends on the utility of consequences, i.e. the function increases with increasing utility of consequences for an ambiguity seeking attitude and decreases for an ambiguity averse attitude. The subjective probability provides a normalised weight to each event in the event-contingent lottery. Hence, the utility of an event-contingent lottery is represented by:

$$u(\sum_i A_i) = \frac{\sum_i \pi(A_i)\Psi(u(x_{Ai}))u(x_{Ai})}{\sum_i \pi(A_i)\Psi(u(x_{Ai}))}$$

Recently, Klibanoff et. al. (2003) and Ahn (2003) developed very similar approaches in capturing ambiguity. In Klibanoff et. al.'s model, the risk attitude is represented by the shape of a VNM utility function. The expected utility of an act is transformed using a Φ function, the shape of which reflects the ambiguity attitude. The utility function is the classic VNM utility function. The utility of an act, f, is calculated by multiplying the utility of each outcome at each state of that act which the corresponding probability of each state, i.e., $u(f) = \Sigma u(f(s))\pi$. The value of an act f is given by:

$v(f)=\int\Phi[\int u(f(s))d\pi]d\mu$, where μ is a subjective measurement of π as the "right" probability.

The Φ function is derived as:

$\Phi(x) = -\frac{1}{\alpha}e^{-\alpha x}$ with constant absolute ambiguity aversion.

Ahn (2003) has a very similar model but argued that in decision making under ambiguity, people might not be able to conceptualise each state of the world and assign consequences to each of them. For example, i.e. applying this concept to Ellsberg's example, people then do not know how many different colours are represented in the 60 balls and nor the payoffs of each colour. In this case, acts are irrelevant because people cannot map states of nature and consequences to acts. Therefore instead of evaluating acts and states, people think of boundaries on the possible consequential probabilities. In Ellsberg's example, when people think of betting on the yellow or black or any other possible colours, the probability of winning $X is bounded between 0 and ⅔. The utility function of Ahn (2003) consists of sets of consequences, ΔX (sets of values of possible $X in the example) and sets of probabilities, μ (sets of values between 0 and ⅔), attached to sets of consequences. A function Φ specifying people's preference over subset of ΔX according to their ambiguity attitude is applied to the utilities. Thus the value of a situation looks like this:

$$v(A) = \frac{\int_A \Phi[u(\Delta X)]d\mu}{\mu(A)}$$,where A is distributions over consequences.

Compared to the 3 models by Hazen (1987), Klibanoff et. al. (2003) and Ahn (2003), the anchor-adjustment model developed by Einhorn and Hogarth (1986) is less suitable for the purpose of this thesis as it allows *ambiguity seeking* behaviour at some levels of probabilities which does not fit with our assumption that people are *ambiguity averse* at all probabilities. On the contrary, the 3 models can be used for our ambiguity analysis that assumed ambiguity aversion at all probabilities by applying a concave Φ function. The 3 models have very similar structures and essentially the functions to incorporate ambiguities are similar. They have the advantage of separating an agent's subjective belief in uncertain probabilities from his attitude toward that uncertainty which is a clear improvement from earlier models in the literature. Mathematically, the application of Klibanoff et. al. (2003) and Ahn (2003) in our SCC analysis is the same. Therefore, models of Klibanoff et. al. (2003) and Hazen (1987) will be used to our analysis.

The decision theories or models discussed so far are static in nature and do not perturb the information structure. However, global warming risks are not only imprecise but are also evolving as scientific uncertainties are resolved over time. "Learn then act" and "Act then learn" are two competing strategies in dealing with global warming. The Precautionary Principle, proposed in the principle 15 at the 1992 Rio conference, advocates the "act then learn" strategy by stating that "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation". On the other hand, different decision models have been built to incorporate learning and some of them prove that "act then learn" strategy does not result the optimal resources allocation for the society (Kolstad, 1996; Ulph and Ulph, 1997). It is important to recognise that the time scale for uncertainties to be resolved in climate change is also unknown. Therefore, the failure of some of these models to fully incorporate people's time preference for resolving uncertainties require caution in applying their models.

2.3 Numerical Estimates of Risk and Ambiguity Premiums

The focus of this section is to review estimates of related risk and ambiguity premiums found in the literature. Many studies have investigated risk and ambiguity aversion behaviours of companies and individuals, and behaviour in the insurance market is of particular interest to us, given the relationship between climate risk and other 'acts of God'. When a consumer buys an insurance policy, the risks he or she faces are transferred to the insurance company in return for the payment of a premium. In setting premium for different policies, insurance companies also exhibit risk and ambiguity aversion behaviours. The motivation behind such behaviours of insurance companies is slightly different from the consumers. Insurance companies are *risk* and *ambiguity averse* not only because of the potential losses of the policies they insure, but also because of the transaction costs associated with bankruptcy, probability of insolvency, etc. (Kunreuther et. al, 1995) Nevertheless, studies estimating risk and ambiguity premiums of insurance companies and individuals still provide valuable indicators for the willingness to pay against risk and ambiguity.

If the expected utility model is used to characterise insurers' risk and ambiguity attitudes, the minimum pure premium (P) charged by the insurers would equal to the expected value (EV) of loss if they are risk neutral (P=EV). If they are risk and/or ambiguity averse, P>EV. Kunreuther et. al. (1995) showed that insurers are *risk averse*: the premiums charged for well-specified probability of a known loss is significantly higher than EV. Insurers have also been found to be *ambiguity averse*: premium rise significantly when probabilities are ambiguous and there is a significant difference between premium charged with known probability and magnitude of loss and unknown probability and/or magnitude of loss. A recent survey of French actuaries by Cabantous (2003) also reported that insurers are *risk averse* and *ambiguity averse* in situations where the imprecise probability of loss is consensual and conflicting.

Table 2.2: Estimates of Risk and Ambiguity Premiums from Insurers Surveys

Risk Premium (% of EV)	Premium in both Risk and Ambig. (% of EV)	Implied Ambiguity Premium (% of EV)	Types of Risk/ Ambiguity	Source
62%	99-182%	37-120%	Earthquake	Kunreuther et. al. (1995)
139%	299-457%	160-318%	Underground tank leakage	Kunreuther et. al. (1995)
34%	78-87%	44-53%	Pollution	Cabantous (2003)
44%	95-101%	51-57%	Earthquake	Cabantous (2003)

The risk and implied ambiguity premiums shown in Table 2.2 are quite high. These large premiums might have operating costs of insurance companies included. But irrespective, they still provide an indication of the degree of risk and ambiguity aversion.

Camerer and Kunreuther (1989), however, produced contradicting results. In an experimental insurance market with subjects taking roles of insurers and consumers, insurance prices (trading prices) approach expected value for a large range of probabilities and loss amounts and that price are affected by ambiguity about the probability of loss only in some cases but not in any consistent direction. In a separate experiment with subjects of professional actuaries and MBA students taking the roles of insurers and consumers, Hogarth and Kunreuther (1989) showed that prices of both consumers and firms indicated aversion to ambiguity and in general, firms showed greater aversion to ambiguity than consumers. As probabilities of losses increased, aversion to risk and ambiguity decreased with consumers exhibiting ambiguity preference for high probability-of-loss events. The results of the insurance market against a $100,000 loss that could result from defective product claims are summarised as follows:

Table 2.3: Consumer Risk and Ambiguity Premiums at Different Probability Levels

Probability of Loss	Consumer Risk Premium (% of EV)	Consumer Premium in both Risk and Ambiguity (% of EV)	Implied Ambiguity Premium (% of EV)
0.01	67%	206%	139%
0.35	7%	16%	69%
0.65	0%	-5%	NIL
0.90	-17%	-26%	NIL

In a simulated insurance market experiment, Di Mauro and Maffioletti (2001) also found that the impact of ambiguity is not pervasive at all probabilities of loss. The results showed ambiguity aversion is stronger at the probability of loss of 3%, declines at higher probabilities and even ceases to exist at high loss probability level of 80%.

Efforts to estimate ambiguity premium over gains in wealth started in the 60's. Becker and Brownson (1964), based on a relatively small sample size of 15, found that people are willing to pay 70% of expected value of a gamble (assuming subjective probabilities of 50:50%). MacCrimmon and Larson (1979) estimated ambiguity premium of 20% of price. Yates and Zukowsky (1976) also estimated ambiguity premium to be 20% of expected value. Curley and Yates (1989) found that on average people are willing to give up an expected value of 5% to avoid an ambiguous option. As mentioned in section 2.1 and 2.2, risk and ambiguity attitudes vary differently over losses and gains across probability levels, ambiguity premium estimates in the gain domain mentioned above only serve as a reference.

The major risk and ambiguity in global warming are catastrophic events which have high impact and low probabilities. Therefore, risk and ambiguity aversion attitudes in global warming should resemble those at low probabilities in empirical studies. Judging from the diverse results of empirical studies, a reasonable range for risk premium might be 7-70%, reflecting the consumer risk premium range from Hogarth and Kunreuther (1989) and 5-57% for ambiguity premium, reflecting the study of Curley and Yates (1989) and the lower range obtained from the more current study by Cabantous (2003).

Chapter 3 - Methodology

The previous two chapters demonstrated the challenges in global warming and have reviewed the major decision theories under risk and ambiguity. This chapter will first introduce the 2 integrated assessment models, Climate Framework for Uncertainty, Negotiation and Distribution (FUND v.2.8) and Policy Analysis for the Greenhouse Effect (PAGE2002 v.1.4), that are used to study the uncertainties of the SCC. Secondly the sources of uncertainties and the scenarios applied will be explained. Thirdly, the methods of estimating risk and ambiguity premiums using decision theories under uncertainty will be explained. Finally, the application of the analytical framework to a meta-analysis of the SCC will be described.

3.1 Introduction of FUND and PAGE2002

Two integrated assessment models are used in this thesis– Climate Framework for Uncertainty, Negotiation and Distribution (FUND v. 2.8) and Policy Analysis for the Greenhouse Effect (PAGE2002 v.1.4). FUND consists of 2 modules, the climate module and the impact module. It distinguishes 16 regions in the world, the USA, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. FUND runs from 1950 to 2300 in time steps of one year.

Climate scenarios developed by Rahmstorf & Ganopolski (1999), who follow the IPCC IS92e scenario (Houghton et al., 1995), are used in FUND for the period until 2100. It is assumed that carbon dioxide emissions are zero as of 2200. The socio-economic (population, technology and emissions) scenario in FUND is close to IS92e until 2100. IPCC SRES scenarios, A1b, A2, B1 and B2, have also been constructed to represent different emission scenarios. Thus, uncertainties in socio-economic development can be analysed in FUND. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996) (Link and Tol, 2004). The impact module considered climate change impacts on forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems.

In FUND, parameters in both the climate and impact modules are modelled as being uncertain in order to perform *Monte Carlo analysis. Monte Carlo* is a type of simulation that randomly generates values for uncertain variables over and over and feed them into the processes of a model to calculate the possible outcomes. In FUND, many parameters in the climate as well as the impact modules are represented by different standard distributions whose mean/ mode have been set to best guess values according to IPCC or the latest relevant studies. Random numbers are sampled from the specified probability distributions for the uncertain parameters and are used to perform the SCC calculation. At the time of writing, the latest version of FUND could only run on a mode with only parameters in the climate module uncertain. Therefore, the probability density functions (pdfs) of the SCC generated in FUND only reflect uncertainties in the climate module.

PAGE2002 (hereafter, PAGE) is an integrated assessment model constructed with 8 regions: European Union, Former Soviet Union & Eastern Europe, USA, China & Central Pacific Asia, India & S.E. Asia, Africa & the Middle East, Latin America and Other OECD countries. The model runs from year 2000 to 2200. Its current emission assumptions are modelled based on the IPCC SRES A2 scenario including all major greenhouse gases. PAGE performs probabilistic calculations with many key parameters set as a distribution. Impacts of global warming are modelled as a function of temperature change. Possible future large-scale discontinuities have been incorporated into the impact calculations (Hope, 2003). *Monte Carlo analyses* are performed on PAGE with climate as well as impact parameters set uncertain to give pdfs of the SCC.

3.2 Sources of Uncertainties

This section will first introduce the 3 major sources of uncertainty to be tested in the models. The formulation of scenarios in each uncertainty area will be explained. Lastly a list of scenario testing on FUND and PAGE will be drawn up.

The following three major sources of uncertainty in SCC estimations will be examined: i) climate sensitivity; ii) catastrophic event; iii) emission scenarios driven by population and economic projections.

3.2.1 Climate Sensitivity

Climate sensitivity refers to the equilibrium response of global surface air temperature to a doubling of the atmospheric CO_2 concentration. It is one of the major parameters in the climate component of integrated assessment models as the resulting global temperature response drives other climatic factors which in turn affect other impact areas. The uncertainty of climate sensitivity not only comes from the current imperfect understanding of the climate system, but also from a variety of factors other than CO_2 that could impact global temperature response. The uncertainty of climate sensitivity also leads to uncertainties in other climatic events and climate change impacts.

Estimates of climate sensitivity are generated from a range of model types, including energy balance models, radiative-convective models and general-circulation models (Kacholia and Reck, 1997). Estimates of different ranges of climate sensitivity are set out in Table 3.1 below:

Table 3.1 Estimates of Climate Sensitivity

Climate Sensitivity (˚C)	Remarks	Source
0.1-8	90% confidence interval of subjective climate sensitivity estimates obtained through climate expert elicitation.	Morgan and Keith (1995)
0.16-8.7	Meta analysis of climate models documented between 1980-1995	Kacholia and Reck (1997)
1.5-4.5		IPCC (2001)
0.94-2.04	90% confidence interval; assumed no anthropogenic sulphate aerosol forcing	Andronova and Schlesinger (2001)
1.90-6.02	90% confidence interval; assumed anthropogenic sulphate aerosol forcing and putative solar forcing	Andronova and Schlesinger (2001)
2.88-17.8	90% confidence interval; assumed anthropogenic sulphate aerosol forcing but no solar forcing	Andronova and Schlesinger (2001)
1.5-4.5	Assumed the range given by IPCC represents a 90% confidence interval	Wigley and Raper (2001)
1.8-6.5	80% confidence interval	Allen and Ingram (2002)
1.4-7.7	90% confidence interval	Forest et. al. (2002)

(Ceronsky, 2004 and own research)

Some ranges are clearly wider than the one given by the IPCC. Forest et. al. (2002) believes that there is 70% chance that climate sensitivity lies within the IPCC range and 23% chance exceed IPCC upper bound of 4.5˚C. Andronova and Schlesinger (2001) suggests that there is a 54% likelihood that climate sensitivity lies outside the IPCC range.

In FUND and PAGE, climate sensitivity has been modelled as an uncertain parameter. While FUND uses a gamma distribution to represent climate sensitivity, PAGE uses a triangular distribution. There is no single pdf that can represent climate sensitivity. Therefore, the impact of SCC will be tested on different pdfs with different ranges using the following scenarios:

Table 3.2: Climate Sensitivity Scenarios

Scenario	Range at 90% confidence interval (˚C)	Mode Value of Climate Sensitivity (˚C)	Remarks
CS1	0.8-3.3	1.5	Reflecting the low estimate of IPCC and the lowest range of estimates of Andronova and Schlesinger (2001)
CS2	1.5-4.5	2.5	Reflecting the range and best guess value given by the IPCC
CS3	1.4-7.7	3.0	Reflecting the distributions given by Forest et. al (2002) and Allen and Ingram (2002)
CS4	2.4-15.0	5.4	Reflecting the widest range estimated by Andronova and Schlesinger (2001)

Subjective probabilities will be assigned to these scenarios according to expert opinions polled by Morgan and Keith (1995) to calculate the expected SCC resulted from all 4 scenarios.

