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The Economics of Global Climate Change: A Historical Literature Review

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Abstract

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Keywords

Economics, climate change, emissions trends, mitigation, adaptation.

JEL Classification

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The Economics of Global Climate Change: A Historical Literature Review

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Introduction

World economic activity is a cause of climate change and climate change impacts economic activity. Governments, firms, and individuals are grappling with establishing policies to reduce emissions of the greenhouse gases that are causing the climate to change - referred to as the mitigation of climate change - and facing up to the need to adapt to a climate that will change quite drastically whatever mitigation actions are taken.

Because the major greenhouses gases are long-lived and mix globally in the atmosphere, it does not matter in terms of climate change neither from where they are emitted nor in terms of mitigation where emissions are reduced. Therefore, climate change is a classic open access resource problem. Emitters impose damage globally and the benefits provided by abaters are shared by all. Climate change depends more on the world economy than on economic activity in any one country and action on climate change requires global cooperation or at least coordination. Adaptation to climate change can occur locally, but involves a fundamental dilemma due to the uncertainty of the timing, intentity and nature of future climate change. Non-optimal adaptation, aggregated across the globe, will have negative implications for growth and well-being for all countries.

We divide the paper into three main sections: trends, mitigation, and adaptation.[1] Impacts of climate change are covered to some degree in the latter two sections. In common with the 1992 United Nations Framework Convention on Climate Change (UNFCCC), we limit our discussion of the causes and mitigation of, and adaptation to climate change to anthropogenic 'climate change' alone. We, therefore, exclude potential causes such as variations in radiation from the sun and the earth's orbit, which are incorporated in the broader concept of climate change.

Our emphasis is on change at the global level as well as differences between regions and countries rather than developments within countries. Our focus is also on impacts on the global economy rather than on the natural environment except where the latter has clear economic implications. The economics of climate change is a fairly new field that has grown very rapidly in the last decade. The literature on climate change trends is the oldest of the three areas we cover and we review some of the earliest studies that laid the groundwork for

[1] Primary authors of the three sections are David Stern (trends, drivers and forecasts of emissions), Frank Jotzo (mitigation of climate change) and Leo Dobes (adaptation to climate change).

today's science and economics. The economic literature on the mitigation of climate change has its origins in the broader literature on pollution externalities and policy responses. Adaptation to climate change is a more recently emergent topic and so there is no classic literature to review.

Trends, Drivers, and Forecasts of Greenhouse Gas and Aerosol Emissions

Understanding historical trends and forecasting future emissions is not only of scientific interest but is also needed in order to provide a baseline or "business as usual" (BAU) scenario against which policy scenarios can be benchmarked. We focus in this paper on carbon dioxide emissions from fossil fuel combustion as this is the most important source of greenhouse gases and the literature itself has primarily focused on these. However, we also review papers on deforestation and land use change, methane emissions, and sulphate aerosols. Other dimensions of climate change that we do not cover include direct economic impacts on the Earth's albedo from land use change and emissions of minor greenhouse gases such as nitrous oxide and CFCs and aerosols such as and black and organic carbon.

Effect of Emissions Growth on the Climate

The science of the so-called greenhouse effect has its origins in the 19th century in the work of Fourier (1827) and Tyndall (1861) (Held and Soden, 2000). Tyndall discovered that carbon dioxide and water vapour were the main greenhouse gases. Arrhenius (1896) more fully quantified the greenhouse effect and was the first to raise the issue of the effect of anthropogenic carbon emissions on the global climate. However, Arrhenius thought that the effects of climate change would be beneficial to society (Kunnas, 2011). Callendar (1938) compared the expected warming effect from accumulated anthropogenic carbon dioxide emissions since the beginning of the century of 0.03°C per decade to the actual warming rate of 0.05C per decade. This was the first analysis of past human-induced warming. However, in predicting future CO_2 concentrations he ignored economic growth and so predicted a concentration of 396ppm in 2100, a level that we have already reached and he predicted a warming of only 0.5ºC as he ignored the water vapour feedback that roughly doubles the effects of increased carbon dioxide (Held and Soden, 2000). Several papers published by Plass in 1956 raised the alarm on climate change in a significant way for the first time. In the most cited of these, Plass (1956a) estimated that carbon dioxide concentrations would rise 30% over the 20th Century and temperatures would increase by 1.1ºC and that warming of the climate would continue for centuries if fossil fuels were extensively exploited. Plass (1956b) presented a less technical account with a clearer warning on future warming. In it, he estimated that burning all then known fossil fuel reserves would raise global temperature by 7ªC once a long-run equilibrium of calcium carbonate solution in the oceans was reached. Plass overestimated the direct effect of carbon dioxide, ignored the water vapour feedback and the length of time for the oceans to reach temperature equilibrium, and of course underestimated fossil fuel resources significantly. Still his estimate of the sensitivity of the climate to doubling carbon dioxide at 3.8ºC was not much higher than today's consensus estimate of 3ºC (Knutti and Hegerl, 2008).

Regular measurement of atmospheric CO_2 concentrations started two years later on Mauna Loa, Hawaii following the International Geophysical Year of 1957 (Keeling, 1960). Within a few years it was obvious that concentrations were rising consistently year-by-year. Keeling *et al.* (1976) showed that between 1959 and 1971 the atmospheric concentration of CO_2 increased by 3.4%. The trend was quite smooth once a pronounced seasonal cycle was removed. Attention turned to the first long-run time series reconstruction of anthropogenic CO_2 emissions from 1860 to 1969 (Keeling, 1973). Keeling's results have stood the test of time and are very close to the most recent estimates (CDIAC website). Global emissions from fossil fuel use rose from 93 million tonnes of carbon content in 1860 to 3,726 million tonnes of carbon in 1969.[2] Cement production added another 74 million tonnes in 1969.

Scenarios and Forecasts of CO_2 Emissions

The articles discussed above show that the anthropogenic climate change problem has been discussed for much longer than may be popularly assumed (Braganza, 2011; Peterson *et al.*, 2008). Economists first addressed the issue of climate change as part of the wave of interest in energy and environmental economics that followed the oil price shock in 1973-4. The first journal article in economics on the issue appears to be d'Arge *et al.* (1982), which references an earlier report (d'Arge *et al.*, 1975) and conference paper by the authors.

Several scenarios and projections for future emissions of carbon dioxide were published the following year (Nordhaus and Yohe, 1983; Ausubel and Nordhaus, 1983; Edmonds and Reilly, 1983a, 1983b). Edmonds and Reilly's model was the basis of the energy module of the later IS92 scenarios commissioned by the IPCC. Many of the most important studies of future emissions have been published as reports of the Intergovernmental Panel on Climate Change (IPCC) and other agencies. The IPCC has commissioned emissions scenarios roughly every decade – the IS92 scenarios (Leggett *et al.*, 1992), the SRES scenarios (Nakicenovic *et*

[2] To convert to mass of CO_2 multiply by 44/12.

al., 2000), and the Representative Concentration Pathways (RCP) scenarios (van Vuuren *et al.*, 2011).

The first IPCC scenarios were produced in 1989. Due to the ending of communism in the USSR and Eastern Europe, the signing of an international agreement on the control of CFCs and new information in various input variables, the IPCC requested a revision only two years later (Leggett *et al.*, 1992). These new scenarios were inputs to the IPCC's 1992 *Supplementary Report* and the 1995 *Second Assessment Report*. These were the first scenarios to include the full suite of greenhouse gases as well as sulphur emissions (Nakicenovic, 2000). In addition to the energy module described above there were deforestation, agriculture, and halocarbon emission modules. These scenarios result in a very broad range of emissions trajectories. IS92e saw emissions rising to the 20 Gt range around 2050 and the 35 Gt by 2100. IS92c predicted that emissions would decline after 2020. The preferred scenario, IS92a, was midway between these extremes with emissions around 20 Gt in 2100. Unfortunately, the authors did not publish a journal article describing their work.

