Better Predictions, Better Allocations: Scientific Advances and Adaptation to Climate Change

Mark C. Freeman[1], Ben Groom[2] and Richard Zeckhauser[3].[*]

August 3, 2015

Abstract

Climate science initially aspired to improve understanding of what the future would bring, and thereby produce appropriate public policies and effective international climate agreements. If that hope is dashed, as now seems probable, effective policies for adapting to climate change become critical. Climate science assumes new responsibilities by helping to foster more appropriate adaptation measures, which might include shifting modes or locales of production. This theoretical article focuses on two broader tools: consumption smoothing in response to the risk of future losses, and physical adaptation measures to reduce potential damages. It shows that informative signals on the effects of climate change facilitate better decisions on the use of each tool, thereby increasing social welfare.

1   Introduction

Climate science aspired to improve understanding of the future, and thereby promote appropriate public policies and effective international climate agreements. With that hope dashed, what contribution can climate science make to policy? This theoretical article shows that receiving clearer signals about the likelihood of future states of a warmer world would provide substantial utility, even in the absence of binding

---
[*][1]School of Business and Economics, Loughborough University. Author for correspondence: m.c.freeman@lboro.ac.uk. [2]Department of Geography and Environment, London School of Economics. [3]Kennedy School, Harvard University.

global agreements, or effective national policies on mitigation. Signals provide the basis upon which the adaptation activities of sovereign nations, regions, firms and even individuals are made so that their expected welfare can be increased.

Informative signals provide benefit in enabling more informed saving and consumption smoothing decisions, but they are particularly valuable when *physical adaptation measures*, such as flood defenses or choice of location, are also available. So, although an important impetus for climate research was to inform and influence high-level negotiations on collective action, knowing more about the likelihood of future outcomes is also a valuable input both for individual governments, and for agents operating at lower, more decentralised organisational levels. These are the parties who will ultimately make adaptation decisions, irrespective of the success of international agreements.

This article focuses on adaptation because it is an inevitable part of the response to climate change [1]. The best predictions so far suggest that, whatever is agreed at the 21st Conference of Parties in Paris in December this year (COP21), there is by now sufficient inertia in the climate system to lock-in temperature increases of between 0.3 and 0.7 degrees Celsius (C) for the period 2016–2035 relative to 1986–2005 [2, 3]. For the period 2080–2100 temperature change is expected to exceed 1.5°C for all but the most stringent Representative Concentration Pathways (RCP) contained in the Fifth Assessment Report of the IPCC (AR5). It is thus unlikely that we will meet 'the scientific view that the increase in global temperature should be below 2 degrees Celsius' compared to the pre-industrial average ([4], article 1) that was agreed in the Copenhagen Accord arising out of the COP15. Indeed RCP2.6, the most stringent of the RCPs, shows that in order for the 2°C limit not to be exceeded, emissions of CO_2 and other greenhouse gases will have to turn negative towards the end of the 21st century.

Adaptation has shifted from a subject lurking in the shadows, as it did in the early years following the United Nations Framework Convention on Climate Change (UNFCCC), to one granted more or less equal status in a recent meeting of the Conference of Parties [5]. Some major players in the past felt that discussion of adaptation would undermine efforts to agree on mitigation targets. Al Gore made this point forcefully when he said that focusing on adaptation represented 'a kind of laziness, an arrogant faith in our ability to react in time to save our skins'. The UNFCCC devoted little time to adaptation, and defined it narrowly as a simple reactive behaviour to future climate change [5].

The prime reason why adaptation has now become a prime policy concern is that agreement on stringent emissions reductions has not been achieved, and will

require a 'miracle' at the COP21 according to some.[1] It has been argued for some time that the nature of climate change as a spatial and intergenerational problem, together with the absence of an enforcement mechanism within the Kyoto Protocol and successive agreements, more or less precludes agreement on collective action [6, 7, 8, 9]. Beyond the straightforward free-rider problems, most countries recognise that a successful international response to climate change mitigation requires the participation of the two major contributors to greenhouse gases (GHGs), China and the US. So far the US has shied away from signing the Kyoto protocol, while China remains a Non-Annex I country with no obligations under the principal of 'shared but differentiated responsibilities'. It has also been shown theoretically and in behavioural experiments that uncertainty surrounding climate change damages discourages agreement, particularly when this uncertainty concerns the location of catastrophic thresholds such as the 2°C limit of the Copenhagen Accord [10].