3.2.2 Catastrophic Event- Marine Methane Hydrate Destabilisation

The destabilisation of marine methane hydrates is modelled. The hypothesis is that such a catastrophic event will bring higher uncertainty to the SCC. The processes leading to a potential release of methane to the atmosphere from marine methane hydrates are highly uncertain. Methane hydrates are naturally occurring clathrates which composed of cages of water molecules that host molecules of methane under moderate to high pressures and low temperatures (Kastner, 2001; Dickens et. al, 1995). Thus they are only stable in the uppermost few hundred or few thousand meters of continental margin sediments (Ceronsky, 2004; Kastner, 2001) Any changes to pressure or temperature, either by a lowering of the sea level or an increase in bottom-water temperature, may trigger the dissociation of the hydrate at its base (Chung and Chang, 2001)

Estimates of the size and spatial distribution of marine methane hydrate reservoirs vary greatly. Best guesses of marine methane hydrate inventory range from 6.67 x 10^5 to 3.2 x 10^7 Mt (megatonnes) of CH_4 (Ceronsky, 2004; Dickens et. al., 1997; Kvenvolden, 2002). Observations seem to suggest that methane hydrates are distributed globally (Kvenvolden and Lorenson, 2001; Gornitz and Fung, 1994). Global warming leading to the warming of deep ocean, the breakdown of thermohaline circulation, etc. may destabilize some of the vast quantities of methane hydrate. Other natural events such as earthquakes or tectonic uplift, may also trigger giant landslides in margins that could rapidly and catastrophically release large quantities of methane to the ocean and atmosphere with complex climatic feedbacks (Kastner, 2001).

Though it has been hypothesize that 55.5 million years ago, there was a rapid escape of CH_4 from marine gas hydrate reservoirs due to a deep ocean water warming of 4-8°C over less than 10^4 years (known as the Latest Paleocene Thermal Maximum event), the dissociation of present day marine methane hydrates is considered to be a low probability consequence of global warming (Katz et. al., 1999; Dickens et. al, 1995). However, if such event materialize, the potential consequences of a rapid release are significant. When methane is released into the ocean, a portion will be oxidized, thus reducing the amount released into the atmosphere. As oxygen is consumed producing CO_2, the capacity of the ocean to incorporate anthropogenic CO_2 might be reduced. Moreover the CH_4 released to the atmosphere will further enhance the greenhouse effect.

The location, timing and quantity of any potential methane release are again highly uncertain. The scenarios studied are crudely constructed as follows:

Table 3.3: Methane Release Scenarios

Scenario	CH_4 Release, Mt/ yr	Start Year	Remarks
MR1	100	2100	Reflecting the low end values of Harvey and Huang (1995) in the case of 1°C warming at the sediment-water interface, Dickens et al. (1995, 1997), Kastner (2001) that assumed 2°C of ocean warming over 100 years

MR2	2307	2100	Reflecting the estimates of Harvey and Huang (1995) in the case of 4°C warming at the sediment-water interface
MR3	8667	2100	Reflecting the high end estimate of Kastner (2001) that assumed 2°C of ocean warming over 100 years

(Ceronsky, 2004 and own research)

The start year of the methane release is 2100 to reflect the time needed for the increase in global temperature or the weakening of the thermohaline circulation (THC) to take place to trigger the destabilisation. In Atmosphere-Ocean General Circulation Models (AOGCMs), higher climate sensitivity will result more rapid declines in the THC (Wigley and Raper, 2001). These methane release scenarios will be compared under the same mode of climate sensitivity of 2.5°C (CS2) and will also be tested on CS3 to look at the added impacts of a higher probability of higher climate sensitivity on SCC.

3.2.3 Emission Scenarios

Future greenhouse gas emissions driven by different population growth, economic growth and technological advancement also pose a significant uncertainty to SCC. The original emission scenario in the FUND model partly follows the one in IS92e while that used in PAGE is the IPCC Special Report on Emission Scenarios (SRES) A2. SRES A1b, A2, B1 and B2 have been adapted and then incorporated into FUND and they will be used to study their impacts on SCC.

A1B scenario sits within the A1 family. It describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, rapid introduction of new and more efficient technologies, substantial reduction in regional differences in per capita income and balanced energy system across all sources.

A2 scenario represents a very heterogeneous world with continuous increase in global population, regionally oriented economic development, fragmented and slower per capita economic growth and technological change.

B1 scenario represents a convergent world with the global population that peaks in mid-century and declines thereafter as in the A1 storyline, but with economic structures changed toward a service and information economy and with the introduction of clean and resource-efficient technologies.

B2 scenario describes a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development and less rapid and more diverse technological change than in the B1 and A1 storylines.

Of the 4 scenarios, A2 and B1 are the extremes. A2 is set to be the most environmentally damaging with the greatest increase in population and slow technological change while B1 has less population increase together with cleaner energies. These scenarios will be applied to different climate sensitivities and methane release scenarios. To distinguish between scenarios applied to the 2 models, this thesis will use the following notations:

- "FUND Original" to represent FUND Original emission scenario which partly followed IS92e;
- "FUND A1b", "FUND A2", "FUND B1", "FUND B2" to represent the SRES scenarios constructed in FUND
- "PAGE A2" to represent the SRES A2 scenario used in PAGE.

3.3 Analytical Framework

Risk and ambiguity of SCC stem from different climate sensitivity, catastrophic events and emission paths driven by different socio-economic development described in the previous section. This section will layout the methods in estimating the risk premium and ambiguity premium to each of the 3 factors.

With parameters set uncertain in FUND and PAGE, 1000 *Monte Carlo* runs are performed in each of the models to generate probability distributions of SCC for each scenario. It is chosen to perform 1000 runs as this is the minimum number of runs that generate stable results, i.e. probability distributions generated from 1000 runs are close to ones generated from 2000 runs or 10000 runs. The SCC is discounted on a discount rate with pure rate of time preference of 3% unless otherwise stated in the analysis.

3.3.1 Risk Premium Calculation

The isoelastic utility function is the most frequently used utility function representing risk aversion. Thus, it is chosen to represent risk aversion attitude in global warming here:

$$U(w) = \frac{W^{1-\theta}}{1-\theta} \qquad (1)$$

where w = wealth;

θ = Coefficient of Relative Risk Aversion (CRRA)

Wealth is used as the argument of the utility function. However, there is a lack of literature on global wealth levels. GDP is chosen as a proxy to wealth. Since SCC is expressed in dollars per ton of carbon, the most recent world GDP figure is converted to dollars per ton of carbon by:

w = World GDP/t C = World GDP/(World CO_2 emissions*12/44)

The coefficient of relative risk aversion determines the curvature of the utility function. The higher the CRRA, the higher the degree of risk aversion and the smaller the increment in utility as wealth increases as shown in the diagrams below:

Fig. 3.1 Iso-elastic Function: CRRA=0.8

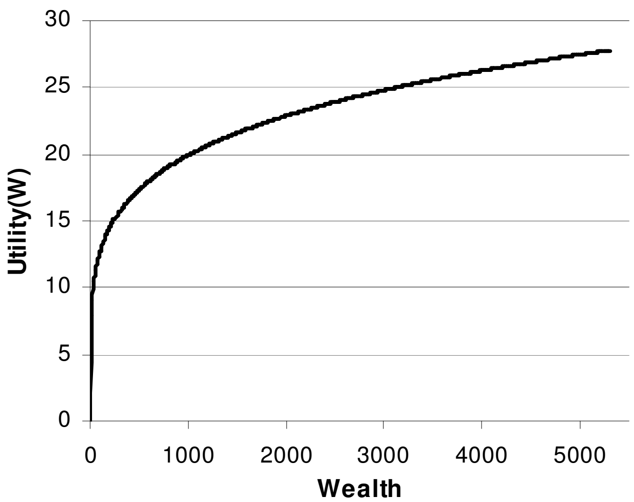
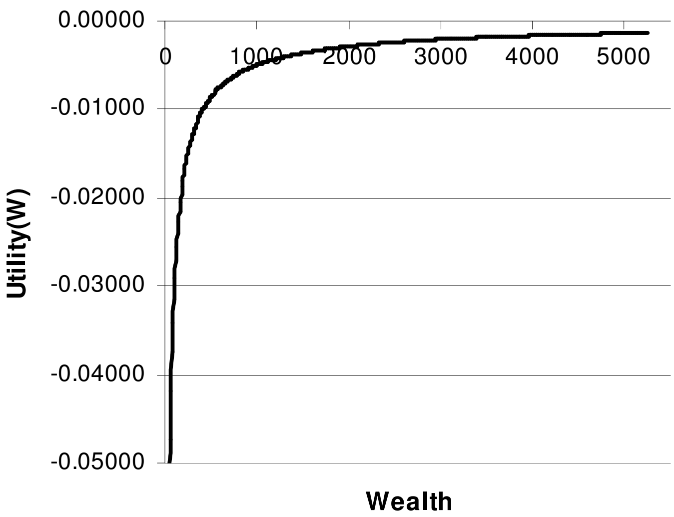


Fig. 3.2 Iso-elastic Function: CRRA=1.8



The lower ranges of CRRA estimated from insurance and consumer expenditure will be applied as CRRA values of from risky assets analysis vary a great deal from different models. The following values of CRRA will be used to the calculations to analyse their impact on the magnitude of risk premium:

CRRA = 0.8 : to reflect low end values of Barsky et. al (1997), Szpiro (1986), and median value of Halek and Eisenhauer (2001). It is within range of Hansen and Singleton (1982)

CRRA = 1.8 : to reflect the upper bounds of Szpiro (1986), Weber (1975)

CRRA = 4 : to reflect mean value of Halek and Eisenhauer (2001), upper bounds of Mankiw (1985) and Hansen and Singleton (1983)

CRRA = 10 : to reflect higher estimates from financial economics

The expected wealth level of each scenario is obtained from:

$$E(w\text{-}SCC_I) = \Sigma(w\text{-}SCC_i)\pi_i \qquad (2)$$

where w = initial wealth

π_i = probability of SCC_i in the probability distribution

(I identifies the scenario; i identifies the distribution within each scenario)

The expected utility of each scenario is given by:

$$EU(w\text{-}SCC_I) = \Sigma U(w\text{-}SCC_i)\pi_i \qquad (3)$$

The expected utility of all scenarios is given by:

$$EU(w\text{-}SCC) = \Sigma EU(w\text{-}SCC_I)\mu_I \qquad (4)$$

where μ_I = subjective probability of the scenario to materialise

By substituting the expected utility of all scenarios into the iso-elastic function in (1), the certainty equivalent wealth is obtained by:

$$w_{ce} = [EU(w\text{-}SCC)*(1-\theta)]^{[1/(1-\theta)]} \qquad (5)$$

The overall expected wealth of all scenarios is given by:

$$E(w\text{-}SCC) = \Sigma(w\text{-}SCC_I)\mu_I \qquad (6)$$

Thus, the risk premium is given by:

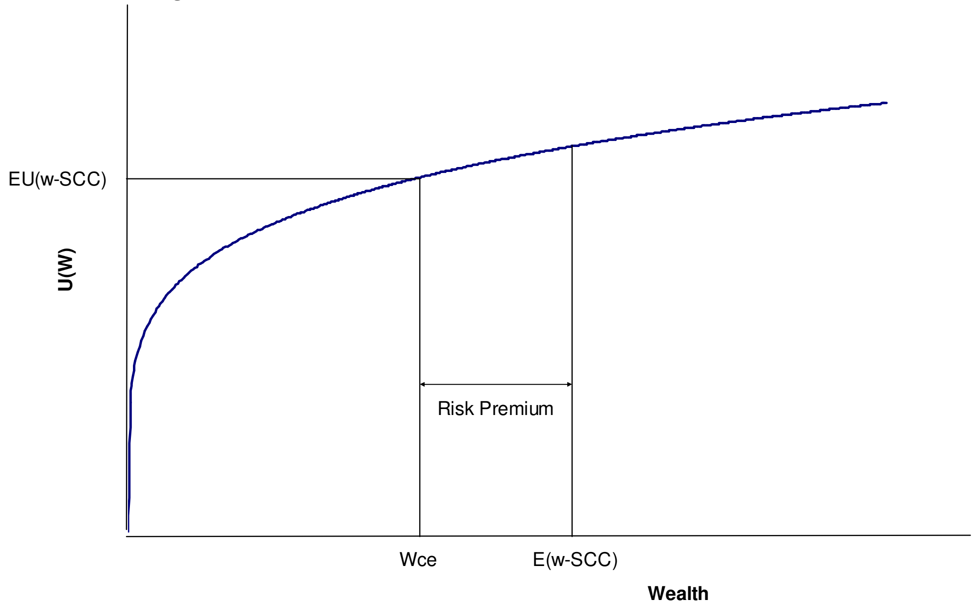
$$RP = E(w\text{-}SCC)\text{-}w_{ce} \qquad (7)$$

Finally, the risk adjusted SCC is:

$$SCC_R=\Sigma SCC_I*\mu_I+RP \qquad (8)$$

The procedure could be summarised in the following graph.

Fig. 3.3 Estimation of Risk Premium from an Iso-elastic Function



3.3.2 Ambiguity Premium Calculation

The model developed by Klibanoff et. al. (2003) and Hazen (1987) will be used and compared. Klibanoff et. al. (2003) has defined the ambiguity function Φ assumed a constant ambiguity aversion for the whole range of utilities and probabilities. Such ambiguity function Φ will be used in both models.

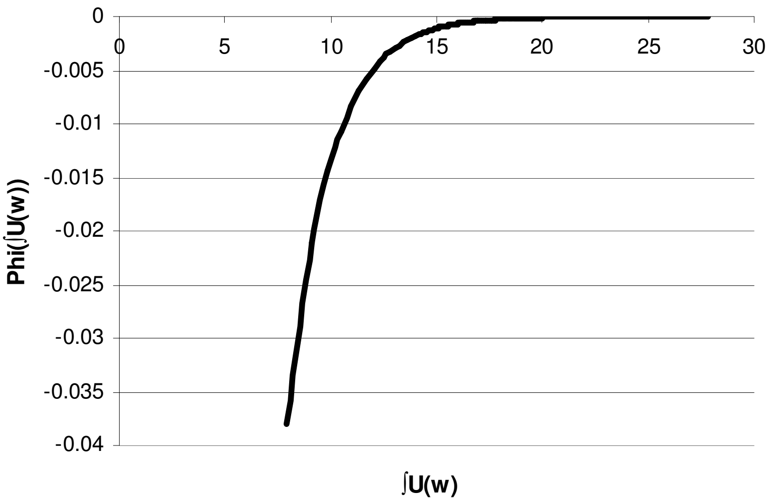
Klibanoff et. al. (2003) derived the ambiguity function Φ as:

$$\Phi(x) = -\frac{1}{\alpha}e^{-\alpha x} \qquad (9)$$

where α is constant absolute ambiguity aversion;
x is $\int u(f(s))d\pi$

Graphically, the ambiguity function Φ looks like this when u(w) has a CRRA of 0.8:

Fig. 3.4 Ambiguity Function Φ: CAAA=0.5



Since ambiguity models are relatively new and a coefficient of absolute ambiguity aversion (CAAA) is a new concept, there is currently a lack of existing estimates of α. Different values of CAAA will be applied to find the plausible range of values of CAAA to ambiguity premium that fit with the range found from empirical studies.