The SRES scenarios prepared for the *Third Assessment Report* (Nakicenovic *et al.*, 2000) are perhaps the best known of the IPCC scenarios. Nakicenovic (2000) discusses the development of these scenarios. Four storylines were developed which vary by population and economic growth, degree of international cooperation and trade, the rate of technological development, and the types of future policies. Five integrated assessment modelling groups cooperated to develop a total of forty scenarios based on the storylines. For each storyline, the results from one of the modelling groups were considered the representative or "marker" scenario of the storyline. The ensemble of results portray greater radiative forcing than the IS92 scenarios mainly because of reduced forecasts of sulphur emissions. Since these scenarios were developed the world economy has been on a very high emissions trajectory (Raupach *et al.*, 2007; Garnaut *et al.*, 2008) following if not exceeding the highest SRES scenario variant A1F1.

van Vuuren *et al.*, (2011) introduce the latest IPCC scenarios known as the Representative Concentration Pathways (RCP) prepared for the *Fifth Assessment Report*. This process is the reverse of previous scenario-building exercises as it starts with concentration pathways based on given radiative forcing targets and then works back to socio-economic scenarios that could lead to those outcomes. This was intended to result in better coordination across scientific disciplines (Moss *et al.*, 2010). These pathways were supposed to be representative of the range of scenarios in the literature and are named for the level of radiative forcing in Watts per square metre in 2100. The RCP 8.5 and 6.0 scenarios might be seen as business as usual under more or less optimistic assumptions about technological change while the RCP 4.5 and 2.6 scenarios assume the introduction of policies to control emissions. The RCP 2.6 scenario results in negative emissions in the second half of the 21st century, which is only possible with biomass combustion combined with carbon capture and storage or air capture of carbon dioxide.

Explaining Historical Emissions

The most popular approaches to explaining historical emissions are the environmental Kuznets curve and the decomposition approach using the Kaya identity. These approaches can also be used to produce simple projections of future emissions given information on the relevant drivers.

The environmental Kuznets curve (EKC) hypothesis proposes that concentrations or per capita emissions of various pollutants rise and then fall as per capita income increases. Plassmann and Khanna (2006) and Brock and Taylor (2010) provide static and dynamic theoretical models of the EKC respectively, while Carson (2010) provides a recent survey. For carbon dioxide, the relevant variable is emissions per capita. Following the original paper on the topic by Grossman and Krueger (1991), the World Bank published an issue of the *World Development Report* timed for the Rio de Janeiro Earth Summit in 1992 that featured an EKC for carbon dioxide among various other environmental indicators. The econometric estimates showed that per capita carbon emissions rise monotonically with per capita income within the observed range (Shafik, 1994). This result was confirmed by Holtz-Eakin and Selden (1995), which is the classic paper on the carbon EKC. They also found that the propensity to emit declines with income. Recent papers by Wagner (2008), Vollebergh *et al.* (2009), and Stern (2010) that each apply new econometric methods to the problem do not substantially change these conclusions despite some intervening papers (e.g. Schmalensee *et al.* 1998) that claimed that there was an inverted U shaped curve for CO_2 with an in sample peak. Holtz-Eakin and Selden (1995) is also a paper that has stood the test of time in terms of projected emissions.

A related literature looks at whether per capita emissions are converging over time across countries. If there is convergence in GDP per capita, then if the income emissions relation is monotonic there should also be convergence in emissions, at least conditionally. Strazicich and List (2003) examined the time paths of carbon dioxide emissions in twenty-one industrial countries from 1960–1997 to test for stochastic and conditional convergence. They estimated both panel unit root tests and cross-section regressions. Overall, they found significant evidence that CO_2 emissions have converged. Subsequent research has tested whether this result holds across both developed and developing countries with mixed results (e.g. Aldy, 2006; Westerlund and Basher, 2008; Brock and Taylor, 2010).

The Kaya identity is an extension of the IPAT identity (Ehrlich and Holdren, 1971) that decomposes total energy-related emissions into the product of population, income per capita, energy intensity, and the carbon intensity of energy carriers (Kaya and Yokobori, 1997). It is important to understand that this framework is an accounting identity and not a causal model. For example, growth in income per capita might drive or be associated with reduced energy intensity so that the factors are not independent.

Raupach *et al.* (2007) is a highly cited example of this literature. They show that global emissions growth since 2000 was driven by a cessation or reversal of earlier declining trends in the energy intensity of gross domestic product (GDP) (energy/GDP) and the carbon intensity of energy (emissions/energy), coupled with continuing increases in population and per-capita GDP. Nearly constant or slightly increasing trends in the carbon intensity of energy were observed in both developed and developing regions and no region was significantly decarbonizing its energy supply. The growth rate of emissions was strongest in rapidly developing economies, particularly China. This research group also published another highly cited paper in 2007 linking emissions growth and its drivers to the atmospheric concentration of carbon dioxide (Canadell *et al.*, 2007).

Many papers examine the role of particular Kaya factors in explaining historical emissions and driving future projections. The most important factor driving declining energy intensity and to some degree carbon intensity is technological change. Grübler *et al.* (1999) present a framework for energy technology analysis and discuss methods that can be used to analyze the impact of technological changes on global warming. In the historical record, they identify characteristic “learning rates" for the reduction in cost of energy technologies that allow simple quantification of the improvement in cost and performance due to cumulative experience and investments. They also identify patterns, processes, and timescales that typify the diffusion of new technologies in competitive markets. Technologies that are long-lived and are components of interlocking networks typically require the longest time to diffuse and co-evolve with other technologies in the network. Such network effects result in high barriers to entry even for superior competitors. The authors show how it is possible to include learning phenomena in micro- and macro-scale models. Doing so can yield projections with lessened environmental impacts that do not necessarily incur a negative penalty on economic activity.

The authors also investigate the final Kaya factor – carbon intensity of energy. They show that, over time, the fuels that power the economy have had progressively more energy per unit of carbon pollution. Such replacement has historically "decarbonised" the global primary energy supply by 0.3% per year.

Besides technological change, another potential driver of declining energy intensity is structural change of the economy towards a service-oriented economy. It is usually thought that such an economy will have lower energy intensity and, therefore, emissions intensity of income. Henriques and Kander (2010) argue that this interpretation is overly optimistic because the shift to a service economy is somewhat of an illusion in terms of real production. The share of an industry in the economy is a function of both the real level of production and the price of output. The share of the manufacturing sector has declined in developed countries because rapid productivity gains have reduced its output price relative to the service sector. When constant prices are used, less of a shift to a service economy is seen. The main driver of the decline in energy intensity in developed countries is, therefore, productivity gains in manufacturing. For emerging economies like Brazil, Mexico, and India, it is the residential sector that drives energy intensity down because of the declining share of this sector in energy use as the formal economy grows, and as a consequence of switching to more efficient fuels in the household.

Another important issue in the decomposition literature is to what degree trade and foreign investment have allowed developed countries to reduce their apparent energy intensity. Since the early days of the environmental Kuznets curve literature, this was seen as a potential explanation of reduced pollution in developed economies (Stern *et al.*, 1996). Most mainstream economists (Levinson, 2010) and economic historians (e.g. Kander and Lindmark, 2006) have argued that the role of trade in reducing energy and emissions intensity is small. Peters and Hertwich (2008), however, find that most developed countries were net importers of embodied carbon dioxide emissions in 2001 – in other words, their imports required more emissions to produce than their exports did. For the United States the difference amounted to 120 Mt C while for the UK the difference was 28 Mt. But this does not imply that if thee countries produced all these products domestically that their net emissions would be this much higher. This is because production in developing countries is much more energy intensive than in developed countries when measured at market exchange rates and some developed countries, in particular China and India are particularly carbon intensive.