As a counter-argument we might look to the recent Sino-US pledges on emissions reductions, where the Obama administration pledged a 26–28% reduction in GHG emissions by 2025, while President Xi simultaneously made a general pledge to commence emissions reduction by 2030. However, the proposed reductions are far from sufficient to contain significant additional accumulations of GHGs. Moreover enforcement is lacking; there are no clear plans of implementation on either side, and the reliance of the US pledge on executive authority means it may well be reversed under a Republican administration.[2] The differences between these respective pledges reflects the inherent asymmetry of the problem more generally. A global agreement must resolve the fact that negotiating countries are at very different stages of development, and that the Least Developed Countries (LDCs) will either require compensation for stringent emissions reductions, or will only commit to mitigation once development has taken place [11]. Optimistically positing significant Sino-US progress beyond their recent pledges, world energy demand is still predicted to increase as incomes, not to mention populations, in LDCs increase in the future [12, 13]. For all of these reasons, adaptation is now an unavoidable feature of the response to climate change, particularly in LDCs. This view is reflected in the high-level institutions of the UN Framework Convention on Climate Change (UNFCCC) with the formation at the COP16 in Cancun of the Cancun Adaptation Framework. Similarly, both AR4 and AR5 [3, 2] have detailed chapters devoted en-

---

[1]The president of France, Francois Hollande, has been quoted to this effect. http://www.theguardian.com/environment/2015/may/20/francois-hollande-calls-for-miracle-climate-agreement-at-paris-talks

[2]See http://www.nytimes.com/2015/04/01/us/obama-to-offer-major-blueprint-on-climate-change.html?

tirely to adaptation. Even the US president has recently highlighted the need for climate preparedness [14].

Of course, as with mitigation, adaptation decisions must be taken despite considerable uncertainty about the impact of climate change in the future. As one looks into the distant future, as is necessary for such problems that stretch across generations, every aspect of the problem becomes increasingly fuzzy. Probability distributions attached to events widen; estimates of key variables become less precise; we are even uncertain about the probabilities to attach to different outcomes in the deep future. Responses to climate change therefore must be taken in an environment of *uncertainty* and *ambiguity* rather than *risk*, and even possibly *ignorance*, where some important possible states of the world cannot be identified [15].

There are three chief sources of uncertainty in our understanding of future climate change: i) the level of future emissions; ii) the impact of emissions on temperatures; and, iii) the damages that arise [16]. Take for instance 'climate sensitivity', which measures the increase in temperature from a doubling of CO_2. Estimates of this parameter in the AR5 come from many and various sources. Climate models are one such source, and disagreement among them is plain to see in Figure 1. Yet, with the passing of time scientific research, and in particular the arrival of additional data, will improve our understanding of such relationships. We can expect the uncertainty surrounding some of these factors to narrow, both in the sense of obtaining more precise predictions or obtaining closer agreement among climate models, not to mention experts, and on the extent of uncertainty. There are good reasons why we may not see a narrowing of the distributions per se, see for instance [17], but we may learn more about the distribution itself, including the likelihood of catastrophic outcomes. We may also expect clearer information from improvements in the estimation of climate damages. Ultimately though, the relevant information to improve adaptation decisions would be provided at a local level. Here too better information could eventually narrow the disagreement among regional models that currently exists. Adaptation in many sectors can then be placed on a firmer footing as a consequence of better, well-targeted information [12, 18, 19].

[*Insert Figure 1 here*]

To address our central question of how more informative signals about climate change can improve adaptation measures, we develop a parsimonious model of an agent who could be an individual, a firm, or a local or national government. The agent can make a 'macro' decision to build up savings to buffer potential future losses, and/or a 'micro' physical adaptation decision that reduces future losses from climate change (though not limiting climate change itself). We then consider how

4

the welfare of this agent is changed through improved understanding of the likely evolution of climate change.

Our work relates to two strands of the preceding literature. In the first, the option value of arriving information has been analysed following a framework long since established [20, 21, 22]. Here the essential problem is that an agent must make a decision today knowing that a better signal will arrive in the future. In this context the agent need not make an investment decision now, but can wait and see how uncertainty is resolved. The problem then becomes one of optimal timing of investment accounting for the fact that both investment (e.g., adaptation) and the resolution of uncertainty (e.g., climate damages) are irreversible and reduce options in the future. See in particular [22] in the context of climate change. In the second strand, the implications for the precision of climate predictions has been analysed for an agent who receives a short-run and a long-run prediction without knowing that the signal (forecast) may improve in time. In this case the question concerns the relative value of short-run and long-run predictions [16, 23].

Our approach differs from these in that it evaluates a world in which information is improving via a future signal, and the agent makes consumption and savings decisions as soon as this signal is received. Evaluated in advance, we capture the welfare value of better scientific information on saving and adaptation decisions, but strip out issues of option value and irreversibility.

As intuition would suggest, we formally prove that a risk averse agent benefits from better scientific information. In the macro adaptation case, this reduces uncertainty in the future and allows the agent to better smooth consumption over time. This effect is monotonic in the strength of the signal. The value of the signal is enhanced when micro adaptation strategies are also available. Then adaptation measures can be better tailored to different states of the world. However, the devil is in the details. Our analysis then examines how properties of the consumption utility function affect levels of savings and physical adaptation. We present both analytic results and numerical calculations. The latter illustrate, for example, the non-monotonic way in which the levels of micro and macro adaptations respond as signals improve.