<u>Procedures for Klibanoff et. al.'s Model</u>

The expected utility of each scenario is transformed by Φ function by substituting x with $EU(w\text{-}SCC_I)$ from (3) into (9). Expected Φ value of all scenarios is:

$$E(\Phi) = \Sigma\Phi[EU(w\text{-}SCC_I)]*\mu_I \qquad (10)$$

By substituting E(Φ) into (9), the certainty equivalent of expected utility without ambiguity is given by:

$$\text{EU(w-SCC)}_{ce} = \frac{\ln(-E(\Phi) * \alpha)}{-\alpha} \qquad (11)$$

By substituting EU(w-SCC)_{ce} into (1), the certainty equivalent of wealth without ambiguity is given by:

$$w_{ce\text{ (no risk and ambiguity)}} = [\text{EU(w-SCC)}_{ce} * (1-\theta)]^{[1/(1-\theta)]} \qquad (12)$$

Thus, the ambiguity premium is given by:

$$AP = w_{ce} - w_{ce\text{ (no risk and ambiguity)}} \qquad (13)$$

Finally, the risk and ambiguity adjusted SCC is:

$$SCC_{R\&AA} = \Sigma SCC_I * \mu_I + RP + AP \qquad (14)$$

<u>Procedures for Hazen's Model</u>

Like in Klibanoff et. al.'s model, the expected utility of each scenario is transformed by Φ function by substituting x with $\text{EU(w-SCC}_I)$ from (3) into (9).

The normalised weight applied to each scenario is given by:

$$P_I = \frac{\mu_I \Phi[u(EU(w - SCC_I)]}{\sum_I \mu_I \Phi[EU(w - SCC_I)]} \qquad (15)$$

The expected utility of all scenarios is given by:

$$\text{EU(w-SCC)}_{ce} = \Sigma\Phi[\text{EU(w-SCC}_I)] * P_I \qquad (16)$$

After obtaining the expected utility of all scenarios above, the procedure from then on is the same as in Klibanoff et. al.'s model and equations (12) – (14) are applied.

Besides adjusting the SCC with risk and ambiguity premiums from risk and ambiguity decision theories, empirical risk and ambiguity premiums will be applied to the SCC and the results will be compared.

3.4 Meta-Analysis

There are a number of existing studies to estimate the SCC and each of them gives a different distribution. Tol (2004) has gathered all the existing SCC estimates and weighted them on the basis of 6 criteria: the age of the study, whether the study has been peer reviewed, whether impacts are independently estimated, the method for estimating marginal impacts, whether the impact model is dynamic and whether the model has included scenarios of both climate and economy. Since SCC estimates continue to be updated through new developments of the underlying IA models and as new impact studies becomes available, estimates since 1999 are used in the meta-analysis in this thesis. The risk and ambiguity analytical framework will be applied to the SCC distributions estimated by different expert and models.

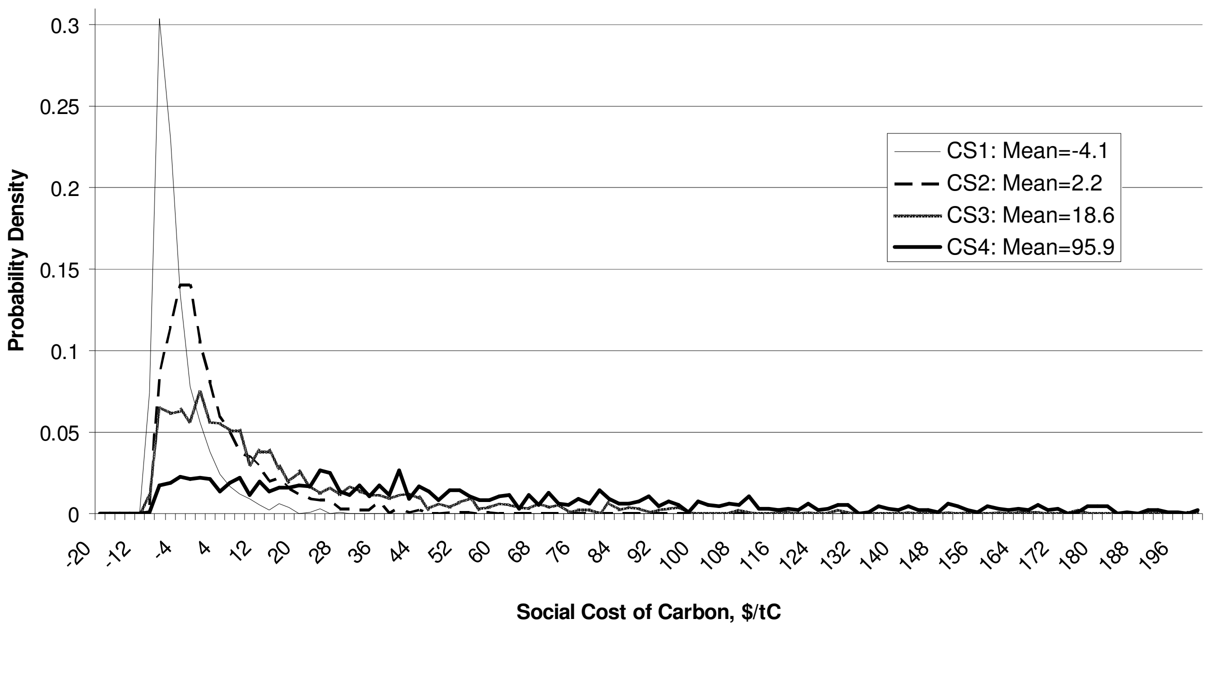
Chapter 4 – Results and Discussion

4.1 Climate Sensitivity

4.1.1 Results in FUND Original, FUND A2 and PAGE A2

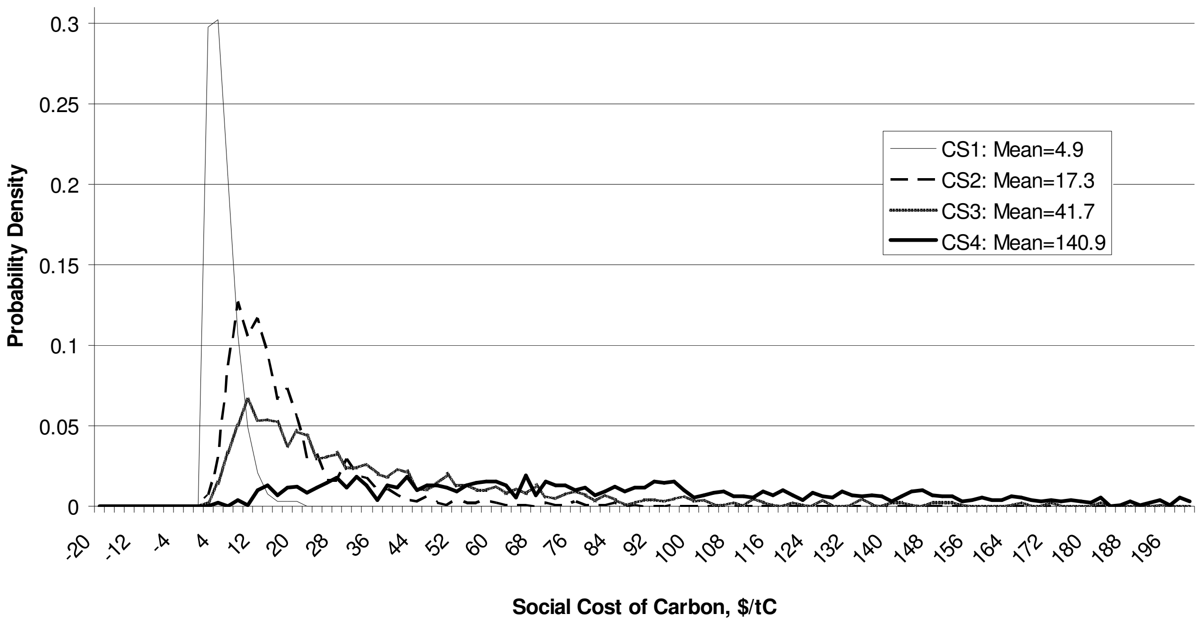
Using the original assumptions of FUND while varying climate sensitivity distributions, 4 pdfs are obtained for scenarios CS1, CS2, CS3 and CS4 as shown in Fig. 4.1. With a narrower range of climate sensitivity in CS1, a right-skewed pdf of SCC is obtained. The distributions widen as the range of climate sensitivity increases until a rather flat curve is obtained for CS4. The upper bounds of the distributions shift to the right representing higher damages as the climate sensitivity range widens to include higher climate sensitivities, leading to more uncertainties in SCC. A flat pdf as in the case of CS4 indicates that there are similar chances for obtaining SCC throughout the whole range of SCC in the pdf. Looking at the results of each climate sensitivity scenario, in cases of CS1 and CS2 under FUND Original assumptions, there is a considerable chance of having benefits (indicated by the negative values of SCC) from global warming. In CS3 and CS4, chances of having benefits are much lower than having damages.

Fig. 4.1 The SCC under Different Climate Sensitivity Scenarios in FUND Original



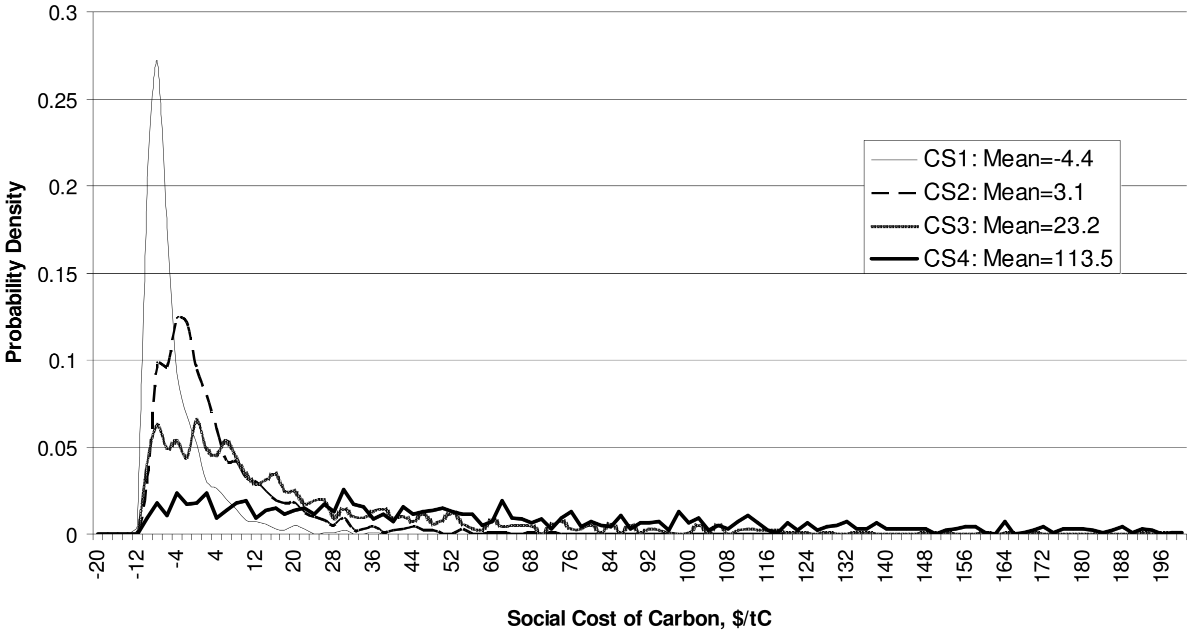
Similar results are obtained by running the same climate sensitivity scenarios with PAGE (refer to Fig. 4.2). In PAGE where the emission scenario is assumed to be the same as the SRES A2 scenario, the chances for having benefits from climate change in CS1 is almost zero. All the lower bounds of the pdfs are higher than that of FUND. The pdfs of CS3 and CS4 are flatter than those in FUND, implying even higher uncertainties in these cases than in FUND.

Fig. 4.2 The SCC under Different Climate Sensitivity Scenarios in PAGE A2



For a better comparison between the 2 models, climate sensitivity scenarios were run on FUND using SRES A2 assumptions. The results are shown in Fig. 4.3. Though the SCC is higher than those from FUND Original assumptions as there are higher probabilities for higher damages in general, the SCC are still lower than those of PAGE A2. Clearly in CS1 and CS2, there are still significant chances of having benefits from global warming. The lower bounds in FUND A2 scenario are much lower than those in PAGE.

Fig. 4.3 The SCC under Different Climate Sensitivity Scenarios in FUND A2



Given 4 distinctive pdfs with different climate sensitivity ranges, subjective probabilities are applied to each pdf to determine the risk and ambiguity premiums. The literature provides some estimates of appropriate subjective probabilities. Morgan and Keith (1995) provides a survey of subjective probability distributions elicited from 16 leading US climate scientists in the US. Their results are used as a guide to determine the subjective probabilities assigned here:

Table 4.1: Mean SCC in the 4 Climate Sensitivity Scenarios

Scenario	Mode/ Best guess Value of Climate Sensitivity (˚C)	Subjective Probability	Mean SCC FUND Original ($/tC)	Mean SCC PAGE A2 ($/tC)	Mean SCC FUND A2 ($/tC)
CS1	1.5	6%	-4.11	4.91	-4.43
CS2	2.5	50%	2.24	17.25	3.07
CS3	3.0	38%	18.59	41.67	23.18
CS4	5.4	6%	95.93	140.92	113.53
E(SCC)			**13.70**	**33.21**	**16.89**

CS3 and CS4 have significantly pulled up the expected SCC. It implies that the subjective probabilities used play a crucial role here.

It is clear that PAGE has significantly higher mean values in all climate sensitivity scenarios and as a result when the same subjectivity probability is applied to each of them the resulting expected SCC, $33, is higher than that obtained from FUND A2. These results suggest that different models have vastly different assumptions and construction to produce such diverse results even with the same climate sensitivity and socio-economic assumptions. Uncertainties from different models also vary. Comparing the SCC ranges given by PAGE A2 and FUND A2, climate sensitivity gives a wider range of SCC values in PAGE than in FUND.