A little researched topic is what happens to the Kaya factors in the short-run over the course of the business cycle. In a response to Peters *et al.* (2012), Jotzo *et al.* (2012) hint that the rate of change in energy intensity follows a strong cycle with the rate of decline slowing in the aftermath of recessions and increasing later in the business cycle. Alternatively, emissions could be seen as responding asymmetrically to increases and decreases in income (York, 2012).

Emissions Other than Carbon Dioxide from Fossil Fuels

Deforestation and land-use change is an important source of emissions of CO_2. Levels of emissions are much lower than from energy related sources, more stable over time, but also very uncertain. Houghton (2003) presents estimates of CO_2 emissions from land-use change from 1850 to 2000, globally and by region. In general, the level of annual emissions rises from 1 to 2 Gt C over the 150 years with an acceleration in the trend around 1950 in common with emissions from energy-related sources. Therefore, there is a clear link with economic growth. Tropical deforestation, particularly in Asia and Latin America is the dominant source of emissions. In recent decades there has been net reforestation in developed countries. The data are increasingly uncertain in recent decades with estimates from different researchers varying substantially (Houghton, 2010).

The third most important greenhouse gas in the atmosphere and the second most important in terms of anthropogenic emissions is methane. In comparison to CO_2, relatively little work has been done on CH_4. Stern and Kaufmann (1996) used available data to reconstruct the first time series of historic emissions from 1860-1993. They found that anthropogenic emissions had increased from 80 million tonnes of carbon in 1860 to 380 million in 1990. The relative importance of the various emissions sources changed over time, though rice farming and livestock husbandry remained the two most important sources.

Offsetting the radiative forcing due to greenhouse gases is a significant negative forcing due to aerosols derived from sulphur oxide (primarily dioxide) emissions. These aerosols do not persist in the atmosphere for usually more than a few days and so the source of emissions is important and effects are localized despite the spread of pollution across borders to neighbouring countries. The main sources of anthropogenic sulphur emissions are coal combustion and metal smelting. Stern (2006) showed that after increasing fairly steadily from 1850 to the early 1990s global emissions began to trend downwards. Emissions in Western Europe and North America as well as Japan had already been trending down since 1970 primarily due to policies to reduce acid rain (Stern, 2005). But this decline was offset by growth in other regions. After 1990, there was a dramatic reduction in emissions from Eastern Europe and the former Soviet Union. The likelihood that emissions will continue to decline in the future will contribute to future warming. Whereas Stern (2006) uses a combination of previously published data and model estimates, Smith *et al.* (2011) provide an inventory of sulphur emissions from 1850 to 2005 using a uniform methodology. The results largely confirm Stern's (2006) findings though the levels are generally a few percent lower.

Mitigation of Climate Change

As shown in the first section of the paper, effective global mitigation would require reversing the historical trend in greenhouse gas emissions. This is likely to result in significant net economic costs. The benefits from reduced future climate change need to be balanced with the costs of mitigation, which is one of the core areas of economic analysis on climate change.

Climate change has been described as "the biggest externality the world has ever seen" (Stern, 2007) because the negative impacts from any person's or firm's greenhouse gas emissions are spread across the globe and over a long period of time. These externalities create coordination problems between countries, because from the perspective of a nation state there are strong incentives for free-riding on other nations' mitigation efforts (Barrett, 1990). There are also important questions about how the global mitigation effort should be distributed between nations ("burden sharing" or "effort sharing"), and how reductions in emissions can be reconciled with economic development especially in the poorer nations.

To minimise the costs of achieving a given mitigation outcome, cost-effective policies are needed. The economic approach is to give incentives to businesses and individuals to change their choices in production and consumption; the regulatory approach is to prescribe or forbid particular processes, products, and activities.

<u>Estimating Costs and Benefits: How Much Mitigation is Optimal?</u>

There is scientific consensus that reducing greenhouse gas emissions is necessary in order to reduce future climate change impacts and to limit the risk of extreme climate change impacts. The global consensus on climate change action is reflected in the 1992 UN Framework Convention on Climate Change, which states that "the ultimate objective of the Convention is to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." (Article 2)

But what degree of climate change is "dangerous"? How much effort should societies make in mitigating climate change, when this means allocating scarce resources away from other goals? In economics, this question is usually approached as a form of cost-benefit analysis. In evaluating a particular climate change mitigation scenario, the costs of reducing emissions are compared to the benefits that arise through reduced damage from climate change impacts. The theoretical condition for optimal mitigation is that the marginal cost of abatement is equal to its marginal benefits. In other words, the cost of reducing the last tonne of emissions should be equal to the marginal damages from those emissions, or the value of the last unit of climate change damages avoided.

The majority of economic analyses of climate change mitigation only look at the economic costs of policies to reduce emissions, not the economic effects of the resulting differences in climate change impacts. A classic reference is Weyant (1993). The academic literature contains thousands of applications using different modelling approaches – most frequently computable general equilibrium models, but also partial equilibrium models, and engineering type models, as well as macroeconomic models – and applications to different scenarios, regions and economic sectors.

Most of the literature on the costs of climate change mitigation also focuses only on the costs of changing production systems to a lower-emissions technologies and practices, not on the potential co-benefits of mitigation action that may occur, in addition to less damages from climate change. An example is the reduction in air pollution that goes hand in hand with reduced or more efficient use of fossil fuels, and which could yield large economic co-benefits (Groosman *et al.*, 2011).

However, there is also a large literature that addresses the more complex empirical question of the optimal amount of mitigation, and the social cost of carbon emissions. The classic global model of optimal mitigation is William Nordhaus' DICE and RICE models (Nordhaus, 1993; Nordhaus and Yang, 1996). This and other models that take the same fundamental approach – for example the PAGE (Hope *et al.*, 1993) and FUND models (Tol, 1997) as well as more recent models such as the WITCH model (Bosello *et al.*, 2010) - are referred to as "integrated assessment models" because they model simultaneously the costs of climate change impacts and the costs of climate change mitigation.

These models yield estimates for the social cost of carbon, and thus the optimal marginal cost of emissions reductions. Meta-analysis of such studies (Tol, 2002) shows a wide range of empirical estimates, due to uncertainty about future economic and environmental parameters, different assumptions about economic relationships, and different methods of evaluation.

Economic models are by necessity limited in the extent to which they can incorporate detailed and reliable cost estimates. This is true in particular for future climate change damages which tend to be much more uncertain than estimates of mitigation costs. For example, most economic integrated assessment models use simple aggregate damage functions that translate temperature increases to changes in economic output. These limitations are generally acknowledged by the creators and users of integrated assessment models, and have been highlighted in the critical literature (Ackerman *et al.*, 2009). Nevertheless, there is a tendency in applied policy assessment exercises to take the results of applications of the models quite literally; ignoring their limitations and relying on assumption-driven model output. Questions remain in particular about the validity of the damage functions used in integrated assessment models (Pindyck, 2013).

A key limitation of assessments of the benefits of climate change mitigation are that typical economic analyses include only the impacts from climate change that are reflected in markets, for example lower agricultural yields, greater costs for infrastructure maintenance, reduced labour supply due to illness, and so forth. Even these may not be completely covered, because some of the likely future market impacts are difficult to quantify. Non-market impacts may include the loss of ecological functions, reduction in quality of life, and loss of cultural values (Garnaut, 2008). Economic analysis sometimes attempts to proxy these costs but the valuations necessarily remain subjective.

A second important limitation is that climate change impacts are uncertain. Future physical impacts from climate change are subject to significant uncertainty, and this is compounded by uncertainty about how physical impacts will translate into economic effects. Some economic modelling exercises attempt to capture this uncertainty by doing a stochastic analysis of impact scenarios, and reporting results as averages over many different model runs. This approach was adopted for example by the Stern (2007) Review, an influential report on the economics of climate change mitigation produced for the UK government (see also Stern, 2008).