2   Scientific Uncertainty in Climate Change

In this section we discuss the pervasive uncertainties associated with climate change. This is done with a view to understanding where continued scientific research may be able to provide better signals about the future of climate change. Taken together, [24] and [16] provide a helpful structure, which we now summarise.

Predicting the future is a difficult task at the best of times, but the sheer complexity and time horizon associated with climate change amplifies these difficulties. Our knowledge about the future of climate change comes from two main sources: i) scientific understanding, including physical laws; and, ii) the empirical predictions of climate models. While the laws are matters of fact, the movement from *laws* to *predictions* leads to an uncertain picture of the future as the models attempt to reproduce extremely complex systems using different assumptions and calibrations. There is a distinction to be drawn between *predictions* or *forecasts* and *projections* in this context. The former 'attempts to account for the correct phase of natural internal climate variations (such as the El Niño Southern Oscillation), whereas the latter does not'. A forecast must be initialised to be in phase with the observed cycles, and becomes a projection as it moves out of phase. A projection is still a valid representation of the statistical properties of the climate system, yet without an explicit conditioning on the phase of the natural variability. Alternatively, the IPCC refers to the most likely projection as a forecast [2]. Whether predicting or projecting the future climate, models are subject to their own errors and potential omissions [25].

In the context of adaptation, the uncertain process of technological change means that the future costs of adaptation are also a source of uncertainty about the future, just as abatement costs are uncertain when thinking about mitigation. More specifically, with regard to climate change and damages, we are much more uncertain about predictions with longer lead times or greater spatial definition. The distant future, and country or regional level predictions are 'fuzzier' than short-term or global predictions [24].

When thinking about adaptation to climate change, decisions will depend upon the uncertainty surrounding future *exposure* to climate damages. Future emissions paths are undoubtedly difficult to predict, but calibrating the damage function is one of the key weaknesses of Integrated Assessment Models and a source of great uncertainty [26, 27]. At present damage functions are constructed on the basis of 'ad hoc assumptions based on loose extrapolations and intuition' [28]. Small changes in parameters lead to large changes in estimated damages and associated policy recommendations, yet the AR5 cites only a dozen or so sources for its estimates of the damage function; many come from the same experts. It is widely regarded as an area ripe for improvements in understanding and more refined information on uncertainty [2].

Together with predicted emissions paths and damage functions, climate sensitivity is one of the key pieces of the climate-change puzzle. In contrast to the damage function, this has received a great deal of scientific research. Despite this, its value

6

remains very uncertain [29, 16]. Figure 1 shows the probability density functions for this parameter value for a large number of prominent climate models. The models clearly disagree on the likelihoods to attach to different values of climate sensitivity; there is uncertainty rather than simply risk.

For decision making purposes, these estimates are typically aggregated into a single density function, either by Bayesian methods as used in AR5 or by using expert assessment. Even then the aggregated climate sensitivity remains a source of great uncertainty. Using such methods the 'likely range' of climate sensitivity, meaning the central 66% of the distribution of estimates, is currently 1.5–4.5°C. This range has remained somewhat steadfast since the First Assessment Report of the IPCC (AR1), with only a brief narrowing of the range at the time of the Fourth Assessment Report in 2007 to 2–4.5°C: the physical reasons for the robustness of the distribution of climate sensitivity have been well documented [17]. As well as the likely range, the summary distribution of climate sensitivity reported in AR5 provides information about the likelihood of extreme, high temperature states of the world. For instance, the likelihood of a temperature rise in excess of 6°C is approximately 10% [29]. Some have argued that climate policy ought to be organised around this information rather than the central ranges, since increases in temperature of this magnitude would represent truly catastrophic outcomes, which make up the vast majority of expected losses [30].

Climate sensitivity and climate damages are good examples of the information we can expect from research on climate change. They guide the analysis of climate scenarios and provide the essential information upon which climate negotiations and adaptation decisions are made. Yet there are several areas where improvements in this kind of scientific information are likely. Experts tend to agree that, as time passes, temperatures and CO_2 emissions will move further into uncharted territory, and scientists will learn more about the complex climatic relationships. The various distributions of climate sensitivity will most likely become more similar, and disagreement among models and experts will most likely diminish. New models and techniques will also arrive. In recent years, the reported hiatus in observed global warming has encouraged greater focus to be placed on the ocean-atmosphere linkages in climate models, while efforts have been made to improve data collection or the interpretation of historical data. Such research endeavours to better inform climate projections in the future [31, 32, 33]. Advances like these improve the accuracy, not to mention the credibility, of climate models and their projections. Similar arguments can be made for the damage function and knowledge of how humans will respond to these changes, for example through migrations, wars, and innovation.