To understand the impact of different CRRA, risk premium analysis was done for PAGE A2 and FUND A2 results. Using world GDP (at current prices) in 2002 as a proxy of wealth and world CO_2 emission in 1999, wealth per ton of carbon is estimated to be $5259 (World Bank, 2004). Risk premium was calculated with different CRRA values:

Table 4.2 Risk Premium due to Uncertainties in CS in PAGE A2

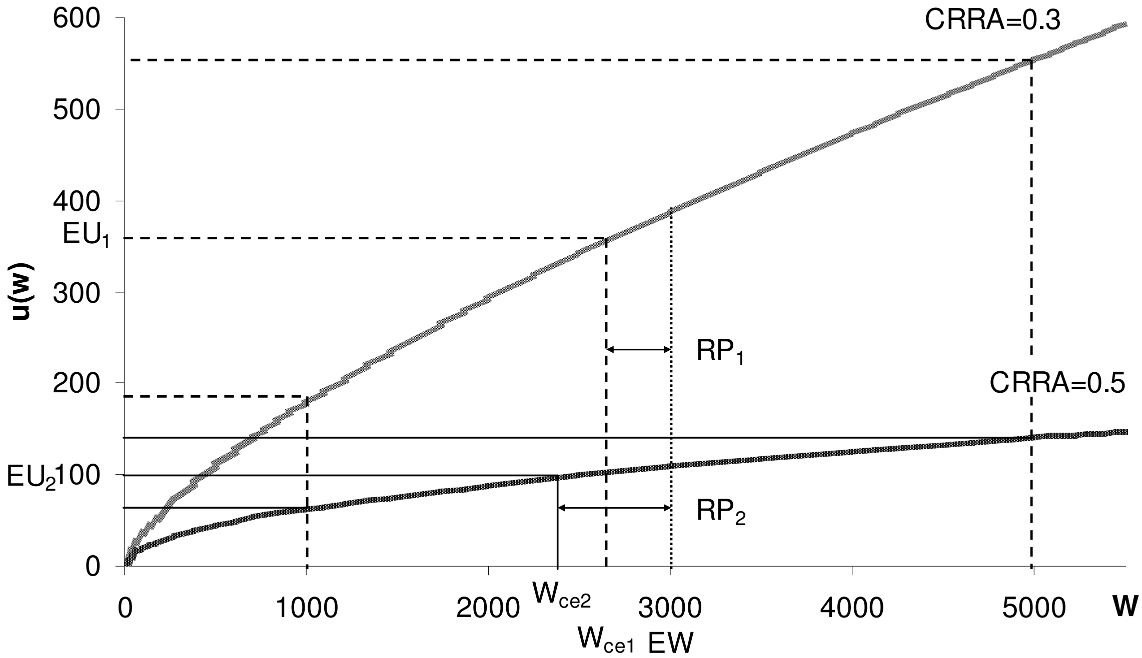
CRRA	E(SCC)	RP	Risk Adj SCC	RP in % of E(SCC)
0.8	33.21	0.26	33.47	0.78%
1.8	33.21	0.60	33.81	1.8%
4.0	33.21	1.4	34.62	4.2%
10.0	33.21	4.2	37.46	13%

Table 4.3 Risk Premium due to Uncertainties in CS in FUND A2

CRRA	E(SCC)	RP	Risk Adj SCC	RP in % of E(SCC)
0.8	16.89	0.23	17.12	1.4%
1.8	16.89	0.54	17.43	3.2%
4.0	16.89	1.3	18.16	7.5%
10.0	16.89	3.9	20.74	23%

Increasing CRRA raises the risk premium. The relationship between CRRA and risk premium is illustrated graphically in Fig. 4.4.

Fig. 4.4 Risk Premium Comparison with Different CRRA

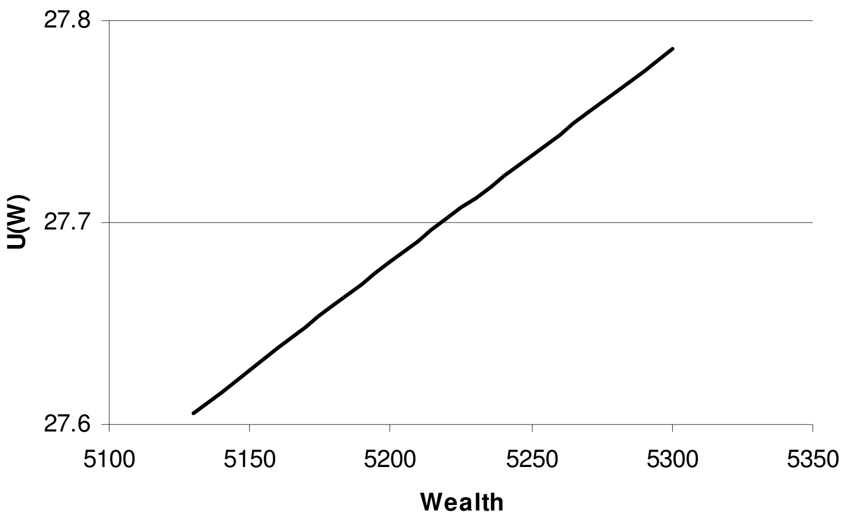


To ease the graphical presentation, a hypothetical case is considered here. Assuming there is a 50% chance of having \$1000 wealth and 50% of having \$5000, the expected utility calculated by applying the iso-elastic function with CRRA of 0.3 and 0.5 are EU_1 and EU_2 respectively. At EU_1 and EU_2, the certainty equivalents were found as W_{ce1} and W_{ce2} respectively. The expected wealth is \$3000. Since W_{ce2} is lower than W_{ce1}, the risk premium, RP_2 is greater than RP_1.

The overall risk premium contributes 0.8% to 23% in SCC which is well lower than many empirical risk premium estimates. The size of risk premium not only depends on CRRA but also on the wealth level. In an isoelastic function, which is concave for $\theta > 0$, there is more curvature[3] at lower wealth levels than at higher wealth levels because the slope of the curve decreases at a decreasing rate as wealth increases. Thus, at high wealth levels, the isoelastic function behaves more like a straight line. As shown in Fig. 4.5, the curvature of the utility curve in the range of SCC affected wealth can hardly be detected.

[3] Mathematically, curvature, $k = f''(x)/[1+(f'(x))^2]^{3/2}$. Because the denominator $[1+(f'(x))^2]^{3/2}$ is close to 1 when CRRA is higher than 1, the curvature of the isoelastic function is highly influenced by u''(w) which has a decreasing absolute value as wealth increases.

Fig. 4.5 Iso-elastic Function: CRRA=0.8



Moreover, while the wealth level is high of over $5000, mean SCC values with different climate sensitivities are rather small compared to wealth. Therefore changes in wealth as a result of SCC are small. As the curve flattens at high wealth levels, curvature within small changes of wealth and utility is minimal. The expected utilities of different climate sensitivity scenarios are therefore very close to each other as shown in the calculations in Table 4.4. Thus, the resulting risk premium is small.

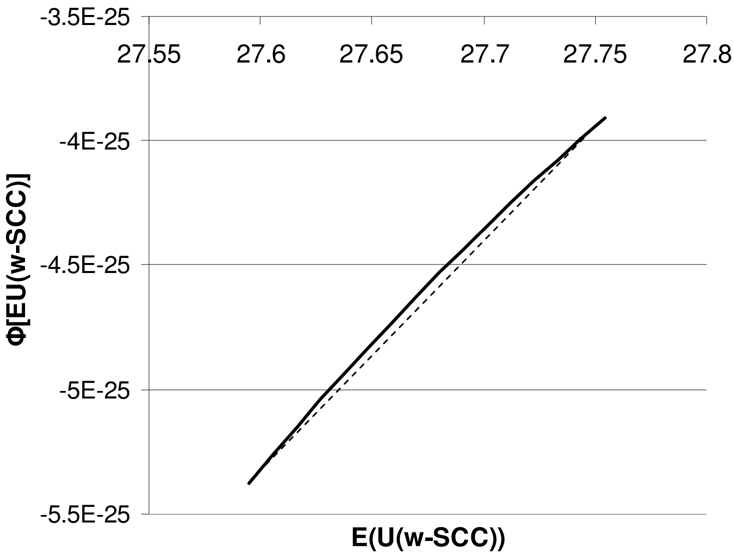
Table 4.4 Expected Wealth and Expected Utiltiy in PAGE A2

CRRA	Scenario, I	Subj. Prob. , μ_I	Exp. Wealth, $\Sigma(w\text{-}SCC_i)\pi_i$	Exp. Utility, $\Sigma U(w\text{-}SCC_i)\pi_i$
0.8	CS1	0.06	5253.92	27.737
	CS2	0.50	5241.57	27.724
	CS3	0.38	5217.15	27.698
	CS4	0.06	5117.90	27.590
Expected Wealth of all Scenarios, $\Sigma(w\text{-}SCC_I)\mu_I$			5225.61	
Expected Utility of all Scenarios, $\Sigma EU(w\text{-}SCC_I)\mu_I$				27.707
Certainty Equivalent Wealth without Risk			5225.36	
Risk Premium			0.26	

The estimation of ambiguity aversion faces a similar issue as risk premium calculation. An ambiguity function Φ, also a concave curve, is used to adjust the expected utility of each scenario. As explained above, the utility figures have values very close to each other, thus even though the utility values are much lower (slope should not be flat in this region), there is still limited curvature given the small change in utility level and $\Phi[EU(w\text{-}SCC_I)]$ values as shown in Table 4.5 and Fig 4.6.

Table 4.5 Expected Utilty and Expected Phi in PAGE A2					
CRRA	Scenario, I	Subj. Prob. , μ_I	Exp. Wealth, $\Sigma(w\text{-}SCC_i)\pi_i$	Exp. Utility, $\Sigma U(w\text{-}SCC_i)\pi_i$	Phi(U), $\Sigma\Phi[EU(w\text{-}SCC_I)]$
0.8	CS1	0.06	5253.92	27.737	-4.04E-25
CAAA	CS2	0.50	5241.57	27.724	-4.15E-25
2	CS3	0.38	5217.15	27.698	-4.37E-25
	CS4	0.06	5117.90	27.590	-5.42E-25
Expected Wealth of all Scenarios, $\Sigma(w\text{-}SCC_I)\mu_I$			5225.61		
Certainty Equivalent Wealth without Risk			5225.36		
Expected Φ value of all Scenarios, $\Sigma\Phi[EU(w\text{-}SCC_I)]*\mu_I$					-4.30E-25
Certainty Equivalent of Expected Utility without Ambiguity				27.706	
Certainty Equivalent Wealth without Ambiguity			5224.30		
Ambiguity Premium (Klibanoff et. al.)			1.05		

Fig. 4.6 Phi Function: CRRA=0.8, CAAA=2



The ambiguity premium is dependent on the coefficient of absolute ambiguity aversion (CAAA), α, as defined in the Φ function and also CRRA. Table 4.6 compares the ambiguity premium using different CAAAs and CRRAs in both Klibanoff et al.'s and Hazen's model.

CRRA	CAAA	E(SCC)	Risk Adj SCC	Ambig. Adj SCC (Klibanoff et. al.)	Ambig Premium (Klibanoff et. al.)	Ambig. Adj SCC (Hazen)	Ambig. Premium (Hazen)
0.8	0.5	33.2	33.5	33.7	0.8%	34.0	1.5%
	1	33.2	33.5	34.0	1.5%	34.5	3.1%
	3	33.2	33.5	35.1	4.9%	36.9	10%
	5	33.2	33.5	36.3	8.7%	39.7	19%
	7	33.2	33.5	37.8	13%	43.0	29%
1.8	7	33.2	33.8	33.8	0.0%	33.8	0.0%
4	7	33.2	35.5	35.5	0.0%	35.5	0.0%
10	7	33.2	38.6	38.6	0.0%	38.6	0.0%

Table 4.6 Comparison of Ambiguity Premium for PAGE A2 results

It is clearly shown that when CRRA is 0.8, as CAAA increases, ambiguity premium increases in both models. Ambiguity premium estimated by Hazen's model is about double of that estimated by Klibanoff et. al.'s model. Ambiguity effects accentuate risk premium effects. A SCC adjusted by a low CRRA of 0.8 and a high CAAA of 7 ($43/tC) is higher than a SCC purely adjusted by a high CRRA of 10 ($39/tC). Therefore ambiguity premium effects on the SCC cannot be ignored. However, when CRRA is 1.8, even a CAAA of 7 only give a negligible ambiguity premium in both models. The reasons for the difference in ambiguity premium can be shown by the following graphs:

Fig. 4.7 Phi Function: CRRA=0.8, CAAA=2

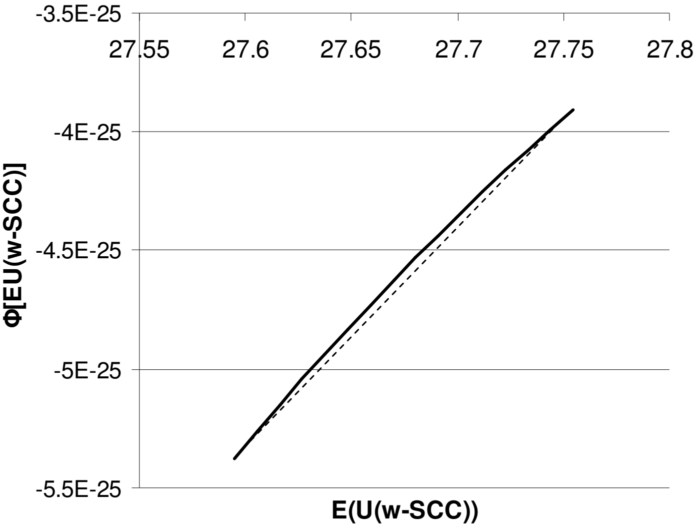
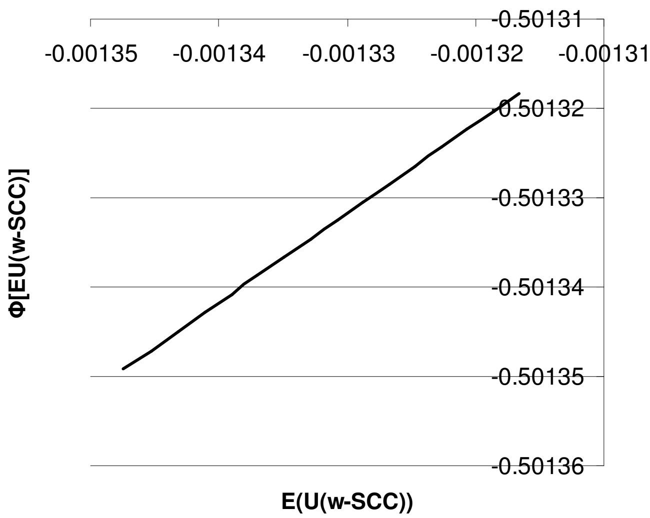


Fig. 4.8 Phi Function: CRRA=1.8, CAAA=2



The utility levels in Fig 4.7 and Fig 4.8 above correspond to the range of expected utilities obtained in the 4 climate sensitivity scenarios by using CRRA of 0.8 and 1.8 respectively. Utilities obtained from the two CRRA differ by orders of magnitude: a utility function with a CRRA of 0.8, the utility of wealth is around 27 while a CRRA of 1.8 gives a drastically smaller utility of around -1.3×10^{-3}. The utilities were applied to the Φ function with the same CAAA of 2 to obtain the graphs. In Fig 4.7, with a CRRA of 0.8, a curvature is clearly observable while in Fig 4.8, with a CRRA of 1.8, a curvature of the Φ function is not easily detected. Ambiguity premium not only depends on CAAA but also on the utility levels. Since the utilities in Fig 4.8 are so small and the differences between them are minimal, curvature in the Φ function is not enough to give a significant ambiguity premium. Therefore, in the computation procedures, as CRRA increases, ambiguity premium becomes smaller and can be negligible. Testing with different CRRA values, it is observed that ambiguity premium becomes insignificant, lower than 0.0%, when CRRA is above 1.5.

4.1.2 Regional Analysis

Climate sensitivity scenarios are further investigated using regional analysis. Each region is endowed with different wealth levels and global warming impacts to each of them are vastly different. Risk premiums and ambiguity premiums are estimated using FUND A2 and PAGE A2 scenarios. The following assumptions are made:

- Global warming impacts vary in different regions. Regions that have higher SCC are assumed to be more risk averse as they are more likely to suffer and regions that are less impacted are assumed to be less risk averse as the risk is more remote to them.
- Ambiguity attitudes across regions are constant at 4.
- Wealth/tC of each region is estimated by summing the GDP of individual countries and dividing the GDP by tons of carbon emitted in that region.