But even so, the question remains whether and to what extent special weight should be given to the possibility of extreme or 'catastrophic' climate change outcomes. As Weitzman (2009) shows, if the probability distribution of climate change impacts has a "fat tail" where the probability of extremely high damages does not quickly tend to zero and there is a non-zero risk of the wipe out of all economic activity, then a theoretically optimal strategy may mean devoting all of society's economic resources to climate change mitigation. To most analysts this is self-evidently not the correct prescription. It shows the limits of the economic analysis of the costs and benefits of mitigation.

A third key point is the importance of the discount rate applied to climate change damages and mitigation costs. The extent to which costs and benefits that occur decades or centuries into the future are valued today can be the decisive parameter choice in the empirical analysis of optimal mitigation and the social cost of carbon. A fundamental question is whether climate change analysis should follow a positive approach and use discount rates calibrated to observed interest rates in markets, or a normative approach (Goulder and Williams, 2012).

A commonly used approach is to follow the Ramsey (1928) rule, where the dollar discount rate is the sum of the pure rate of time preference and the rate at which future generations' income should be discounted in order to account for the fact that they are expected to be richer than people today. The latter is a multiple of elasticity of the marginal utility of consumption and the future rate of economic growth. Stern (2008) made the case for a near-zero pure rate of time preference in climate change analysis, and today this is a widely accepted normative assumption (Gollier, 2012). However, there is ongoing debate about the relevant parameter range for the elasticity of the marginal utility of consumption (Quiggin, 2008). The social discount rate also relies on assumptions about the future growth in per capita income. Thus a wide range of different social discount rates can be justified, and they lead to different conclusions about the optimal extent of global mitigation.

Economic welfare analysis of climate change policy is further beset by the necessity to aggregate individual welfare into a collective welfare function, putting a value on lives lost, and many other issues that require normative judgments. As a result, the question of how much the world should mitigate greenhouse gas emissions is not just one of economic analysis, but fundamentally one of ethics and values.

Equity: Who Should Pay for Mitigation?

Inherent in climate change and mitigation are fundamental inequities. The climate change impacts experienced and the associated costs and benefits will differ greatly across individuals, groups in society, and nations. The opportunities to reduce emissions and the costs of achieving a given reduction vary across countries, as does their economic capacity to pay for these costs. The annual contribution to global greenhouse gas emissions also varies greatly among countries on a per capita basis, and accumulated emissions over time vary even more.

A large literature on "burden sharing" or "effort sharing" examines different models for distributing the effort and cost of mitigation action between the world's nations. A central tenet in trying to resolve conflicting views over who should pay for mitigation is the question of equity, and the quest for fairness in allocating the global mitigation burden (Grubb, 1995). It can be argued that because effective mitigation requires the voluntary collaboration of many sovereign nations, the distribution of costs and benefits needs to be acceptable to individual nations. Of course, notions of what is fair differ among both individuals and nations, and will often be influenced by self-interest (Lange *et al.*, 2010).

Developing countries occupy a special place in discussions of equity and effectiveness of global mitigation. The rising share of developing and industrialised countries in global emissions means that they will need to be fully engaged in mitigation for any effective global results. On the other hand, poorer countries have strong arguments on equity grounds that they should be free to catch up in their economic development, and/or that richer countries should pay for the cost of some or all of the mitigation action undertaken in poorer countries. The historical responsibility for greenhouse emissions already accumulated in the atmosphere lies predominantly with developed countries, a fact which has been used to underpin the argument that developed countries should shoulder the bulk of the global mitigation burden or the costs of a more distributed mitigation approach.

As shown in Part 1, it is not possible to reduce global emissions if developing countries follow a similar pattern of emissions intensive growth as the industrialized nations have. Therefore, a pressing question is how development objectives can be best met in tandem with mitigation. The climate change issue and how it relates to development is part of the broader question of sustainable development (Beg *et al.*, 2002), more recently termed 'green growth'.

Policy Frameworks: How Can We Achieve Mitigation Cost-Effectively?

Economic modelling of mitigation usually assumes that emissions reductions are made in the most cost-effective manner, usually represented by a uniform price signal on emissions, through an emissions tax or an emissions trading scheme. The largest such actual price-based scheme is the European emissions trading scheme (Ellerman *et al.*, 2007).

In reality, many other types of economic and regulatory policies are being used for mitigation, which differ in their stringency and marginal costs, and have overlaps and interactions. Overlapping policies will usually increase the economic costs relative to the first-best outcome (Sorrell and Sijm, 2003). On the other hand, existing market failures will require specific interventions that go beyond uniform pricing of emissions. A prominent example is innovation of lower carbon technologies, where knowledge externalities can result in suboptimal private investment even in the presence of emissions pricing (Jaffe *et al.*, 2005). Social rates of return on R&D are usually higher than private rates of return (Griliches, 1992). Different policy instruments may also serve policy objectives that are distinct from but connected with mitigation, for example support for renewable energy technologies with the objective of giving new industries a competitive advantage or improving domestic energy security (Boyd, 2012; Kennedy, 2013).

A further constraint on the efficacy and cost effectiveness of economic policies for mitigation is the credibility of the interventions. Many mitigation options rest in investments in physical assets with long lifespans. Thus investment decisions will be influenced more by expectations about future policy settings than present policy settings (Ulph and Ulph, 2013). To be effective, mitigation policies need to be credible and their stability assured in the face of political change. Designing such policy frameworks includes creating constituencies for the retention of policies over time. An example of economic thinking that aims for such policy sustainability is the McKibbin/Wilcoxen (2002) proposal which would allocate long term emissions permits to individuals, in the hope that this would create a lobby for the retention and possibly strengthening of carbon emissions constraints.

Policy models that could perform well in theory often are not feasible in practice because of institutional and political constraints. A large body of applied literature investigates alternative international mitigation policy frameworks (e.g. Aldy and Stavins, 2007).

In the end, both qualitative and policy oriented research as well as more stylized formal analysis (Wood, 2011) put the spotlight once more on the difficulty of achieving cooperation between nations. Coupled with a tendency to put a relatively low weight on uncertain future climate change impacts relative to pressing immediate economic concerns, this can yield a negative assessment of the prospects for strong global climate change mitigation.

The less climate change mitigation action is undertaken, the greater the need for societies to adapt to impacts from climate change, and the more important the role for economic approaches to adaptation policy. This is the subject of the third section of the paper.

Adaptation to Climate Change

Defining and Framing Adaptation

Adaptation to the impacts of climate change was generally regarded in the 1980s as a policy complement to the reduction (mitigation) of greenhouse gas emissions, but was largely ignored by the scientific community until the past decade or so. Tol (2005) drew attention to the political incorrectness of adaptation 'because it presumably implies accepting defeat in the battle against evil emissions', and Pielke *et al.* (2007) agreed that the topic of adaptation was something of a taboo for a long time.

It is true that the Intergovernmental Panel on Climate Change (IPCC) included adaptation in each of its Assessment Reports, but treatment was relatively cursory when compared with mitigation and the projected impacts of climate change. As Kates (1997) noted, the second volume of the 1995 IPCC Second Assessment Report devoted only 32 pages (less than 4%), spread over 18 chapters, to adaptation. He attributed this to the existence of two contending schools of thought: 'preventionists', who considered that adaptation might weaken societies' willingness to reduce greenhouse gas emissions, and 'adaptationists' who argued that little adaptive action was required because climate change would occur slowly enough for nature and humankind to adjust normally. Klein and Maciver (1999) further note that it took the IPCC ten years to organise a workshop on adaptation to climate change, first held in Costa Rica in 1998.