Yet learning is also likely in relation to more esoteric issues, such as how best to

aggregate models and expert opinions [25, 34]. For instance, expert opinions provide a useful source of information for estimating climate sensitivity since their subjective probabilities are calculated using their experience with a variety of climate models and their expert views of their advantages and shortcomings. However, experimental evidence indicates that experts at times violate the axioms of rationality that motivate the use of subjective probabilities in the first place [34]. Probabilities derived this way may paint a more optimistic or pessimistic picture of the uncertainties that we face, compared to more appropriate aggregation methods [34, 24]. Even without these behavioural/rationality issues, others argue that simply combining the results from climate models to form a single distribution of climate sensitivity only captures a fraction of the uncertainty that we face, and ignores the deeper uncertainties contained in individual climate models. It could well be that other representations of uncertainty might be more appropriate [25, 35], or alternative decision-making frameworks should be used to account explicitly for the inherent ambiguity of climate sensitivity [24, 23].

Furthermore, making predictions at higher levels of geographical definition represents another source of profound uncertainty. Country level predictions of the evolution of climate change are notoriously imprecise since they depend on local environmental factors such as topography. This is particularly true for precipitation, since the science of cloud formation is subject to stochastic processes which are less well-understood. Consider, for example, the predictions for temperature and precipitation in China for the decades up to 2050 and 2100 coming from three prominent climate models: the Hadley Centre Coupled Model (HCMIII), the Parallel Climate Model (PCM2), and the Community Climate Model (CCM2) [18].[3] While each predicts more or less the same temperature rise on average, some predict greater precipitation in the future, while others predict significantly less [18]. Improving the accuracy and precision of spatially defined predictions is one area where additional research could bear fruit [23, 16].

There are several areas where scientific research will be able to either improve predictions or at least provide more informative signals about the level of uncertainty we are facing. Some scientists believe that a tripling of current funding levels would reduce uncertainty in transient climate response, an element of climate sensitivity, by approximately one third [16, 36]. Others argue that, irrespective of scientific advances, it is the actual delivery of existing information to those who need it that provides the informative signal. Developments of this kind have similar effects upon decision-makers who were previously 'in the dark' [37]. There is no doubt that there

---

[3]http://www.cgd.ucar.edu/pcm/; http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadcm3; http://www.cgd.ucar.edu/cms/ccm3/

are frequent calls for such tailored information to improve adaptation decisions and to avoid 'maladaptation' [14, 19].

Simple practical examples exist of where a clearer picture of the uncertainty facing potential agents assisted in their adaptation/risk management decisions. In the Netherlands maps have been produced that clarify the probability of flooding in different locales [38]. Elsewhere, better predictions of the danger zones for natural disasters have also been provided [39]. There is a growing demand for such information from international and governmental organisations, commercial quarters, and local planners alike [23]. The provision of such information is also taken seriously by major global organisations. For example, provision of this kind of information is a major component of the World Meteorological Organisation's Global Framework for Climate Services [16]. In Southern Africa, informative climate signals about the El Niño Southern Oscillation have assisted agricultural decisions since 1997 [37].

Of course, we must remain mindful that uncertainty surrounding some aspects of climate analysis is likely to be irreducible. The processes of cloud formation, the path of future emissions, and many other socio-economic processes, are extremely difficult to narrow down. Such quantities may well dominate uncertainty in the long-run [16, 23]. It is striking to note that the distribution of climate sensitivity has not narrowed significantly since the early estimates in the 1970s [30]. Yet, more informative signals about the likelihoods of different future states of the world are possible in some of the areas described above, and are widely seen as an important input to adaptation decisions in many different circumstances [14, 36, 16].

Improvement in the information about the future can in principle come from any or all of the sources of uncertainty discussed above. In our formal analysis the signal concerning the probability of the severe (high temperature, high damage) state stems from better information on future climate or emissions, rather than damages. Before going into the details, we discuss some specifics of adaptation.

3   Adaptation as a response to climate change

3.1   Increased emphasis on adaptation

Three main factors have led to the increased emphasis on adaptation. First, inertia in the climate system means that the full effect of historical emissions is yet to be felt. To quote the Stern Review, 'there are some unavoidable impacts of climate change to which the world is already committed' [40]. Second, equity concerns have dictated a shift in focus towards the impact on developing countries, which are the most vulnerable to climate change due to their reliance on climate sensitive sectors

such as agriculture, forestry and fisheries [41]. Third, a strong sense developed that the focus on mitigation to reduce climate risks in the future ignored the very real prospect of current climate and non-climate related development issues, such as the control of malaria. The objectives of adaptation strategies often overlap with those of development more generally [5].