The result for FUND A2 is summarised in Table 4.7 below (unless specifically indicated, all ambiguity premiums in Table 4.7 and hereafter are calculated using the model of Klibanoff et. al.):

Table 4.7 Regional Analysis for FUND A2 Results							
Region	CRRA	CAAA	SCC (CS1)	SCC (CS4)	E(SCC)	RP	AP
China +	10.0	4.0	-2.06	47.56	6.66	1.151	0.000
Western EU	10.0	4.0	-0.56	22.71	3.52	0.089	0.000
USA	7.0	4.0	0.44	11.20	2.28	0.026	0.000
Japan & Korea	7.0	4.0	-1.44	9.97	0.26	0.018	0.000
FSU	4.0	4.0	0.14	6.36	1.26	0.019	0.000
S.E. Asia	4.0	4.0	-0.25	4.34	0.58	0.003	0.002
S. America	4.0	4.0	-0.02	3.77	0.55	0.004	0.003
South Asia	4.0	4.0	-0.24	3.55	0.39	0.003	0.000
Middle East	1.8	4.0	-0.27	3.39	0.27	0.001	0.000
Sub-Saharan Africa	1.8	4.0	0.30	3.27	0.86	0.001	0.000
North Africa	1.8	4.0	0.12	2.98	0.63	0.001	0.000
C. America	1.8	4.0	-0.15	2.73	0.30	0.000	0.000
Canada	0.8	4.0	0.04	1.88	0.26	0.000	0.000
E. EU	0.8	4.0	-0.05	1.43	0.18	0.000	0.000
Small Island States	0.8	4.0	-0.01	1.35	0.18	0.000	0.000
Oz & NZ	0.8	4.0	-0.04	1.28	0.11	0.000	0.000
				Total	**18.31**	**1.32**	**0.006**
			RP in % of E(SCC)			**7.2%**	

The expected value of SCC estimated from a regional level is different from that obtained at the aggregated level of 16.9 because of the discrepancies in estimating the pdf of each region. It is clearly observed that China, Western European Union and USA are the hardest hit in CS4 and they dominate the expected SCC. With higher CRRA assigned to these regions, their risk premium dominates. The total risk premium from all the regions in % of expected SCC is about 7%, similar to previous result when overall CRRA is assumed to be 4.

Given the higher CRRA applied to major impacted regions, the risk premium obtained is still quite low. One reason is that the regional impacts have a much narrower range of SCC between CS1 and CS4 than the aggregated world impacts, therefore changes in wealth and utilities are too small to detect any curvature in the iso-elastic function and Φ function. Moreover, some of the major impact areas have wealth much higher than world average such as Western EU, USA and Japan & Korea. As explained previously, there is limited curvature in the utility function at high wealth levels. Risk premium is thus low in these regions. In China, because the region has relatively low wealth and moderate range SCC (therefore overall more curvature in the utility function), risk premium is quite high at about 17% of expected SCC. Ambiguity premium detected is minimal as the CRRA used in high impact regions are higher than 1.5. If the analysis were further disaggregated to the country level and the high impact regions were ones that have lower wealth, risk premium of those countries would increase and might result higher overall risk premium in the world.

The same procedure is done on PAGE regional results and Table 4.8 below is the summary:[4]

Table 4.8 Regional Analysis for PAGE A2 Results							
Region	CRRA	CAAA	SCC (CS1)	SCC (CS4)	E(SCC)	RP	AP
India & SE Asia	10.0	4.0	2.39	65.15	14.68	2.807	0.000
Latin America	10.0	4.0	1.55	39.77	8.91	0.380	0.000
Africa & Middle East	10.0	4.0	1.44	36.43	8.13	0.466	0.000
EU	7.0	4.0	0.35	9.54	2.03	0.006	0.000
China & CP Asia	4.0	4.0	0.18	4.40	0.94	0.002	0.000
USA	1.8	4.0	0.13	2.92	0.64	0.000	0.000
Other OECD	1.8	4.0	0.13	2.53	0.55	0.000	0.000
FSU & EE	0.0	0.0	0.00	-3.61	-0.65	0.000	0.000
				Total	**35.2**	**3.66**	**0.000**
				RP in % of E(SCC)		**10.4%**	

The expected SCC is again different from $33/tC obtained at the aggregated level because of the discrepancies in regional pdf estimation. Results from PAGE give a vastly different picture showing India & SE Asia, Latin America and Africa & the Middle East as the hardest hit regions instead of China and Western EU. Differences in model construction account for such contrasting regional results. PAGE uses regional damage estimates in terms of % of GDP from the IPCC TAR on Impacts, Adaptation and Vulnerability. Such estimates have considerable uncertainty. FUND, on the other hand, modelled 13 impact areas for 16 different regions using different impact studies which cover all the regions for consistency. Therefore the underlying variation in regional SCC estimates lie in the different assumptions in the studies that IPCC TAR used and the impact studies that FUND aggregated.

In the estimation of risk premium and ambiguity premium, as explained previously, one of the crucial factors is the wealth level. With coarser regional groupings in PAGE, vastly dissimilar wealth levels within the regions are masked and thus risk aversion of poorer countries cannot be fully reflected in the risk premium. The overall risk premium of 10% is dominated by India and SE Asia with a risk premium of 19% of expected SCC of that region. The overall risk premium is higher than that resulted from FUND because there are 3 regions in PAGE, India & SE Asia, Latin America and Africa & the Middle East, which have a wider range of damages.

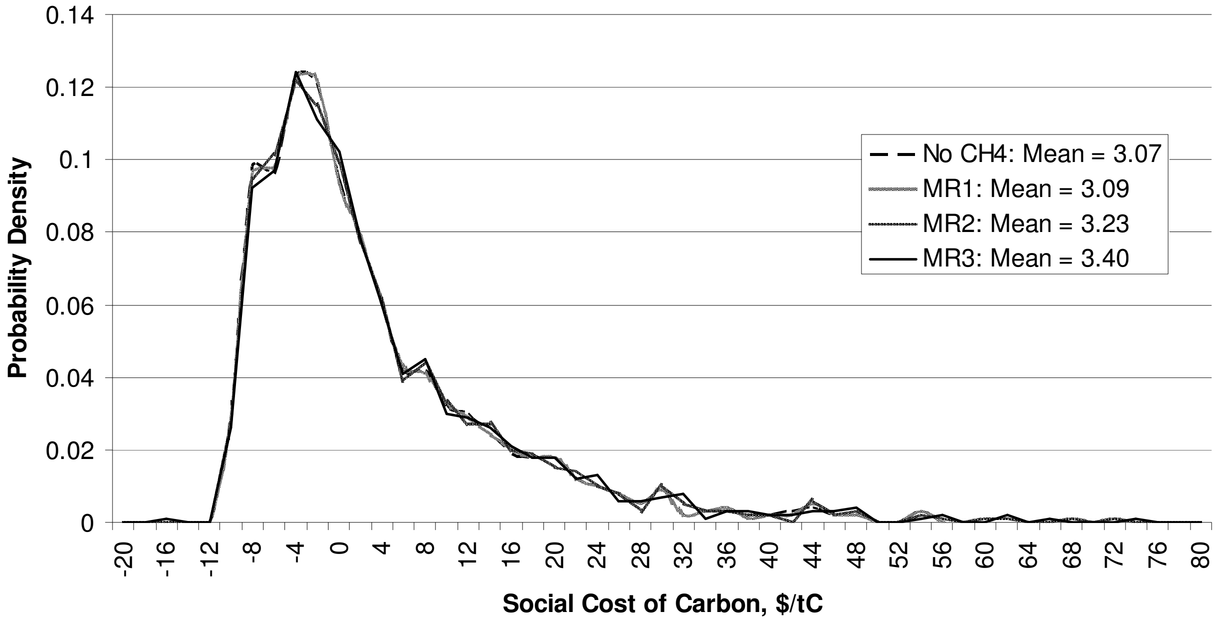
[4] Note that in Table 4.8, the CRRA and CAAA set for FSU and EE are both zero. This is because the regional analysis revealed a mean gain from global warming for the Former Soviet Union and Eastern Europe at all climate sensitivity scenarios. While there is not enough data to comment on whether this is a reasonable result, it is worthwhile to scrutinize the validity of the modelling procedures and the underlying assumption.

4.2 Marine Methane Hydrate Dissociation

4.2.1 Results in FUND A2 and PAGE A2 under CS2

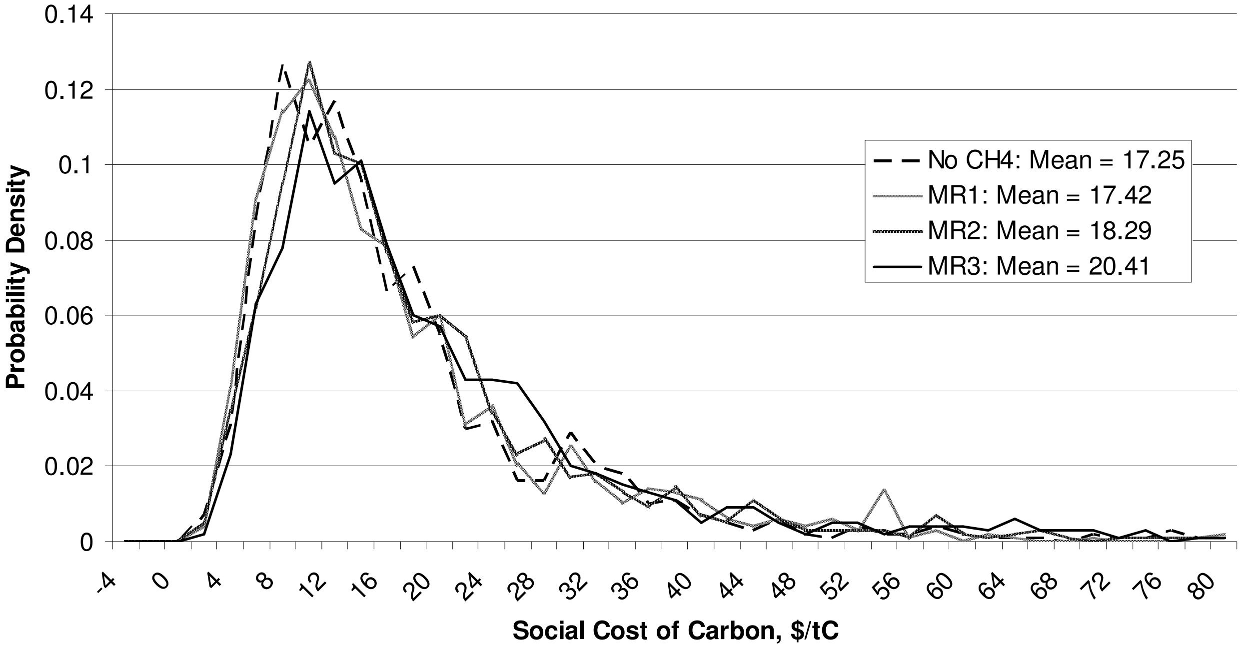
The A2 scenario is used to estimate the impact of methane release. Figure 4.9 shows the pdfs of different rate of methane release in the FUND model.

Fig. 4.9 Marine Release Scenarios under CS2 in FUND A2



Though the pdfs follow very closely together, the mean SCC for MR2 is 5% higher than that for no methane release and the mean SCC for MR3 is 11% higher. The differences in SCC under different methane scenarios are much less compared to the climate sensitivity scenarios. The same assumptions and methane scenarios are applied to PAGE and the result is set out in Figure 4.10.

Fig. 4.10 Methane Release Scenarios under CS2 in PAGE A2



Results in PAGE have clearly shown that there is shifting of curves to the right, i.e. as the rate of methane release increases, there are higher probabilities in the higher SCCs. The mean also shows significant increase from the no methane release scenario, with MR2 having a mean of 6% higher and MR3 having a mean of 18% higher.

As mentioned in the previous sections, the calculation of risk and ambiguity premiums requires the assignment of subjective probabilities to the scenarios. These methane release scenarios are built from studies that have used if-then analyses whereby certain climate conditions, such as the warming of ocean or the warming at the sediment-water interface, are needed to trigger the release of methane. Thus, the methane release scenarios do not have a probability attached to them and there is also a lack of literature concerning the probability of different ocean warming scenarios. The subjective probabilities used in this analysis are therefore arbitrary and the calculation only intends to serve as a guide only. Assuming that there is a 10% probability of methane release with a climate sensitivity of 2.5°C and there is an equal probability of each of the methane release scenarios, the subjective probabilities applied are set out in Table 4.9.

Table 4.9 Subjective Probability applied to Methane Release Scenarios under CS2

Scenario	Subjective Probability
No CH4	0.900
M1	0.033
M2	0.033
M3	0.033

The risk and ambiguity premiums estimations are summarised below:

Table 4.10 Risk and Ambiguity Premiums under Methane Release Scenarios and CS2 in FUND A2

CRRA	CAAA	E(SCC)	Risk Adj SCC	RP in % of E(SCC)	Ambig. Adj. SCC	AP in % of E(SCC)
0.8	7.0	3.09	3.10	0.3%	3.10	0.0%
1.8	7.0	3.09	3.11	0.7%	3.11	0.0%
4	7.0	3.09	3.14	1.7%	3.14	0.0%
10	7.0	3.09	3.22	4.2%	3.22	0.0%

Table 4.11 Risk and Ambiguity Premiums under Methane Release Scenarios and CS2 in PAGE A2

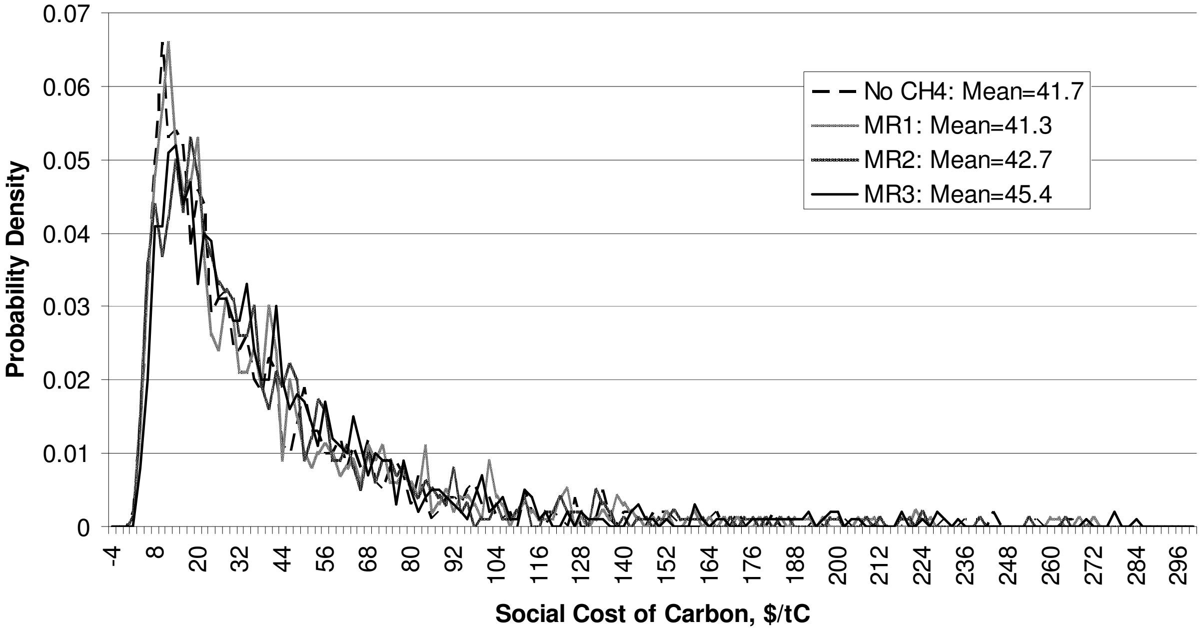
CRRA	CAAA	E(SCC)	Risk Adj SCC	RP in % of E(SCC)	Ambig. Adj. SCC	AP in % of E(SCC)
0.8	7.0	17.40	17.41	0.1%	17.4	0.0%
1.8	7.0	17.40	17.43	0.2%	17.4	0.0%
4	7.0	17.40	17.46	0.4%	17.5	0.0%
10	7.0	17.40	17.56	1.0%	17.6	0.0%

The risk premium in both FUND and PAGE results are small. Risk premium in FUND results only becomes more substantial when CRRA is 10 and risk premium in PAGE results is minimal. Low risk premiums are obtained because the ranges of SCC given by the 3 methane scenarios are narrow in both models and the subjective probabilities applied to extreme methane scenario MR3 are also low. For the same reasons, ambiguity premium is also negligible.