A particular problem in analysing adaptation to climate change is the varied effects and impacts that climate change will have and the ways these impacts will affect different activities and be experienced by individuals (Berkhout, 2005). Scheraga and Grambsch (1998) highlighted the difficulty of generalising. The spatial impacts of climate change are likely to differ: although average global temperatures may have risen to date, some parts of North America have experienced falls, with increases in others. Different demographic groups will similarly experience the effects of climate change differently, and adapt to them in different ways. Even a single effect may simultaneously generate costs and benefits: increased water temperatures may reduce the viable habitat of cool water fish like trout, but increase that of other fish sought for recreational fishing. Implementation of adaptation measures may yield benefits but it also comes at a cost: both must be assessed in considering various trade-offs, including residual impacts. Different climate change effects may occur simultaneously, so their effects on complex systems cannot be considered independently. For example, the establishment of fish hatcheries to replenish stocks reduced by climate change may alter biodiversity in fishing grounds, reduce genetic diversity, or facilitate transmission of diseases and parasites.

The possibility that climate change can have differential effects within society reinforces the need for detailed study of particular systems, rather than precipitate implementation of apparently obvious universal solutions. A pertinent example is a study by Ludwig *et al.* (2009) who modelled the effect of a large decline in rainfall on a number of sites in the Western Australian wheatbelt. Simulations indicated that not only did crop yields *not* fall, but also leaching of fertiliser decreased (thus reducing costs to farmers), and the spread of dryland salinity was reduced significantly. Further, beneficial profit outcomes were obtained through minor variations in planting periods for two wheat varieties. Because of this diversity, sectoral studies, often at a localised or regional level, are common. Agriculture in particular is a field well traversed (e.g. Laube *et al.*, 2012; Liu *et al.*, 2008; Howden *et al.*, 2007; Chen and Zong, 1999; Erda, 1996; Tri *et al.*, 1998), with some attention devoted to the health sector (e.g. Kovats and Akhtar, 2008; McMichael *et al.*, 2006; Kinney *et al.*, 2008; Patz *et al.*, 2005) and coastal protection (e.g. Zhu *et al.*, 2004). Economic analyses of adaptation in the secondary and tertiary sectors are rarer. Possibly reflecting the techno-scientific approach of the IPCC, studies of consumer preferences for adaptation priorities and willingness to pay as an indication of benefits to be achieved, are virtually absent.

Social perceptions of the effects of climate change will inevitably change over time, and will, therefore, affect concepts of requisite or desirable adaptation. For example, the Summer 2003 heat wave in Europe is considered to have caused significantly more deaths among the elderly than normal, and understandably led to considerable public concern. However, one might also envisage a situation where habituation over a longer period could result in heat-related deaths among the elderly being regarded as a 'normal' aspect of European summers (Oppenheimer, 2005). Alternatively, gradual acclimatisation may reduce heat-related mortality. It is, therefore, necessary to recognise that adaptation can change in form and nature over time.

Adaptation does not necessarily mean implementation of 'climate proofing' measures that are intended to totally offset the biophysical effects of climate change. For example, installation of air conditioning in all buildings and vehicles in a city may be feasible, but would be costly.

In practice, residents may be willing to internalise some of the effect of higher temperatures in order to contain costs or taxes.

Implementation of adaptation measures can also result in so-called maladaptation (Mendelsohn, 2000). Barnett and O'Neill (2010) posit five types of maladaptation, including concomitant emissions of greenhouse gas emissions, shifting of costs to the poor, and reductions in incentives to adapt. In their study of flood responses in Norway, Naess *et al.* (2005) report that local government construction of dykes under pressure from vested interests to fix short-term problems resulted in damage to fish spawning grounds as well as removal of vegetation favoured by birds.

Just as cost-benefit analysis requires specification of 'standing' (the perspective from which analysis is to be conducted), adaptation policy requires clarity about risk, scale, values and governance. The specific interest (values) of someone whose seaside house is about to fall into the sea is to press for construction of a seawall or regular sand replenishment along the beach, but government coastal authorities may have broader environmental or social interests that do not encompass saving an individual house (Adger *et al.*, 2009). Urwin and Jordan (2008) express a similar sentiment in writing that analysis of bottom-up perspectives on policy implementation shows 'how divorced much activity at the street level' is from formal top-down approaches.

Strategic, 'planned' adaptation implemented by techno-scientific experts and government agencies on the basis of their expectations of climatic impacts, can be contrasted with 'autonomous' adaptation by individuals acting in their own self-interest by adjusting to changes in local conditions. Klein and Maciver (1999) portray such autonomous adaptation as being reactive by definition, while planned adaptation can be both reactive and pro-active.

There are large uncertainties involved in predicting both the overall extent of future climate change and the frequencies and severity of extreme events, as well as the socioeconomic conditions that will determine their impacts (Mearns *et al.*, 2001: 756; Visser *et al.*, 2000; Jones, 2000; Giorgi, 2005). Though the IPCC (2012) has provided detailed assessment of the uncertainties associated with various climate impacts, Curry (2011: 730) argues that the IPCC's consensus approach is biased because it excludes contrary views.

Katz and Brown (1992) highlight a further uncertainty in predictions of climate impacts relevant to adaptation. While global climate models focus on averages, the impacts on society will be felt primarily through extreme events. Katz and Brown (1992) and others (e.g. Wigley, 2009; Cooley, 2009; Hunter, 2010) recommend the use of extreme value distributions to better estimate likely effects. Weitzman (2009) considers that the structural uncertainty contained in the "fat tails" of extreme value distributions to be even more important than the debate about discount rates in assessing the costs and benefits of climate change. But in an iterative Delphi survey of environmental economists on adaptation to climate change Doria *et al.* (2009: 818) found that there was no agreement on whether a 'risk-based approach [was] more appropriate than [a] welfare economic or vulnerability framework', or whether mitigation should be included in any definition of adaptation.

Over the last two centuries, governments across the globe have increasingly adopted the role of managers of the risks faced by their citizens. Limited liability for entrepreneurs and shareholders was followed by, among others, workers' compensation, unemployment benefits and other social services, disaster relief, consumer protection legislation, health and disaster insurance, environmental protection, and mitigation of greenhouse gas emissions (Moss, 2002). There seems little reason to believe that governments will not seek to extend their role into issues related to adaptation to climate change. The key question is: how can they best go about it?

Governments at all levels face a fundamental dilemma. Premature or unnecessarily excessive adaptation today will involve immediate costs, while any benefits gained may not be reaped until the future, possibly the distant future. On the other hand, undue procrastination or inadequate measures may result in property damage or even loss of life. Care is required, however, in attributing increased losses to climate change itself. For example, Pielke and Landsea (1998) and Crompton and McAneney (2008) show that there has been little or no discernible trend in the frequency of hurricanes and other meteorological hazards once damage values have been normalised for inflation, wealth, and coastal populations.

Maladaptation can further increase costs at the risk of gaining no benefit or even worsening the situation. Mendelsohn (2000, 2006) argues that individuals and markets in traded sectors such as agriculture will adapt efficiently, unless governments intervene inappropriately through policies such as subsidising water or insurance, which encourage the continuation of risky behaviour rather than efficient adaptation. Government support is, however, required for public goods such as biodiversity. Where impacts involve both markets and public investment, such as water, coastal defences, or heat stress, a combination of markets and government intervention is required to ensure efficient outcomes. Fankhauser *et al.* (1999) add that research funding and the removal of legal, social and political constraints are also valid functions of government.

Decision Making Aids

Recognising that the natural and social sciences have different implicit and explicit conceptual understandings of 'adaptation', Smit and Wandel (2006) identify four broad analytical approaches that have been adopted by researchers:

- composite indices;
- statistical, equilibrium, and scenario modelling;
- cost-benefit, cost-effectiveness and multi-criteria analysis;
- 'bottom up' studies at the local level.

Indices of Vulnerability, Adaptive Capacity, and Resilience

Much of the academic literature has focused on exploring concepts such as the "vulnerability" of a particular area or community, "adaptive capacity" in that location, and hence its overall "resilience" to climate change impacts. Extensive reviews and categorisations of the literature can be found in Fuessel and Klein (2006), Janssen *et al.* (2006), and Miller *et al.* (2010). But analyses based on these concepts provide little practical guidance for operationalising adaptation strategies, particularly in terms of the timing of implementation or its optimal level.