Precisely these arguments have elevated adaptation to more or less equal status with mitigation in high-level negotiations and associated institutions. The outcome of the COP16 in Cancun and agreement on the Cancun Adaptation Framework (CAF) testify to this.[4] The salient aspects of the CAF and associated Adaptation Committee for the purposes of this article concern their role in the provision of information and the promotion of scientific research on climate change. For instance, the Cancun Agreement in Article I, Section 14(h) and (i) states that a key role of the CAF is: 'Strengthening data, information and knowledge systems; and, improving climate-related research and systematic observation for climate data collection .... in order to provide decision makers at the national and regional levels with improved climate-related data and information'. Furthermore, the Adaptation Committee's objectives include 'Sharing of relevant information, knowledge, experience and good practices; and, providing information and recommendations, drawing on adaptation good practices, for consideration by the COP when providing guidance .... on adaptation actions'. In short, adaptation is now a prime concern for high-level climate institutions, and the provision of scientific information to potential adapters is now an important part of the adaptation framework. Nationally, National Adaptation Plans are also being developed and implemented in line with the Cancun Agreement. There are even parallels in the U.S., albeit apart from these international processes, with the need for climate preparedness and information provision being underscored in President Obama's recent climate policy announcements [14].

3.2   Categories of adaptation

Adaptation can be reactive or anticipatory [44, 1]. Reactive activities are immediate responses to events caused by climate change, for example, stacking sandbags to prevent flood damage [38]. Anticipatory adaptation is pro-active [45], as would be building dikes against the sea, or designing houses to better withstand storms. Adaptation decisions can be planned, as are migration policies from threatened areas set by the government of Bangladesh, or public health measures taken in the tropics.

---

[4]The Delhi Declaration of 2002 which called for a greater focus on the plight of developing countries in international negotiations, leading to the Bali Action Plan of 2007, and arguments in academia have all assisted in the integration of adaptation into the UNFCCC [5, 42, 43].

Alternatively, they can be autonomous and decentralized, as when farmers switch crops or businesses air condition factories [45, 46, 47]. Autonomous decisions are taken by individual actors. Planned decisions are generally undertaken by governments; international agreements may be required to deal with border-crossing issues, such as river basins, as well as to coordinate other issues such as substitute and complementary adaptations [44].

Our primary focus is on anticipatory adaptation, namely measures undertaken either by saving, or by investing in physical adaptation. Some adaptation measures, such as creating or restoring wetlands and moving citizens inland, reduce risk exposure. Others, such as moving electrical equipment out of basements, reduce damage should risks arrive. Having individuals save funds for when flood losses are incurred represent still a third, insurance-style, approach to adaptation. Our formal analysis allows for the possibility that physical adaptation measures are constrained, and that households must rely on consumption-savings decisions to adapt to future climate change.

4 The Framework

In this section we describe the framework with which we value the arrival of an informative signal on future climate change for a decision maker deciding on how to adapt to future states of the world. We use a stripped down two-period model, which reduces the problem to the essential features we wish to explore. The model reflects the aforementioned aspects of adaptation decisions that the agent may adapt by either saving money or investing in damage reduction. The agent we consider can just as well be thought of as a sovereign nation planning adaptation unilaterally: e.g., Bangladesh, the Netherlands, or the UK; or an individual household making adaptation decisions: crop choice, flood defenses, or saving; or anything in between. The agent should be thought of as being at the appropriate organizational level for the decisions at hand, and choosing wisely how much adaptation to undertake. Decisions are made against a backdrop of exogenous mitigation policies and available information about the damage that climate change will cause.

4.1 The impact of adaptation: measurement issues

Our analysis considers adaptation measures at an aggregated level. Thus, for example, we do not assess whether a house is built on stilts, a wetland is restored, a factory is put in a less convenient but better protected position or a less valuable but more drought-resistant crop is planted. The first part of our model focuses merely on how

much expected welfare and period 1 consumption are raised or lowered as the signal on the period 2 climate effects, i.e., the level of the future income (or 'endowment'), arrives. Subsequently, in our numerical calculations, we consider period 1 physical adaptation expenditures.

Most economic analyses of climate change focus on GDP, and treat it almost equivalently to welfare. Though our analysis is fundamentally economic, and pays primary attention to consumption levels, it differs from these treatments in several ways. First, it recognizes that climate change may bring about effects quite apart from GDP that affect welfare. For example, a higher sea level might destroy recreational beaches. Higher temperatures may impair health via pollution effects or disease vectors. If climate change is severe, a sizeable portion of the welfare losses, whether GDP-related or not, may result from human actions in response to climate change that adversely affected other humans. For example, should climate change promote significant human migration, this may in turn create debilitating ethnic tensions, wars or political disruptions. Humans would then be much worse off, even if GDP were not reduced. Such non-GDP effects are implicitly included in the loss of income in future periods.