4.2.2 Results in PAGE A2 under CS3

Methane release is potentially triggered by the weakening of thermohaline circulation or the warming of deep ocean due to global warming. It is hypothesised that the higher the climate sensitivity, the higher the probability of methane release and the higher the SCC. Scenarios for the release of methane from marine methane hydrate dissociation have also been tested with CS3 where there is a higher likelihood for higher climate sensitivity in PAGE A2. The resulting pdfs are shown in Fig 4.11.

Fig. 4.11 Methane Release Scenarios under CS3 in PAGE A2



Under CS3, a moderate methane release (MR2) from marine methane hydrate will cause SCC to increase by 3% and a high methane release (MR3) will raise SCC by 9% from the scenario without any methane release. With increased likelihood of higher climate sensitivity, the chances for methane release are assumed to double. The subjective probabilities applied are as follows:

Table 4.12 Subjective Probability Applied to Methane Release Scenarios under CS3

Scenario	Subjective Probability
No CH4	0.800
M1	0.067
M2	0.067
M3	0.067

The risk and ambiguity premium effects are summarised below:

Table 4.13 Risk and Ambiguity Premiums under Methane Release Scenarios and CS3 in PAGE A2

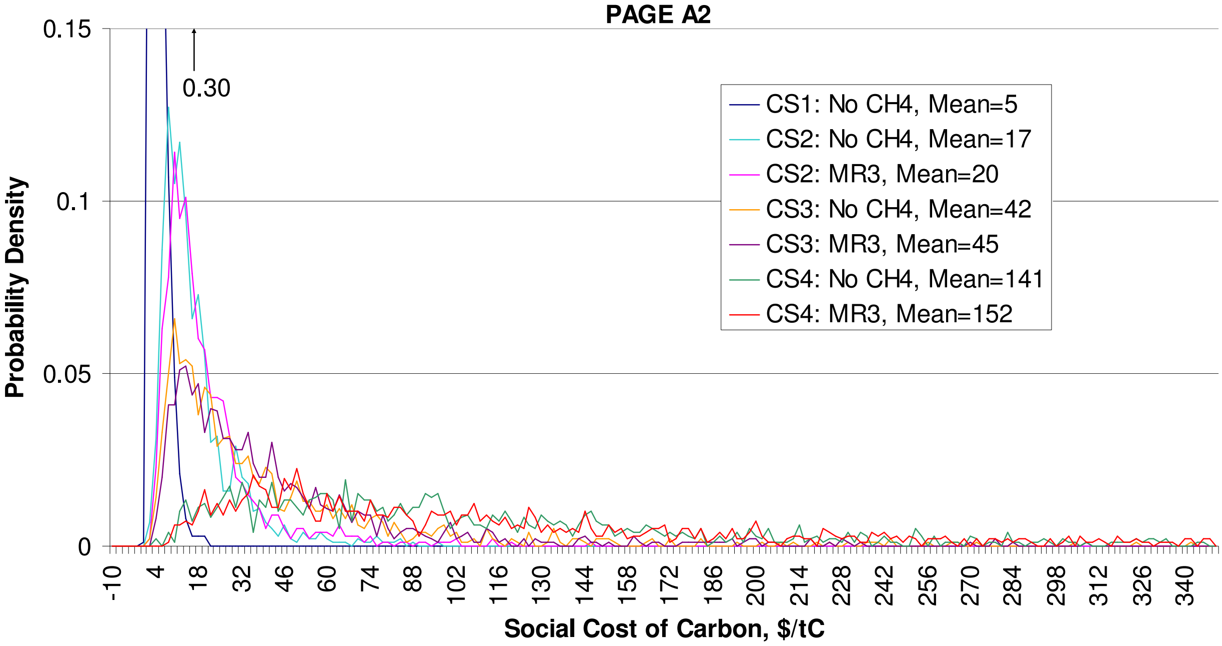
CRRA	CAAA	E(SCC)	Risk Adj SCC	RP in % of E(SCC)	Ambig. Adj. SCC	AP in % of E(SCC)
0.8	7.0	42.0	42.2	0.45%	42.2	0.0%
1.8	7.0	42.0	42.4	1.0%	42.4	0.0%
4	7.0	42.0	43.0	2.4%	43.0	0.0%
10	7.0	42.0	44.7	6.4%	44.7	0.0%

Clearly, with higher probabilities attached to methane release scenarios, risk premium increases to 6.4% from 1% in the previous scenario of CS2.

4.2.3 Results in PAGE A2 under Different Climate Sensitivity Scenarios

Considering both climate sensitivity and methane release scenarios together, the overall SCC under PAGE A2 is obtained. Only the high methane release (MR3) scenarios are used to simplify the analysis. The distributions of SCC are shown in Fig. 4.12 below:

Fig. 4.12 The SCC under both Climate Sensitivity and Methane Release Scenarios in PAGE A2



Subjective probabilities are applied such that probabilities of each climate sensitivity scenario and the probability of the high methane scenario (MR3) within each climate sensitivity scenario are taken into account. It is assumed that at higher climate sensitivity, the probability of methane release is higher. The following subjective probabilities are used:

Table 4.14 Subjective Probability Applied to Climate Sensitivity and Methane Release Scenarios

Scenario	Subjective Probability
CS1: No CH4	6%
CS2: No CH4	45%
CS2: MR3	5%
CS3: No CH4	31%
CS3: MR3	7%
CS4: No CH4	3%
CS4: MR3	3%

Taking into account risk aversion and ambiguity aversion at various degrees, the range of SCC is found to range between $34/tC and $45/tC. The calculation is summarised in Table 4.15 below:

Table 4.15 Risk and Ambiguity Premiums for both CS and MR Scenarios in PAGE A2

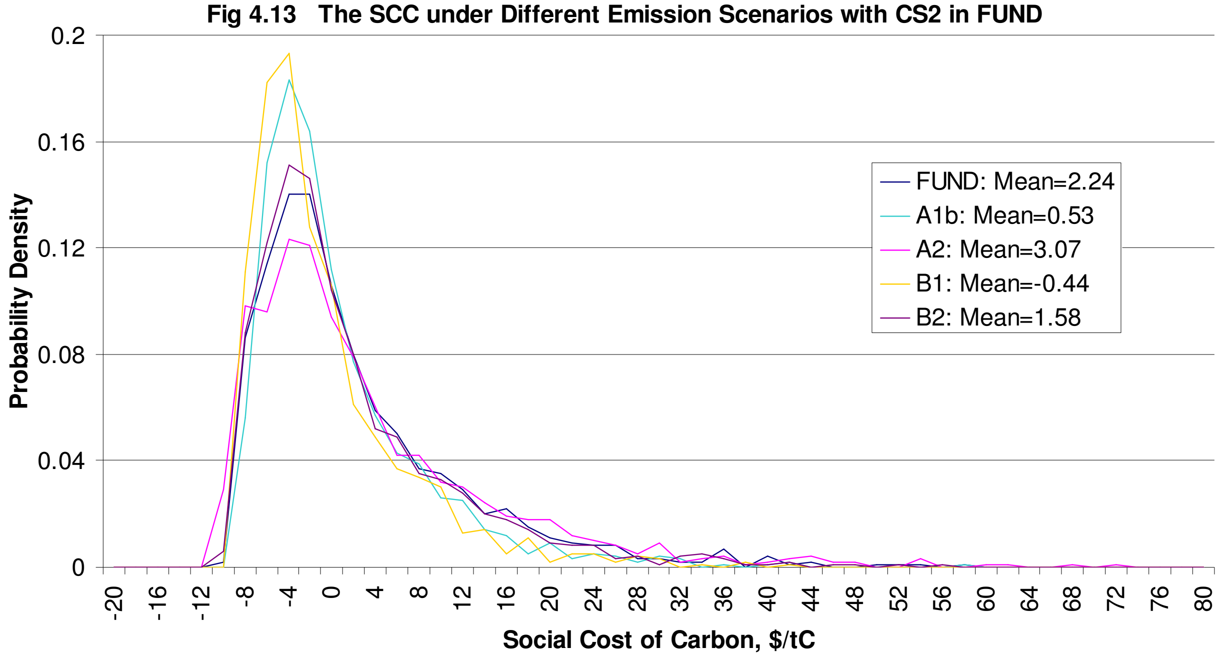
CRRA	CAAA	E(SCC)	Risk Adj SCC	Risk Premium	Ambig. Adj SCC (Klibanoff et. al.)	Ambig. Premium (Klibanoff et. al.)	Ambig. Adj SCC (Hazen)	Ambig. Premium (Hazen)
0.8	1	34.0	34.2	0.8%	34.8	1.6%	35.4	3.3%
	3	34.0	34.2	0.8%	36.0	5.2%	37.9	11%
	5	34.0	34.2	0.8%	37.4	9.3%	41.0	20%
	7	34.0	34.2	0.8%	38.9	14%	44.7	31%
1.8	7	34.0	34.6	1.9%	34.6	0.0%	34.6	0.0%
4	7	34.0	35.5	4.5%	35.5	0.0%	35.5	0.0%
10	7	34.0	38.6	14%	38.6	0.0%	38.6	0.0%

4.3 Emission Scenarios

4.3.1 Results in FUND under Different Emission Scenarios

The FUND Original scenario and 4 IPCC SRES scenarios are compared with the same climate sensitivity scenario CS2. These 5 emission scenarios certainly do not exhaust all emission scenarios driven by different socio-economic development possibilities. IPCC itself has developed 35 emission scenarios in SRES. Each of the four SRES scenarios used in this thesis represents an illustrative scenario for each of the 4 families of scenarios developed. The following pdfs of SCC under the 5 scenarios including the FUND Original scenario are obtained.

Fig 4.13 The SCC under Different Emission Scenarios with CS2 in FUND



Compared to climate sensitivities, emission scenarios produce a much narrower range of SCC from -0.44 to 3.07. A2 produced the most gloomy picture with higher probabilities at higher SCCs and the highest mean SCC while B1 has considerable probability in having a gain from global warming. This result is expected. A2 scenario assumed continual global population growth and fragmented technological change and these assumptions in general generate higher greenhouse gas emission levels. Interestingly, B1 scenario with less population growth and more resource-efficient technologies results a mean gain. Comparing the contrasting results of A2 and B1 scenarios by sectors, it is observed that in both scenarios, the dominating sectors are agriculture and the economic loss in energy consumption for cooling. In both scenarios, the net gain in agriculture is similar, however, the economic loss in energy consumption for cooling in B1 is significantly smaller than in A2. As a result, B1 has an overall gain while A2 has an overall loss. This result implies that the rapid deployment of energy efficient technologies in B1 can significantly reduce the SCC. FUND scenario produced relatively high SCC as the emission scenario is partly constructed with the highest emission scenario IS92e.

Equal weights are applied to each emission scenario because all IPCC SRES scenarios are considered to be equally likely. Taking into account of all the 5 scenarios, the mean SCC is found to be 1.4. Applying the risk premium analysis, with CRRA ranged from 0.8 to 10, the risk premium ranged from 0.5% to 6.4%. These results are summarised in Table 4.16.

Table 4.16 Risk and Ambiguity Premiums under Different Emission Scenarios in FUND

CRRA	CAAA	E(SCC)	Risk Adj SCC	RP in % of E(SCC)	Ambig. Adj. SCC	AP in % of E(SCC)
0.8	0.5	1.397	1.404	0.5%	1.404	0.0%
0.8	3.0	1.397	1.404	0.5%	1.406	0.2%
0.8	5.0	1.397	1.404	0.5%	1.408	0.3%
0.8	7.0	1.397	1.404	0.5%	1.409	0.4%
1.8	7.0	1.397	1.412	1.1%	1.412	0.0%
4	7.0	1.397	1.432	2.5%	1.432	0.0%
10	7.0	1.397	1.486	6.4%	1.486	0.0%

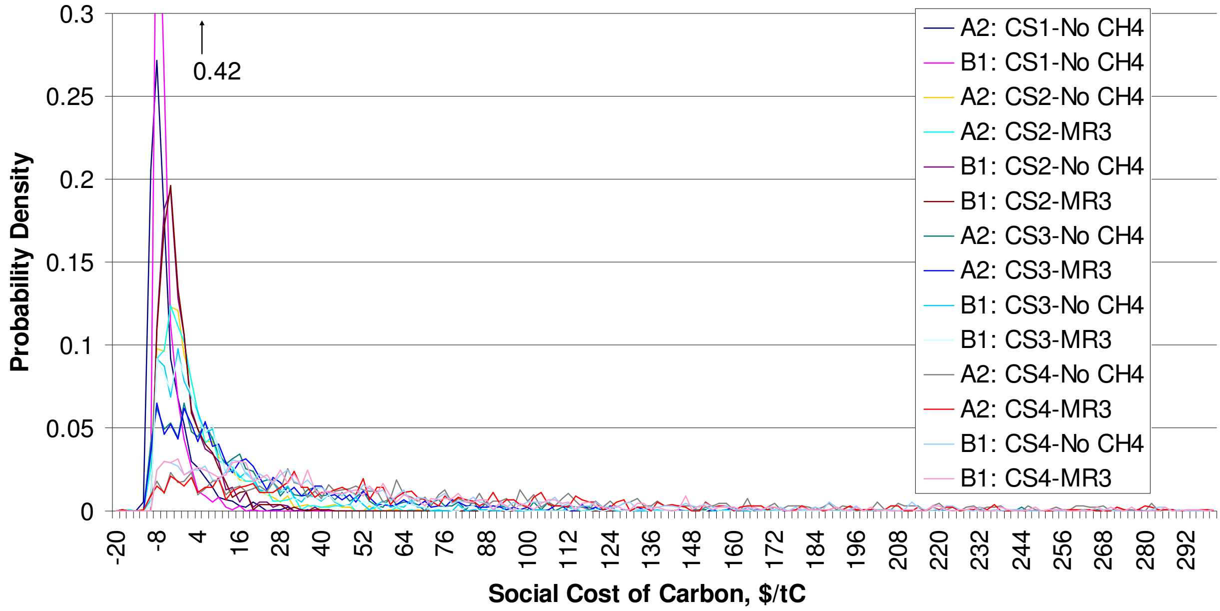
The risk premiums found in different emission scenarios are much smaller than that in climate sensitivities since the range of mean SCC from the 5 scenarios is much narrower. The resulting wealth levels of the 5 scenarios, and thus the utility, lie very close together and as a result, lower risk premiums are obtained. This result also makes intuitive sense because if the range of SCC from different emission scenarios is narrower, it implies that there is less uncertainty in SCC due to emissions driven by socio-economic factors and therefore lower risk premium is required.