Some analysts have promoted composite indices that aggregate weighted scores for aspects of the "vulnerability" of particular areas (e.g. Perch-Nielsen, 2010; Hahn *et al.*, 2009; Sullivan and Meigh, 2005; Harmeling and Eckstein, 2012). While vulnerability indices at one level are just descriptive summaries, there is an inevitable tendency to treat them as decision-making tools, with implicit or explicit assumptions that, for example, the most vulnerable areas should have the greatest claim on adaptation funds. Fuessel (2009b: 8) concludes that indices of vulnerability 'show substantial conceptual, methodological and empirical weaknesses.' Cox (2009) further points out that impacts that are chosen for inclusion in indices may not accord with the essential condition of additive independence if the impacts are interactive. Where risks are correlated, additive indexes 'can perform even worse than setting priorities randomly' (Cox, 2009: 942), with obvious implications for setting funding priorities. Pollitt (2010) is also less than enthusiastic about the use of composite indicators and indices to reduce multifaceted, complex, and sometimes countervailing issues and criteria to single numbers. Vincent (2007) points out that composite indices cannot be scaled from specific local data to globally comparable indicators.

Modelling Scenarios

Much of the early adaptation literature flowed from the focus of the IPCC on identifying and specifying the impacts of climate change scenarios. Burton *et al.* (2002) offer a number of reasons why 'models and climate scenario-based methods have not yielded useful results for the purposes of adaptation response and policy options'. Climate scenarios are generally global or regional, while adaptation needs to be site-specific, and is determined by extreme climatic events rather than the average values produced by climate models. Scenarios themselves only offer a range of possibilities in diverse fields (health, education, energy, eco-systems etc), thus compounding the uncertainties of modelling climate impacts: decision-makers have no concrete basis for making decisions. Further, impact analysis is not designed to assess alternative adaptation measures such as reducing perverse incentives such as long-term drought support. Universal, 'obvious' adaptive responses also ignore the realities of local institutions, culture, and potential barriers to change. Human societies have always adapted to changes in climatic environments, so that adaptation policy should be considered more holistically, for example in the context of broader agricultural policy. Mercer (2010) takes a similar position in terms of considering climate change within the context of development policy.

Statistical and equilibrium models have been used to estimate the net costs of climate impacts with and without adaptation (e.g. Mendelsohn *et al.*, 2000; Tol, 2002). Such broad scale studies tend to assume that some form of assumed or hypothetical adaptation will automatically occur, and that its marginal cost is equal to the marginal benefit of avoiding the impact. Hanemann (2000) critiques aspects of impact models, pointing out that adaptation may involve changes in preferences (habituation or hedonic adaptation) as well as in behaviour. In commenting on the Ricardian approach pioneered by Mendelsohn *et al.* (1994, 2000) to assess global market impacts of climate change on agriculture and other sectors, Hanemann (2000) contrasts it with agronomic models that estimate the impact of climate change on crop yields to predict the economic effect on agriculture. In contrast, the Ricardian approach uses cross-sectional data from different locations to estimate the effect on land values of changes in climate variables such as temperature or rainfall, while controlling for soil types and other geographic and socioeconomic factors. Different scenarios are then used to assess the impact of climate change on the value of farmland, and, by inference, on agricultural productivity. Although Hanemann's (2000) focus is on errors in estimation of the agronomic and Ricardian approaches, he notes that the latter assumes that all farmers have identical choice sets in terms of crops to plant, costs, etc. More recent work by Kurukulasuriya and Mendelsohn (2008) seeks to integrate the agro-economic and Ricardian approaches by allowing for switching of output choices by African farmers, using a multinomial logit model while distinguishing different agro-ecological zones. The intricacies and limitations of various modelling approaches are reviewed by Darwin and Tol (2001), Hitz and Smith (2001), and Callaway (2004).

Geographic (spatial) and historical (temporal) analogues can also inform decision-makers about the likely impacts of different climates and therefore suggest possible adaptation strategies. Hallegatte *et al.* (2007) simulate climate scenarios with two climate models and identify 'reasonable analogues of the future climates of 17 European cities' in terms of temperature and rainfall and the costs of adaptation to the state of analogue cities. For example, Paris can be expected to be either Bordeaux-like or Cordoba-like in the future, requiring more thermal insulation and air conditioning for buildings, reduced density, and more vegetation for shade, etc. Mendelsohn *et al.* (1994) also use spatial comparisons in modelling of impacts on agriculture from a Ricardian perspective. In another example, van der Eng (2010) uses the effect of drought on rice farmers in Java in the 1930s as a model of the adaptability of rice markets in potentially similar climatic conditions in the future. Orlove (2005) draws on cases such as the abandonment of Viking settlements in Greenland as analogues. Tol *et al.* (1998) review a number of other studies that employed temporal and spatial analogues to gauge the nature and extent of adaptation that may be required in the future.

Cost-Effectiveness, Multi-Criteria Analysis and Cost-Benefit Analysis.

Cost-effectiveness analysis is often used in everyday life, and it is easily presented to, and understood by policy makers. A measure of technical efficiency, it expresses a result in terms of the cost of achieving a specific objective: for example, the number of lives saved for the cost of a dyke. At its most simple, it can reveal projects that generate the "biggest bang for the buck." Although generally used only for a single output or effect, cost-effectiveness analysis can be extended to multiple outputs and inputs through data envelopment analysis or stochastic frontier analysis and related techniques. However, the very lack of a common variable or numeraire to represent "adaptation" means that comparisons can be made only between projects of a very similar nature. It is not possible to compare a dyke project with a water project, for example, if the comparison made is between number of lives saved per dollar and kilograms of additional rice grown per dollar. Cost-effectiveness analysis also cannot be used to assess which projects will generate the largest benefits for society as a whole. It is, therefore, of only limited use as a policy decision tool for comparing different adaptation projects and programs.

Multi-criteria analysis is a seductively simple approach to developing policy recommendations. Unlike cost-benefit analysis, however, it lacks an established theoretical basis, and is inevitably subjective in the choice of impact attributes, weights, and scores. Multiple results are possible for any given study because their focus is generally "single-issue", compared to evaluating the effect of a measure on society as a whole. Multi-criteria analysis, essentially a form of composite index, involves the aggregation of incommensurable quantities and therefore breaches the mathematical principle of dimensionality (Dobes and Bennett, 2009).

De Bruin *et al.* (2009) provide an example of the application of multi-criteria analysis to identify and rank adaptation priorities in the Netherlands. Their study considers 96 specific adaptation measures for seven climate-sensitive sectors in the Netherlands. Although he suggests further work in the area, Fuessel (2009a) notes the subjective nature of the criteria used, a systematic bias in favour of comprehensive policy options, and vague definitions. De Bruin *et al.* (2009), themselves, acknowledge that two out of their five scoring criteria are not mutually exclusive and may, therefore, involve double-counting.

Some authors (e.g. Agrawala and Fankhauser, 2008: Table 1.1) assess adaptation measures in terms of so-called 'cost-benefit' analysis. However, such approaches are more accurately characterised as 'cost-cost' studies, because they compare the cost of implementing an adaptation measure with the cost of avoided damage due to climate change effects. While there is sometimes no alternative to using the 'damage costs avoided' approach, it can only provide a rough proxy for benefits in terms of willingness to pay or willingness to accept. For example, flood damage to a household will generally underestimate economic costs because it will not include the value of destroyed photographs or other family memorabilia. Valuing the destruction of crops, on the other hand, may overestimate damage costs because farmers may adapt in future by planting alternative crops or by substituting capital in the form of irrigation drip systems. At the international level, estimating the likely costs of the impact of future climate change is a popular line of inquiry, probably because it provides a negotiating basis for requesting financial assistance. However, the estimation of damage costs alone provides little policy basis for determining the socially desirable extent or nature of adaptation activity. In this respect, Dietz and Maddison (2009: 303) note that surprisingly little is known 'about people's preferences for a particular climate or their willingness to pay to avoid negative impacts of climate change'.