Second, GDP, as currently measured, does not consider capital destroyed or rendered less valuable. Regions that experience natural disasters often experience rises in measured GDP, given the reconstruction activity that follows. That would be true even if all the reconstruction dollars came from the affected communities. However, that is just a mis-measurement problem. Our focus is on consumption as commonly understood, goods and services available to provide consumptive pleasures. This avoids accounting problems associated with attending to losses to capital stock due to climate change or any rebuilding that is required. The adaptation measures explicitly considered here all take place in the first period. Of course, whether climate change is moderate or severe, there will also be responsive adaptation in the second period, such as moving production facilities or building a sea wall. The reader should think of the cost of those measures being added to any losses in second-period consumption as being part of the reduction of the second-period endowment.

Thus, the basic framework we are considering chooses consumption and (subsequently) physical adaptation expenditures in period 1 taking into account what is known about the period 2 endowment. Its primary goal is to determine how knowledge of the likely endowment, improved via an informative signal, affects expected welfare and first-period expenditures. There is one class of (controversial) measures that could be undertaken to cope with climate change that is not explicitly part of this analysis: research into geoengineering and geoengineering itself, which has been discussed at length in a special issue of the Philosophical Transactions of the Royal

Society A [48]. Geoengineering could be thought of either as adaptation or mitigation. The former interpretation looks at its potential to decrease the losses from climate change; the latter sees that, if successful, it actually reduces climate change. Readers who wish to, however, could interpret first-period undertakings related to geoengineering as being self insurance expenditures.

4.2 The Theoretical Model

We consider an agent at time $1 - \delta$ who is anticipating decisions that he or she might make one instant later at $t = 1$, the outset of period 1. The level of income for period 1, e_1, is known now, but the decision the agent must make is how much to consume immediately, c_1, and how much instead to save in a zero-interest rate bank account.

The agent knows that in the second, and final, period, the level of climate change will be either *moderate* or *severe* and assigns unconditional probabilities of p and $1-p$ respectively to those two states occurring. Income for period 2, net of adaptation expenditures and hence available for consumption, e_2, will be high, h, if climate change is moderate, or low, l, if it is severe. See Figure 2 for the sequence of events.

[*Insert Figure 2 here*]

The model treats scientific knowledge as a signal that arrives in the interval $t \in [1 - \delta, 1]$ on the future state of the world, namely the outcome in period 2. This signal, which can be *good* or *bad*, helps the agent refine the probabilities of the moderate and severe states. A good signal increases the probability that the agent assigns to climate change being moderate to $p + \varepsilon_G$ for $0 \leq \varepsilon_G \leq 1 - p$, whereas a bad signal reduces that probability to $p - \varepsilon_B$ for $0 \leq \varepsilon_B \leq p$. The realisation of climate change at time 2 is consistent with these revised probabilities. In the case when $\varepsilon_G = \varepsilon_B = 0$, the signal is completely uninformative. When $\varepsilon_G = 1 - p$ and $\varepsilon_B = p$; the signal is fully informative and all uncertainty is resolved at $t = 1$ rather than $t = 2$. Other permissible values of ε_G and ε_B that do not lead respectively to a sum of 1 or 0 represent *partial signals*. See Figure 3.

[*Insert Figure 3 here*]

The primary contribution of a signal is to improve adaptation decisions in period 1. At time $1 - \delta$, the agent does not know whether the signal will be good or bad. However, he is anticipating scientific advances that will result in probability π of the good signal arriving and $(1 - \pi)$ of the bad signal arriving. The parameter values

13

π, ε_G, and ε_B are all known at $t = 1 - \delta$. For consistency with the unconditional probabilities, these three variables are constrained through the relationship $\varepsilon_B = \pi \varepsilon_G / (1 - \pi)$ for any p.

Since the bank interest rate is zero, the agent faces the budget constraint that $c_1 + c_2 = e_1 + e_2$, where c_2 is period 2's consumption level. Absent a fully informative signal, e_2 remains unknown at $t = 1$; thus uncertainty over period 2 income will remain when the savings decision is made. c_1 is chosen to maximise the agent's expected total welfare over the two periods, Ψ. It is assumed that this welfare can be expressed as the sum of utility, $U(c)$, that the individual derives from his spending in each period.[5] The agent's optimisation problem can then be expressed as:

$$\Psi = \max_{c_1} E_1 \left[U(c_1) + U(c_2) \right] \qquad \text{subject to } c_1 + c_2 = e_1 + e_2$$

In line with the welfare functions that are most commonly employed in economic theory, it is assumed that the utility function has a positive first derivative, a negative second derivative, and a non-negative third derivative; $U' > 0$, $U'' < 0$, $U''' \geq 0$.