With a CRRA of 0.8, ambiguity premium is found to range from 0.0% to 0.4%. As discussed before, when utility levels are very close together, a smaller curvature in the ambiguity function is then used to measure ambiguity premium. With a CRRA at 1.8 or higher, where utility levels are made even closer together, ambiguity premium obtained is negligible.

4.3.2 Results in FUND under Different Climate Sensitivity and Methane Release Scenarios

Having analysed climate sensitivities, methane release and emission scenarios individually, the following section will integrate all the scenarios to come up with an overall SCC using the FUND model. As in section 4.2, 4 climate sensitivity scenarios, no or high methane release (MR3) scenario and emission scenarios A2 and B1 are used. The subjective probabilities used are the same as in section 4.2 except that all probabilities in the 7 scenarios are evenly divided among A2 and B1 scenarios and 14 scenarios resulted. The pdfs of the scenarios are given below:

Fig. 4.14 The SCC under Climate Sensitivity and Methane Release Scenarios in FUND A2 and B1



Taking into account of all emission scenarios, different climate sensitivities and methane scenarios, the expected SCC is found to be $12/tC. The risk premium ranges from 1% to 22% and the ambiguity premium ranges from 0% to 34%. The calculation is summarised in Table 4.17 below:

Table 4.17 Risk and Ambiguity Premiums under Different CS, MR and Emission Scenarios in FUND

CRRA	CAAA	E(SCC)	Risk Adj SCC	RP in % of E(SCC)	Ambig. Adj. SCC (Klibanoff et. al.)	AP in % of E(SCC) (Klibanoff et al.)	Ambig. Adj. SCC (Hazen)	AP in % of E(SCC) (Hazen)
0.8	1	11.78	11.94	1.4%	12.17	1.9%	12.40	3.9%
0.8	3.0	11.78	11.94	1.4%	12.66	6.1%	13.42	13%
0.8	5.0	11.78	11.94	1.4%	13.19	11%	14.59	22%
0.8	7.0	11.78	11.94	1.4%	13.77	16%	15.92	34%
1.8	7.0	11.78	12.15	3.1%	12.15	0.0%	12.15	0.0%
4	7.0	11.78	12.65	7.4%	12.65	0.0%	12.65	0.0%
10	7.0	11.78	14.42	22%	14.42	0.0%	14.42	0.0%

4.3.3 Results in FUND with a Different Initial Wealth Level

So far, wealth/tC estimated by the current GDP and emissions level has been used to calculate the risk premium and ambiguity premium. In this section, it is assumed that utility level drops to minimum when SCC reaches the level of $1000/tC since in case such event happens, global warming impacts would be drastic. To execute this assumption, wealth level is set to 0 when SCC reaches $1000/tC. Using the scenarios in section 4.3.2, the risk and ambiguity premiums are computed as follows:

Table 4.18 Risk and Ambiguity Premiums Assuming Utility Drops to Minimum at a SCC $1000

CRRA	CAAA	E(SCC)	Risk Adj SCC	RP in % of E(SCC)	Ambig. Adj. SCC (Klibanoff et. al.)	AP in % of E(SCC) (Klibanoff et al.)	Ambig. Adj. SCC (Hazen)	AP in % of E(SCC) (Hazen)
0.8	1	11.8	13.0	10%	14.2	10%	15.5	22%
0.8	3.0	11.8	13.0	10%	17.6	39%	23.7	91%
0.8	5.0	11.8	13.0	10%	22.6	82%	37.9	212%
0.8	7.0	11.8	13.0	10%	29.9	144%	58.6	387%
1.8	7.0	11.8	16.0	36%	16.0	0%	16.0	0.3%

With CRRA of 0.8, risk premium has drastically increase from 1% to 10% and maximum ambiguity premium increases from 34% to 387%. It is also observed that in Hazen's model, ambiguity premium increases at a faster rate than in Klibanoff et. al.'s model as CAAA increases. It becomes significantly more than double of that in Klibanoff et. al's model when CAAA is 7.0. Risk premium also increases significantly to 36% with CRRA of 1.8 while ambiguity premium remains minimal. These results show that with more curvature at wealth levels of $1000/tC or lower, larger risk premium is obtained. At higher CRRA, the estimation of ambiguity premium suffers the same problem as described in section 4.1.1.

4.4 Application of Empirical Risk and Ambiguity Premiums

As indicated in section 2.3, empirical risk premium from the literature is found to range from 7-70% of expected value and ambiguity premium from 5-57%. If the mid-points are taken from both ranges, a risk premium of 38% and an ambiguity premium of 31% can be used to apply to the SCC estimates under the 14 climate sensitivity, methane dissociation and emission scenarios. The risk adjusted SCC is found to be $16/tC and the risk and ambiguity adjusted SCC is $20/tC. These results are within the range of $13-59/tC calculated from the iso-elastic and ambiguity functions in section 4.3.3.

4.5 Meta-Analysis

In the existing literature, SCC estimates varied widely. Many different judgements and therefore diverse assumptions have been put into different models. Taking into account the SCC estimates since 1999, SCC without equity weighting[5] ranges from -$6.6/tC to $142. Tol (2004) has conducted a meta-analysis of the all the distributions of SCC by different researchers. Distributions from 7 studies since 1999 are used for the risk and ambiguity premium analysis (Tol, 1999; Roughgarden and Schneider, 1999; Nordhaus and Boyer, 2000; Tol and Downing, 2000; Tol, 2002; Newell and Pizer, 2003; Mendelsohn, 2003). The subjective probabilities are derived from weights used by Tol (2004) based on whether the study has been peer reviewed, age of the study, etc. The results are summarised below:

Table 4.19 Risk and Ambiguity Premiums for Meta-Analysis

CRRA	CAAA	E(SCC)	Risk Adj SCC	Risk Premium	Ambig. Adj SCC	Ambig. Premium
0.8	1	22.1	22.2	0.4%	22.9	3.0%
	3	22.1	22.2	0.4%	24.3	9.6%
	5	22.1	22.2	0.4%	26.0	17%
	7	22.1	22.2	0.4%	27.8	25%
1.8	7	22.1	22.3	1.0%	22.3	0.0%
4	7	22.1	22.6	2.1%	22.6	0.0%
10	7	22.1	23.3	5.5%	23.3	0.0%

Applying risk and ambiguity premium to the wide range of studies, SCC ranges from $22/tC to $28. From a methodological point of view, several caveats must be noted. Firstly, in many distributions, only best guess values are given and they are assumed to be the mean. Secondly, the SCC is highly biased towards authors who give a large number of distributions from a single study and therefore more of their results are counted towards the expected SCC. Thirdly, all the distributions are estimated from vastly different assumptions such as scenarios used, discount rate, impacts considered, etc. It is, strictly speaking, methodologically incorrect to aggregate over different *ethical* assumptions as though they were *uncertain* parameters, rather than parameters that society is able to choose between. While the application of risk and ambiguity premium does not suggest such methods can resolve the differences between estimates, it serves as a useful way to integrate the variety of SCC estimates into a single range.

[5] Equity weighting is a method by which estimates of the SCC are weighted to reflect the underlying utilities of individuals at different income levels.

Chapter 5 – Limitations and Future Development

This thesis aims to apply existing decision theories under uncertainty to the global warming problem. While the existing literature offers a vast number of different decision models to capture risk and ambiguity attitudes in people's behaviours, application of these theories to environmental problems is rare. Only through more frequent application of the developed theories can economists improve their models. In the application of a concave utility function to estimate the risk premium in SCC, it is found that the use of wealth or change of wealth as an argument of the utility function has significant impact on the estimation of risk premium. A utility function representing risk aversion has a curvature that defines the degree of risk aversion. If change of wealth is used as an argument of the utility function, the risk premium calculated will be much larger than if wealth is used. This is because the curvature of the utility function decreases as wealth or change of wealth increases. The expected SCC estimated in different scenarios in this thesis ranged from -$4.4 to $152/tC is fairly small compared to wealth/tC of $5259. There is limited curvature at high wealth levels that are not greatly reduced by the SCC and as a result, the risk premiums obtained are relatively small. On the contrary, if change of wealth is used instead, the risk premium will be larger because the changes of wealth, SCC/tC, are relatively small numbers located in the higher curvature regions of the utility curve. However, as explained in section 2.1, there is not sufficient reason to use change of wealth instead of wealth as an argument for a utility function.

The iso-elastic utility function and ambiguity function used in this thesis attempt to separate risk and ambiguity to analyse their different effects on the SCC. However, the coefficient of relative risk aversion, CRRA, is estimated empirically in situations where ambiguity is also present. Therefore, the CRRA estimated by insurance, consumer expenditure and equity premium models might not be accurate as it might already have ambiguity premium embedded in it.

The risk and ambiguity premiums estimated from the decision theories for risk and ambiguity are a lot smaller than empirically found. Besides the magnitude and proximity of utilities as explained in Chapter 4, there are other possible reasons. The risk premium estimated empirically from surveys of insurers ranging from 34% to 139% of expected value is much greater than the risk premium computed in this thesis ranging from 0.45% to 36%. Part of the reason might be that the premium charged by insurers includes the operating cost of insurance companies. Therefore, a higher premium and an inflated risk premium result. Many empirical estimate of ambiguity premium comes from survey of insurers who are found to be more risk and ambiguity averse than consumers and therefore they naturally has higher risk and ambiguity premiums (Hogarth and Kunreuther, 1989). Moreover, the risk and ambiguity analyses are done on an aggregate level, i.e. risk and ambiguity is applied on a world level, which might be less than if risk and ambiguity premiums are added together from all individuals' utility and ambiguity functions. At an aggregate level, changes of wealth due to SCC are all aggregated. The high risk premium of some individuals who might be severely affected by global warming and have high degree of risk aversion might not have been sufficiently reflected since all the wealth levels and risk aversion have been averaged out in a world aggregated level. The less severe aggregated changes of wealth then render lower risk premium. The same logic could also be applied to the low ambiguity premium computed.

In the application of the ambiguity function Φ derived in Klibanoff et. al. (2003), the coefficient of absolute ambiguity aversion (CAAA) is used without exploring in detail the possibility of applying the coefficient of relative ambiguity aversion (CRAA). Fundamentally, the difference between CAAA and CRAA is that CAAA concerns with absolute ambiguity while CRAA deals with ambiguity in proportion to the utility in a given situation. Currently, there is a lack of literature addressing the application of CAAA and CRAA. In an attempt to apply CRAA instead of CAAA in the computation of ambiguity premium in this thesis, a crucial problem discovered is that when the coefficient of relative risk aversion (CRRA) is greater than 1, the negative utilities obtained cannot be applied to ambiguity functions which assume CRAA. Ambiguity aversion theories need to be further developed to clarify the use of CRAA and CAAA and to improve and solve the difficulty in the application of negative utilities in ambiguity functions.

Applying Klibanoff et. al.'s and Hazen's model to estimate ambiguity premiums, it is found that ambiguity premiums become very small when CRRA is greater than 1.5. The reasons for the small ambiguity premium from a mathematical point of view have been discussed in chapter 4. Existing literature suggests that attitudes toward ambiguity are roughly uncorrelated with attitudes toward risk (Camerer, 1999). While the CRRA and CAAA reflect different risk and ambiguity attitudes, there is no empirical evidence or reasons for ambiguity premiums to be minimal when CRRA is large. This might suggest that further research on ambiguity premium and their interactions with the utility function and Φ function is needed and ambiguity models might need to be further developed to address this issue.

Chapter 6 – Conclusion

The consideration of risk and ambiguity aversion in the estimation of the social cost of carbon is important. The magnitude and probabilities of global warming impacts involve both risk and ambiguity. Society as a whole needs to make prudent decisions to ensure long-term survival and balance intergeneration welfare. Facing tremendous scientific and impact uncertainties, this thesis is not advocating the extreme view that we should avoid all possible risks at any cost, but to give a realistic account of risk and ambiguity aversion in the estimation of the SCC. While there is no global consensus of whether there is a dominant risk averse or ambiguity averse attitude in the issue of global warming, this thesis has started from the (very plausible) assumption that there are sufficient numbers of people who are risk averse or ambiguity averse with respect to global warming such that a risk premium and an ambiguity premium should be applied to the SCC to protect their right for a stable climate.

The potential for learning should not invalidate the risk and ambiguity aversion analysis undertaken here. Putting risk and ambiguity premium to the SCC, therefore raising the SCC, might result in greater mitigation efforts through different economic instruments, such as carbon taxes, which go against the "Learn then Act" strategy. Adopting greater mitigation efforts now can be justified by reasons of future uncertain risk exposure, option value and irreversibility. Carbon dioxide emitted accumulates in the atmosphere due to its long lifetime. Continuous increase in emission now might cause global warming risks to exacerbate. Some researchers have argued that carbon dioxide emission path is reversible in the sense that emissions can be cut in the future, however, previous experiences have shown that energy consumption can be sticky, therefore not easily reversible. Thus, the emission reversibility might have to rely on technological advancement which itself is also uncertain. As current emissions accumulate in the atmosphere, flexibility in future emission policy might be lost as the world may run into a situation where mitigation is a must for survival. The option value for choosing an appropriate carbon dioxide concentration might be lost even when knowledge has improved to enable such decision to be made. Moreover, impacts of global warming and climate change are irreversible. Human deaths, species extinction, land and habitat loss due to sea level rise, etc. are not reversible and their total economic value[6] is also unknown. To a certain extent, some impact costs still cannot be valued accurately. Due to the uncertain nature of both timing and the magnitude of impacts and the time needed to resolve these uncertainties, the application of risk and ambiguity aversion is necessary to reflect the degree of risk and ambiguity that society is willing to take given our current knowledge.

[6] Total economic value includes use value, option value and non-use value.

This thesis studied the impacts of risk and ambiguity aversion under different uncertain scenarios in global warming. It is found that in taking account of uncertainties in climate sensitivity, a risk premium of 0.8-23% need to be added to the SCC. Considering uncertainty in marine methane hydrate destabilisation, a 0.1-6.4% of risk premium needs to be added. The uncertainty in emission scenario also gives a similar range of risk premium of 0.5-6.4%. When climate sensitivity, marine methane hydrate destabilisation and emission scenarios are considered, a risk premium of 1.4-22% need to be added to the SCC. In an attempt to calibrate Klibanoff et. al.'s ambiguity model to the empirical evidence, it is found that an ambiguity premium of 2%-16% of SCC can be obtained by applying a CAAA of 0.8-7. In Hazen's model, a CAAA of 0.8-7 gives an ambiguity premium of 3.3-34%

One may disagree with applying a global risk and ambiguity aversion to the SCC analysis. However, in order to protect individuals' right to a stable climate so that no one is forced to take global warming risk without being compensated, the risk and ambiguity aversion of individuals must be recognised. Global warming impacts vary in different regions. Regions that potentially suffers large damages by global warming might be more risk averse than others. The regional analysis under different climate sensitivity scenarios was aimed to investigate the risk premium effect if there are different degrees of risk and ambiguity aversion across different regions depending on their potential damages. It is assumed that there is a high risk aversion (high CRRA) in regions which are potentially highly impacted and a low risk aversion (moderate to low CRRA) in regions that only have small damages. The results from such analysis imply that the size of the overall global risk premium depends on whether there is a high risk aversion in regions that have low wealth and high potential damages. From the results of FUND and PAGE in which only regions that potentially suffer high damages have high risk aversion, SCC will need to be adjusted by a risk premium of 7-10%.