Bottom-Up Studies

Generally prevalent in the grey literature, 'bottom up' studies, seek to describe practical adaptation measures at local levels on the basis of community experience (e.g. Jabeen *et al.*, 2010). They tend to support 'mainstreaming' of adaptation measures within established systems and processes. Their findings are generally limited to local conditions and circumstances, but may nevertheless provide useful lessons for communities in climatically analogous situations.

<u>Decision Making Approaches and Instruments</u>

Uncertainty and "Real Options"

One approach to dealing with the inherent uncertainty of climate change is the use of "real options" to extend conventional cost-benefit analysis by estimating quasi-option values using techniques originally developed for financial options by Black and Scholes (1973). In essence, real options analysis posits that additional value is gained from flexibility in the face of uncertainty about future costs and benefits if it is possible to delay or partially delay a decision to fully implement a decision until better information becomes available. Dixit and Pindyck (1994), Trigeorgis (1997) Luerhman (1998), Amram and Kulatilaka (1999), and Copeland and Antikarov (2001) all adopt different approaches to estimating the value of real options. Borison (2005) finds that the different approaches can produce contradictory results, depending on assumptions made. Real options have been applied to adaptation-type issues by Michelsen and Young (1993), Nordvik and Liso (2004), Hertzler (2007), Dobes (2010), Leroux and Crase (2010), McClintock (2010), IBRD (2010), Dobes (2012), Linquiti and Vonortas (2012), Maybee *et al.* (2012), and Gersonius *et al.* (2013).

Linquiti and Vonortas (2012) compare five strategies that boundedly-rational planners or decision-makers might employ to protect Dhaka and Dar es Salaam by constructing seawalls from uncertain levels, frequency, and timing of inundation. They use stochastic simulation modelling employing a Monte Carlo approach to incorporate the uncertainties involved in physical, economic, and decision-making processes. Apart from the status quo option, two strategies are inflexible: building a 100-year event wall immediately, and building a wall and raising it in pre-determined stages over the course of a century. A flexible strategy examined is a sequence of cost-optimising decisions to either raise or not raise the wall for a series of 20-year periods, with each decision representing a real option of a fixed period. A heuristic is used for a further flexible strategy where planners simply observe maximum sea levels during the year. If the maximum sea level comes within 0.5 metres of the top of the sea wall (initially built for a 10-year event with a 0.5 meter safety factor), then the wall is raised in the next year to the observed maximum sea level plus 0.5 meters. With one exception, Linquiti and Vonortas (2012) conclude that there is always value to flexibility and the ability to delay action, as shown by the greater values of mean net present values achieved by the two flexible strategies.

In another example, Dobes (2012) infers that the combination of features in the business strategy of the legendary Australian cattle king, Sir Sidney Kidman, effectively afforded strategic flexibility in the form of real options, especially during severe region-wide droughts. Kidman's properties were invariably stocked at less than full capacity, and were generally contiguous, forming chains that straddled stock routes and watercourses in the most arid zone of central Australia. Railheads at the ends of the chains provided access to the main capital city markets, and Kidman's drovers supplied a wealth of information on competing cattle movements. Faced with a highly variable and unpredictable climate, combined with the onset of erosion and the rapid spread of rabbits, Kidman demonstrated that it is possible to adapt to environmental change on a continental scale without government assistance.

Flexibility and Adaptive Management

An underlying theme discernible in the literature (e.g. Anda *et al.*, 2009; Ingham *et al.*, 2007) and some government agency documents (e.g. Productivity Commission 2012) is the desirability of flexibility and adjustment to new information in the face of uncertainty. The term "adaptive management" is sometimes used to characterize a flexible strategy that is adjusted continuously over time as circumstances change and new knowledge is acquired (e.g. Thompson *et al.*, 2006). Hallegatte (2009) presents a list of five methods which can promote implicitly flexible ‘uncertainty management’: (i) selection of ‘no regrets’ strategies that produce net benefits even in the absence of climate change, (ii) preference for reversible and flexible options, (iii) incorporation of ‘safety margins’ in new investments, (iv) promotion of soft adaptation strategies, and (v) reduction of decision time horizons. Of these, at least three are inherent in the heuristic strategy analysed by Linquiti and Vonortas (2012) where planners raise or do not raise a sea wall by a 0.5 metre safety factor above maximum sea levels each year. The basic principle underlying “adaptive management” is thus conceptually equivalent to the “real options” approach.

Robust Decision Making

Cost-benefit analysis utilising real options requires specification of the probabilities for future scenarios - or at least the form of probability distributions if using Monte Carlo methods - to identify optimal strategies. An alternative quantitative approach to incorporating uncertainty about future climate change is Robust Decision Making (RDM), which emphasizes robustness rather than optimality in decision making (e.g. Lempert *et al.*, 2006; Ranger and Garbett-Shiels, 2011). RDM characterises uncertainty in terms of multiple plausible scenarios of the future produced through computer simulation of sets of probability distributions and strategies that can evolve over time in response to new information. Robust strategies are identified through regret functions that compare various strategies with the best-performing one. However, analysts still make subjective judgments about probabilities and scenarios and their relative robustness, including through techniques such as multi-criteria analysis. IBRD (2010: 37) notes that a key disadvantage of RDM is that it depends on complicated computer algorithms and software, with significant work required to make it suitable for evaluating specific projects.

Insurance

It is common to list insurance as a means of ameliorating the financial consequences of the physical impacts of climate change (e.g. Hallegate, 2009; Adger *et al.*, 2005). Some regard the establishment of insurance-based climate risk funding as a particularly efficient way of channelling disaster relief to developing countries (e.g. Linnerooth-Bayer and Mechler, 2006).

The perspective adopted in the adaptation literature generally emphasises the potentially catastrophic consequences of floods, hurricanes, and other disasters exacerbated by climate change. To the extent that climatic impacts will be slow-onset in nature, however, insurance may not offer an effective adaptation strategy. A key principle of insurance is that events must be fortuitous; the corollary being that pre-existing conditions or reasonably foreseeable outcomes cannot be insured. This issue does not appear to have been addressed specifically in the adaptation literature. It, therefore, remains an open question whether predicted phenomena such as gradual sea level rise, increasing temperatures, or their respective contributions to storm surge or cyclonic activity, will be treated as 'losses in progress' and therefore uninsurable. Another aspect that seems to have been ignored in the literature is that the pooling of risk within families is a form of insurance used in all societies. Ergas (2008) surmises that intra-family insurance may even dwarf commercially provided insurance.

Efficient insurance systems require the pooling of risk for uncorrelated events, with perfect information about the risks available to both insurers and the insured. In practice, asymmetric information can generate adverse selection and moral hazard. In an adaptation context, an example of adverse selection might be the purchase of flood insurance by the owner of a property at risk, but where the insurer is not fully aware of the risk or cannot reflect it in premiums. An owner who obtains insurance may rely on the availability of compensation for flood damage and neglect to take action to limit that damage, a case of 'moral hazard' that is generally obviated by insurers imposing 'deductibles', coinsurance or coverage exclusions that force the insured party to bear the cost of some proportion of any damage. These problems will be compounded if climate change increases the number of correlated risks, with likely increases in insurance premiums. Zeckhauser (1995), Herweijer *et al.* (2009), and Kunreuther and Michel-Kerjan (2009) provide reviews.