The role of each of the first three derivatives of the utility function has a clear interpretation. The positive first derivative means that more consumption is always preferred to less, and that we are never satiated. The negative second derivative applies if we are risk averse so that, for two gambles with the same expected payoff, we would always prefer the one with less risk. The strength of this preference is captured by the Pratt-Arrow measure of absolute risk aversion, $A = -U''/U'$. A further implication of $A > 0$ is that, if we have fixed total wealth, W, that we wish to consume over two periods — c_1 in period 1 and $c_2 = W - c_1$ in period 2 — then welfare, Ψ, is maximised if $c_1 = c_2 = W/2$. Smoothing spending patterns over time is always preferred by a risk averse individual. The negative third derivative captures what economists call the 'precautionary savings motive', which was originally described by [49]. The stronger this motive is, as measured by absolute prudence, $P = -U'''/U'' \geq 0$ [50], the more we will save today against potentially bad outcomes given a future risky income stream. This feature of utility functions is used to explain, amongst other observed phenomena, why household savings go up and interest rates go down before periods of high unemployment.

The primary variable of interest is $E_{1-\delta}[\Psi]$, the welfare that the agent currently expects to enjoy in the future. Specifically, how greatly do scientific advances in the interval $t \in [1 - \delta, 1]$ increase $E_{1-\delta}[\Psi]$ despite the fact that the signal neither enables the agent to reduce greenhouse gas emissions nor directly protect himself

---

[5]More formally, the welfare function assumes the rate of time preference is zero and that utility is time-separable over a single consumption good.

from the economic consequences of climate change? A second variable of interest is $E_{1-\delta}[c_1]$. Under what circumstances will a signal lead to an increase in the expected consumption level the next instant? Deriving answers to these two questions under a variety of circumstances is the principle goal of our model.

To begin, we compare the case of a full signal ($\epsilon_G = 1 - p$, $\epsilon_B = p$) to that of no signal, ($\epsilon_G = \epsilon_B = 0$); we relax these assumptions to obtain Result 2 below and in our numerical illustrations. In the simpler case:

Result 1. If we receive a full signal in the interval $[1 - \delta, 1]$, then compared to the case of receiving no signal:

1.1 Expected welfare, $E_{1-\delta}[\Psi]$, increases.

1.2 Expected time $t = 1$ consumption, $E_{1-\delta}[c_1]$, increases (stays the same) if prudence is positive (prudence is zero).

A formal proof of the result is presented in the appendix, but the intuition behind it is straightforward. If all uncertainty is removed at time 1 then we can perfectly smooth consumption between times 1 and 2. $c_1 = c_2 = (e_1 + h)/2$ if the signal is good or $c_1 = c_2 = (e_1 + l)/2$ if the signal is bad. Smooth consumption is always optimal in this economy because $U'' < 0$. Therefore a perfect signal allows us to make the best possible consumption decision at $t = 1$ and expected welfare increases.

While we do not formally model a multi-period environment in this paper, the extension of Result 1.1 to this framework is straightforward. Since welfare is gained through smoother consumption paths, the earlier the signal arrives the more effectively this can be undertaken. Therefore, in a multi-period framework, the earlier that science can inform us about likely future climate paths, the more expected welfare will be increased.

Result 1.2 follows from the prudence of the individual. A full signal completely eradicates uncertainty and therefore the precautionary savings demand is eliminated as well, raising the expected consumption level at $t = 1$.

Result 1.1 verifies the importance of scientific advances even when such enhanced knowledge does not lead to better (or even different) policies, hence neither does it lead to any alterations in either temperature or future economic damages. In the appendix we prove that this result applies also to partial signals for any value of p. We define a signal as *getting stronger* if ε_G increases, implying that ε_B also increases since $\varepsilon_B = \pi \varepsilon_G / (1 - \pi)$.

Result 2. As the strength of any signal that we receive in the interval $[1 - \delta, 1]$ gets stronger:

2.1 Expected welfare, $E_{1-\delta}[\Psi]$, increases.

2.2 Expected time $t = 1$ consumption, $E_{1-\delta}[c_1]$, increases (stays the same) if prudence is positive (prudence is zero).

This demonstrates that any scientific advance increases expected welfare as it allows the agent to make a better consumption-savings choice in period 1. This is our central qualitative lesson.