The risk and ambiguity adjusted social cost of carbon, not only can help governments in their cost-benefit analysis but more importantly understand how major uncertainties affect the SCC to prudently allocate resources for resolving uncertainties, mitigation and adaptation. No one policy can be the ultimate fix to global warming challenges. Balancing the mix of strategies given the current limited knowledge in climate change is therefore an important task for governments.

References

Ahn, D. (2003) Ambiguity without a State Space: primary job market paper. Working Paper. Available on http://www.stanford.edu/~ahnd/research.html (Last accessed on 31 Aug 2004)

Allen, M. R. and Ingram, W. J. (2002) Constraints on future changes in climate and the hydrologic cycle. *Nature,* 419 -232.

Andronova, N. G. and Schlesinger, M. E. (2001) Objective estimation of the probability density function for climate sensitivity. *Journal of Geophysical Research*, 106 (D19): 22605-22611

Arrow, K.J. (1965) *Aspects of the Theory of Risk-Bearing*. Helsinki: Yrjö Hahnsson Foundation.

Arrow, K. J. (1971) *Essays in the Theory of Risk-Bearing*. Chicago: Markham Publishing Co.

Barsky, R. B., Juster, F. T., Kimball M. S., and Shapiro, M. D. (1997) Preference Parameters and Behavioral Heterogeneity: An Experimental Approach in the Health and Retirement Study. *Quarterly Journal of Economics,* 112(2): 537-579.

Becker, S. W. and Brownson, F. O. (1964) What price ambiguity? Or the role of ambiguity in decision making. *Journal of Political Economy*, 72(1): 62-73

Blake, D. (1996) Efficiency, Risk Aversion and Portfolio Insurance: An Analysis of Financial Asset Portfolios Held by Investors in the United Kingdom. *The Economic Journal,* 106: 1175-1192.

Cabantous, L. (2003) Ambiguity and Conflict Aversion in the Field of Insurance: Insurers' Attitude to Imprecise Probabilities. Working Draft. Available on http://w3.toulouse.inra.fr/leerna/english/cahiers2003/0320126.pdf (Last accessed on 30 Aug, 2004)

Camerer, C. and Kunreuther, H. (1989) Experimental Markets for Insurance. *Journal of Risk and Uncertainty*, 2: 265-300

Camerer, C. and Weber, M. (1992) Recent developments in modelling Preferences: Uncertainty and Ambiguity. *Journal of Risk and Uncertainty*, 5: 325-370

Camerer, C. (1999) Ambiguity-Aversion and Non-additive Probability: Experimental Evidence, Models and Applications. In Luini, Luigi, ed. *Uncertain decisions: Bridging theory and experiments*. Boston, Dordrecht and London: Kluwer Academic 53-79

Campbell, J. Y. (1996) Understanding Risk and Return. *Journal of Political Economy* 104(2): 298-345.

Ceronsky, M. (2004) Checking the price tag on catastrophe: An investigation of the sensitivity of FUND's Social Cost of Carbon estimate to the incorporation of non-linear climate responses. Environmental Change Institute, Oxford

Chung, S. H. and Chang, S. F. (2001) Review and prospect of methane hydrate. *Bulletin of the Central Geological Survey*, 14: 35-82

Clarkson, R. and Deyes, K. (2002) Estimating the Social Cost of Carbon Emissions. *GES Working Paper 140*. London: HM Treasury

Cohen, M., Jaffray, J. Y. and Said, T. (1985) Individual Behaviour under Risk and under Uncertainty: An Experimental Study. *Theory and Decision*, 18: 203-228

Curley, S. P. and Yates, J. F. (1989) An empirical evaluation of descriptive models of ambiguity reactions in choice situations. *Journal of Mathematical Psychology*, 33: 397-427

Di Mauro, C and Maffioletti, A. (2001) The Valuation of Insurance under Uncertainty: Does Information about Probability Matter? *The Geneva Papers on Risk and Insurance Theory*, 26: 195-224

Dickens, G., O'Neil, J., Rea, D. and Owen, R. (1995) Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. *Paleoceanography,* 10 (6): 965-971.

Dickens, G., Castillo, M. and Walker, J. (1997) A blast of gas in the latest Paleocene: Simulating first-order effects of massive dissociation of oceanic methane hydrate." *Geology,* 25 (3): 259-262.

Eeckhoudt, L., Schieber, C. and Schneider, T. (2000) Risk aversion and the external cost of a nuclear accident. *Journal of Environmental Management*, 58: 109–117

Einhorn, H. J. and Hogarth, R. M. (1985) Ambiguity and Uncertainty in Probabilistic Inference. *Psychological Review*, 92: 433-459

Einhorn, H. J. and Hogarth, R. M. (1986) Decision Making Under Ambiguity. *Journal of Business*, 59(4): 224-249

Ellsberg, D. (1961) Risk, Ambiguity and the Savage Axiom. *Quarterly Journal of Economics*, 75(4): 643-669

Forest, C. E., Stone, P. H., Sokolov, A. P., Allen, M. R. and Webster, M. D. (2002) Quantifying uncertainties in climate system properties with the use of recent climate observations. *Science,* 295 (5552): 113-117.

Friend, I. and Blume, M. E. (1975) The Demand for Risky Assets. *American Economic Review*, 65: 900-922

Gardenfors, P. and Sahlin, N. E. (1982) Unreliable Probabilities, Risk Taking and Decision Making. *Synthese*, 53: 361-386

Gilboa, I. and Schmeidler, D. (1989) Maxmin expected utility with non-unique prior. *Journal of Mathematical Economics*, 18(2): 141-153

Gollier, C., Moldovanu, B. and Ellingsen, T. (2001) (2001) Precautionary Principle: The economic perspective. *Economic Policy*, 33: 301-325

Gornitz, V. and Fung, I. (1994) Potential Distribution of Methane Hydrates in the Worlds Oceans. *Global Biogeochemical Cycles*, 8 (3): 335-347

Halek, M. and Eisenhauer, J. G. (2001) Demography of Risk Aversion, *Journal of Risk and Insurance,* 68(1): 1-24

Hansen, L. P. and Singleton, K. J. (1982) Generalized Instrumental Variables Estimation of Nonlinear Expectations Models. *Econometrica*, 50: 1269-1286

Harvey, D. and Huang, Z. (1995) Evaluation of the potential impact of methane clathrate destabilization on future global warming. *Journal of Geophysical Research,* 100 (D2): 2905-2926.

Hazen, G. B. and Lee, J. S. (1991) Ambiguity Aversion in the Small and in the Large for Weighted Linear Utility. *Journal of Risk and Uncertainty*, 4: 177-212

Hazen, G. B. (1987) Subjectively Weighted Linear Utility. *Theory and Decision,* 23: 261-282.

Higgins, P., Mastrandrea, M. and Schneider, S. H. (2002) Dynamics of climate and ecosystem coupling: Abrupt changes and multiple equilibria. *Philosophical Transactions of the Royal Society,* 357 (1421): 647-655.

Hogarth, R. M and Kunreuther, H. (1989) Risk, Ambiguity and Insurance. *Journal of Risk and Uncertainty*, 2: 5-35

Hogarth, R. M. and Einhorn, H. J. (1990) Venture Theory: A Model of Decision Weights. *Management Science*, 36: 780-803

Hope, C. (2003) The marginal impacts of CO2, CH4 and SF6 emissions. *Judge Institute of Management*, Cambridge University, Research Paper No.2003/10

Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (1995) *Climate Change 199*5, Cambridge: Cambridge University Press

Intergovernmental Panel on Climate Change. (2001) *Working Group I: The Scientific Basis*, Geneva: United Nations Environmental Program, World Meteorological Organization.

Kacholia, K. and Reck, R. A. (1997) Comparison of global climate change simulations for 2xCO2-induced warming: An intercomparison of 108 temperature change projections. *Climatic Change,* 35 (1): 53-69.

Kahn, B. E. and Sarin, R. K. (1988) Modelling Ambiguity in Decision Making Under Uncertainty. Journal of Consumer Research, 15: 267-272

Kahneman, D. and Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica,* 47, 263-291

Kastner, M. (2001) Gas hydrates in convergent margins: Formation, occurrence, geochemistry, and global significance. In *Natural Gas Hydrates: Occurrence, Distribution, and Detection*, Vol. 124 (Eds, Paull, C. and Dillon, W.) Washington, D.C.: American Geophysical Union.

Kattenberg, A., Giorgi, F., Grassl, H., Mehl, G.A., Mitchell, J.F.B., Stouffer, R.J., Tokioka, T., Weaver, A.J. & Wigley, T.M.L. (1996): Climate Models - Projections of Future Climate. In: Houghton, J.T., Meiro Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. & Maskell, K. (eds.), *Climate Change 1995: The Science of Climate Change -Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Chang*e, 1st edition, Cambridge, Cambridge University Press, pp. 285-357

Katz, M., Pak, D., Dickens, G. and Miller, K. (1999) The source and fate of massive carbon input during the Latest Paleocene Thermal Maximum. *Science,* 286 (5444): 1531-1533.

Klibanoff, P., Marinacci, M. and Mukerji, S. (2003) A Smooth Model of Decision Making under Ambiguity. *Working paper. Kellogg Graduate School of Management*, Northwestern University

Kolstad, C. D. (1996) Learning and Stock Effects in Environmental Regulation: The Case of Greenhouse Gas Emissions. *Journal of Environmental Economics and Management*, 31: 1-18

Kunreuther, H., Meszaros, J., Hogarth, R. M. and Spranca, M. (1995) Ambiguity and Underwriter Decision Processes. *The Journal of Economic Behavior and Organization*, 26 (3): 337-352

Kvenvolden, K. (2002) Methane hydrate in the global organic carbon cycle. *Terra Nova,* 14 (5): 302-306.

Kvenvolden, K. and Lorenson, T. (2001) The global occurrence of natural gas hydrate. In *Natural Gas Hydrates: Occurrence, Distribution, and Detection*, Vol. 124 (Eds, Paull, C. and Dillon, W.) Washington, D.C.: American Geophysical Union.

Link, P. M. and Tol, R. S. J. (2004) *Possible economic impacts of a shutdown of the thermohaline circulation: An application of FUND*, Centre for Marine and Climate Research, Hamburg University.

Machina, M. J. (1987) Choice under Uncertainty: Problems Solved and Unsolved. *The Journal of Economic Perspectives*, 1(1): 121-154

MacCrimmon, K. R. and Larsson, S. (1979) Utility Theory: Axioms versus Paradoxes. In Allais, M and Hagen, O (Eds), *Expected Utility and the Allais Paradox*. Dordrecht, Holland: D. Reidel Publishing Co., 333-409

Mankiw, N. G. (1985) Consumer Durables and the Real Interest Rate. *Review of Economics and Statistics,* 67(3): 353-362

Mankiw, N. G. and Zeldes, S. P. (1991) The Consumption of Stockholders and Nonstockholders, *Journal of Financial Economics,* 29: 97-112

Mendelsohn, R.O. (2003), *The Social Costs of Carbon: An Unfolding Value*, presented at the DEFRA International Seminar on the Social Costs of Carbon, London. Available on http://www.defra.gov.uk/environment/climatechange/carbonseminar/index.htm (Last Accessed on 30 Aug, 2004)

Morgan, M. G. and Keith, D. W. (1995) Subjective judgments by climate experts. *Environmental Science and Technology,* 29 (10): 468A-476A.

Nakicenovic, N. and Swart, R. (Eds.) (2000) *Emissions Scenarios*. Special Report of the Intergovernmental Panel on Climate Change. UK: Cambridge University Press

Newell, R. G. and Pizer, W. A. (2004) Uncertain discount rates in climate policy analysis. *Energy Policy*, 32: 519-529.

Nordhaus, W.D. (1994) *Managing the Global Commons: The Economics of Change*. Cambridge, MA: MIT Press

Nordhaus, W. D. and Boyer, J. (2000) *Warming the world: economic models of global warming*. London: MIT Press

Palsson, A. (1996) Does the Degree of Relative Risk Aversion Vary with Household Characteristics? *Journal of Economic Psychology,* 17: 771-787

Parker, J. A. and Julliard, C. (2003) Consumption Risk and Cross-Sectional Returns. *NBER Working Papers 9538*. National Bureau of Economic Research, Inc.

Pearce, D. (2003) The Social Cost of Carbon and its Policy Implications. *Oxford Review of Economic Policy*, 19(3): 362-383

Plambeck, E. L. and Hope, C. (1996) PAGE95: An updated valuation of the impacts of global warming. *Energy Policy*, 24(9): 783-793

Pratt, J.W. (1964) Risk Aversion in the Small and in the Large. *Econometrica*, Vol. 32, p.122-36.

Rahmstorf, S. & Ganopolski, A. (1999): Long-term global warming scenarios computed with an efficient coupled climate model. *Climatic Chang*e, 43: 353-367.

Roughgarden, T. and Schneider, S. H. (1999) Climate change policy: quantifying uncertainties for damages and optimal carbon taxes. *Energy Policy*, 27: 415-429.

Savage, L. J. (1954) *The Foundations of Statistics*. New York: Dover

Slovic, P. and Tversky, A. (1974) Who Accepts Savage's Axiom? *Behavioral Science*, 19: 368-373

Stott, P. A. and Kettleborough, J. A. (2002) Origins and estimates of uncertainty in predictions of twenty-first century temperature rise. *Nature*, 416: 723-726

Szpiro, G. G. (1986) Measuring Risk Aversion: An Alternative Approach. *Review of Economics and Statistics*, 68(1): 156-159

Tol, R.S.J. (1995) The Damage Costs of Climate Change Toward More Comprehensive Calculations. *Environmental and Resource Economics*, 5: 353-374

Tol, R.S.J. (1999) The Marginal damage costs of Greenhouse Gas Emissions. *The Energy Journal,* 20 (1): 61-81.

Tol, R.S.J. (2004) The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties. Research Unit Sustainable and Global Change FNU-19, Centre for Marine and Climate Research, Hamburg University.

Tol, R.S.J. and T.E. Downing (2000) *The Marginal Damage Costs of Climate Changing Gases*. Institute for Environmental Studies D00/08, Vrije Universiteit, Amsterdam.

Tvesky, A. and Kahneman, D. (1992) Advances in Prospect Theory: Cumulative Representation of Uncertainty. *Journal of Risk and Uncertainty*, 5: 297-323

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

Varian, H. R. (1999) *Intermediate Microeconomics: A Modern Approach*. London : Norton

von Neumann, J. and Morgenstern, O. (1944) *Theory of Games and Economic Behavior*. Princeton NJ: Princeton Univ. Press

Weber, W. E. (1970) The Effect of Interest Rates on Aggregate Consumption. *American Economic Review*, 60: 591-600

Weber, W. E. (1975) Interest Rates, Inflation and Consumer Expenditures. *American Economic Review*, 65: 843-858

World Bank (2004) *World Development Indicators*. Washington, D.C.: The World Bank

Wigley, TML, Raper, SCB (2001) Interpretation of high projections for global-mean warming. *Science*, 293 (5529): 451-454

Yates, J. F. and Zukowski, L. G. (1976) Characterization of ambiguity in decision making. *Behavioral Science*, 21: 19-25