Kunreuther and Pauly (2006) argue that ex-post disaster relief in the USA discourages investment in protective measures before disasters, resulting in unnecessarily costly and poorly targeted assistance after the event, especially before elections. Disagreeing with the view that 'charity hazard' associated with disaster assistance reduces incentives to purchase insurance (e.g. Naess *et al.*, 2005; Raschky and Weck-Hannemann, 2007), they argue that people avoid even subsidised insurance because of misperceptions of risk, as well as premiums that are high relative to income. Where insurance is taken out, it is often cancelled if no claims are made within a few years, even in flood-prone areas where it is compulsory. Kunreuther and Pauly (2006) reject the conventional expected utility approach to determining the purchase of insurance, positing instead a sequential choice model based on the past experience of individuals. Given consumer reluctance to purchase insurance, they argue for a compulsory ‘all perils’ scheme with deductibles and premia reflecting individual risks, but with public subsidies to low-income residents and government-sponsored reinsurance for particularly hazardous regions such as hurricane-prone Florida. Nevertheless, they concede that more research into risk perceptions and current institutional arrangements is required.

Noting that most approaches to catastrophic loss conclude that governmental intervention is required in the form of compulsory insurance or regulation such as enhanced building codes, Priest (1996) compares it to private insurance markets. Compulsory participation in insurance schemes does not necessarily reduce adverse selection because governments generally do not allow discrimination between policy-holders, especially those with low incomes. Because there is little focus on controlling adverse selection, government insurance programs typically encounter severe budgetary problems. Where compulsory insurance is used for potential disaster situations, compulsion also diminishes the ability to reduce risk through aggregation: declaration of an event as a disaster involves highly correlated losses in the insured pool. Government’s ability to control moral hazard is also diminished to the extent that policies do not provide for deductibles, coinsurance or coverage exclusions. Finally, governments are no better able to control moral hazard or adverse selection in incomplete insurance markets (e.g. floods, riots, and, presumably, climate change) than private insurers. They simply redistribute income under the guise of insurance programs.

Other Impacts and Responses to Climate Change

Conflict

There is little agreement among analysts about the likely effect of future climate change on the frequency, nature, or intensity of conflict. This is partly due to varying definitions of conflict, ranging from wars between nations (Tol and Wagner, 2010), to civil war (Zhang *et al*., 2006; Fan, 2010), and a broader concept of 'security' (Barnett, 2003) that encompasses threats such as the effect of sea level rise on low islands in the Pacific. Analysts also differ in the choice of potential explanatory factors examined, including environmental migration due to floods or droughts, environmental degradation, loss of habitat due to sea level rise, and reduced food output due to high or low temperatures.

Little systematic, quantitative research has been published, so that there is considerable scope for conjecture and unsupported speculation. On the other hand, quantitative analysis can place undue emphasis on single or averaged variables such as the frequency of conflicts, or mean temperatures rather than extremes, while ignoring the contextual influence of other, non-climatic factors. As a result, many authors conclude (e.g. Tol and Wagner, 2010; Fan, 2010; Barnett, 2003; Hartmann, 2010) that it is necessary to be cautious about the causal links between climate change and conflict.

Reviews of conflict due to environmental and climate change issues by Gleditsch (1998, 2012) offer the most comprehensive critique of methodologies. There is little hard data on the effect of climate change – as distinct from particular severe weather events – on conflicts. Omission of important aspects of variables such as the political systems of states (e.g. democracy, autocracy) engaged in conflict can bias analyses. On the other hand, complex theoretical conflict models may not be testable in practice, while single-factor versions may be overly simplistic. Case studies cannot offer valid explanations of conflict without comparable control groups where no conflict has occurred. Because the future is unknown, and because of the paucity of hard data on past conflicts due to climate change, Gleditsch (1998, 393) points out that many authors stress the 'potential for violent conflict in the future'. In effect, they use their conjectures about the future as evidence to support current hypotheses about conflict.

Some analysts see so-called climate or environmental refugees as potentially exacerbating the potential for conflict (e.g. Reuveny, 2007: 660), either through international or internal migration. However, the migration literature is, if anything, just as speculative and subject to conjecture as the conflict literature.

Migration

Migration away from areas affected by climate change, environmental degradation, or natural disaster is an age-old form of adaptation to adverse local circumstances. Whole settlements have been abandoned throughout history as a result of environmental and other factors (Orlove, 2005; McLeman, 2011). However, there is little contemporary agreement on the typologies or definitions of so-called ‘environmental’ or ‘climate’ refugees (Dun and Gemenne, 2008). McLeman and Smit (2006: 32) warn against considering migration as ‘a simple or automatic response to a singular risk, climate-related or otherwise’. Black *et al.* (2011: 433) note that even a specific factor like drought can result in either higher or lower out-migration: if a greater proportion of the household budget is spent on food due to higher prices, less will be available to finance long-distance migration.

In reviewing studies focused on the destinations of environmental migrants, Findlay (2011) argues that most migrants have a strong preference for staying in their current location, even if available economic and social attractors elsewhere indicate potential gains to be achieved by moving. Once a decision to move has been taken, migrants’ preferences are to move shorter, rather than longer distances, but those that do move will generally be those with the resources to do so, or with the social capital to be successful at their destination. Final destinations are generally selected because they are socially or culturally more accepting. Often these are urban centres rather than areas that are environmentally similar to the regions of origin.

In a detailed critique of estimates of environmental refugee numbers, Gemenne (2011) is highly critical of the speculative manner in which projections have been produced, often with the apparent aim of attracting sensationalist media attention. Because there is no global system in place to capture refugee flows, especially within countries, figures are often highly speculative. This is compounded by lack of consensus on what constitutes an environmental refugee, including distinctions between voluntary and forced migration, displacement versus mobility, international versus internal, and voluntary versus forced movement. A major problem is that projected refugee flows have generally been estimated in a deterministic manner on the basis of populations at risk of inundation or desertification, etc, without taking into account local adaptation, internalisation of impacts, or different projections of the pace of climate change. An even more serious issue is that none of the projections of refugee flows (invariably found in the non-peer reviewed grey literature) can be tested against actual numbers because of the lack of reliable statistics.

Because projections of refugee numbers have tended to rely on variables such as population affected by sea level rise, or vulnerability due to low incomes, Kniveton *et al.* (2011: S34) employ agent-based modelling to isolate the effect of environmental factors on migration flows for Burkina Faso. Hassani-Mahmooei and Parris (2012) similarly use an agent-based model with district-level data to simulate likely internal migration patterns in Bangladesh as a result of climatic shocks such as drought, floods and cyclones. However, such models do not appear to have been applied on a global scale to simulate overall refugee flows.

Recognising that there is still an ‘open debate’ about the causes of migration, Perch-Nielsen *et al.* (2008) nevertheless consider that many analyses propose deterministic linkages between future climate change and migration. Such analyses are often based on ostensibly ‘common sense’ assumptions that ignore real-life human reactions and adaptation. Instead, migration is but one of various adaptation options available in response to chains of contingent events.

<u>Other Perspectives and Issues</u>

Unsurprisingly, a farrago of other perspectives on adaptation exists, reflecting the special interests or conceptual frames of the proponents. Preston (2010) advocates regulation combined with judicial review, while McDonald (2010: 257) raises the possibility of increased uncertainty arising from tort litigation due to different geographical circumstances.). Planners and engineers tend to look to the presumed safety of increased standards (e.g. Standards Australia/Standards New Zealand, 2009) and tighter design guidelines (e.g. Engineers Australia, 2004; Royal Academy of Engineering, 2011). du Vair *et al.* (2002) promote the prioritised fortification of infrastructure. Butzengeiger-Geyer *et al.* (2011) review market mechanisms that have been advocated for mitigation, with a view to applying them to adaptation, although they concede that it would first be necessary to define a ‘unit’ of adaptation. Julia and Duchin (2007) and Mendelsohn (2006) consider the potential role of international trade as an economic adjustment mechanism, Schipper (2009) investigates links to the disaster management literature, and an idiosyncratic article by Liao *et al.* (2012) proposes consideration of biomedical modifications such as reducing the size of humans to facilitate the mitigation of climate change.

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