5 Numerical examples

We now consider the quantitative magnitude of the effects described in the previous section. For our numerical examples, we define the moderate state to be the least damaging 70% of possible outcomes and the severe state to include the most damaging 30% of outcomes. We are currently at year -5 and will, over the next five years, through the advances of science, receive with equal probability ($\pi = 0.5$) a good or a bad signal about future climate change. Since $\pi = 0.5$, $\varepsilon_G = \varepsilon_B = \varepsilon$. This will then enable us to update our probability of the moderate state occurring to $70\% + \varepsilon$ or $70\% - \varepsilon$ depending on which signal we receive for $\varepsilon \in [0, 0.3]$. $\varepsilon = 0$ represents an entirely uninformative signal. When $\varepsilon = 0.3$, a good signal is fully informative but a bad signal is not. There is no material greenhouse gas effect over this initial five year period. Then, t_1 years after the initial signal, the true state of the world is perfectly revealed and, for $t_2 = 300 - t_1$ years, we evaluate the economic damages. Given the implications of climate change will play out over long time horizons, the welfare effect of anticipatory adaptation decisions will be felt over a similar period. For this reason we choose a time horizon of 300 years. This is a stylised representation of what will be a gradual process of uncertainty resolution over the long term. For the baseline calibration we set $t_1 = 50$ years but, in sensitivity analysis, also consider $t_1 = 100$ years.

Equilibrium climate sensitivity (ECS) will take the value of S_m or S_s depending on whether the state of the world is ultimately moderate (m) or severe (s). We define $T_{m,t} = 2S_m \left(1 - 0.5^{t/100}\right)$, which loosely follows [51], to describe how temperature evolves should the state be moderate. This implies that, at $t = 100$, temperature changes equal the ECS and as $t \to \infty$ so $T_{m,t} \longrightarrow 2S_m$. We define the variable $T_{s,t} = 2S_s \left(1 - 0.5^{t/100}\right)$ analogously for the severe state.

It is assumed that over the first time interval, $t \in [1, t_1]$, the agent is currently certain that the temperature will follow $T_{m,t}$. During the second period, which ends three hundred years after the signal is received, the temperature also follows

$T_{m,t}$ if the state is moderate. However, if the state is severe, then temperatures move smoothly away from the $T_{m,t}$ path towards the $T_{s,t}$ trajectory as $t \rightarrow 300$. Specifically, if the state is severe, then for $t \in [t_1 + 1, 300]$, $T_t = w_t T_{m,t} + (1 - w_t) T_{s,t}$ for a weighting function w_t defined by:

$$w_t = \frac{1}{1 + \exp(\tau)}, \qquad \tau = 0.04 \left(t - (t_1 + 300)/2 \right).$$

This is an inverted $S-$shaped sigmoid function that transits smoothly over the period $[t_1 + 1, 300]$. Notice that when $t = t_1 + t_2/2$, or half way through the second period, the temperature is half way between $T_{m,t}$ and $T_{s,t}$.

The values of S are calibrated as follows. [51] describes the probability density function for the ECS as a displaced gamma distribution, $\Gamma(\alpha, \theta, \chi)$ with shape parameter $\alpha = 3.8$, scale parameter $\theta = 0.92$ and location parameter $\chi = -1.13$. This gives a mean, standard deviation and skewness for the ECS of 3 degrees, 2.11 degrees and 9.76 respectively. We take the "moderate" outcome to represent values of the ECS that are less than 3.8 degrees. This is the value at which the cumulative distribution function for $\Gamma(\alpha, \theta, \chi)$ is 70%. The severe outcomes represent values of ECS above 3.80 degrees.

To choose S_m and S_s, we take the mean of the truncated displaced gamma distribution $\Gamma(\alpha, \theta, \chi, u, l)$ where u and l are the upper and lower points of the truncation of the distribution: see [52] for closed-form expressions for these averages. For the moderate state, $u = 3.80$ and $l = \chi$, while for the severe state, $u = \infty$ and $l = 3.80$. This gives values of $S_m = 1.89$ degrees and $S_s = 5.59$ degrees. At $t = 300$, these correspond to temperature rises of 3.31 degrees and 9.74 degrees respectively if $t_1 = 50$ years, both well exceeding the 2 degree limit. We plot the evolution of temperature for the severe and moderate states in the top graph of Figure 4.

[Insert Figure 4 around here]

The change in temperature over time is converted into damages as follows. Let $e_0 = 1$ describe the level of income today. In the absence of climate change damage, the endowment in future years also equals 1, but the analysis could be easily adapted to consider non-zero core growth rates. In the presence of climate change, the endowment is affected by a loss function $L(T_t)$ which depends on the level of temperature change at that time. We take a multiplicative loss form, $e_t = L(T_t)$ where the loss function is given by a negative quadratic exponential form used by [53] and [51, 54]: $L(T_t) = \exp(-\beta(T_t^2))$ for some constant β. We set this parameter value equal to $\beta = 0.003206$. This represents a 5% loss in income should the temperature rise by 4 degrees centigrade. [51] notes that this is consistent with

17

the IPCC upper 83% estimate of potential damages for this level of temperature change. The bottom graph in Figure 4 plots income levels under the moderate and severe scenarios over the interval $t \in [0, 300]$ when $t_1 = 50$ years. This estimate may, though, be too low because it fails to take into account the expectation of GDP losses, correctly measured, that human actions, such as war and ethnic strife might bring to the world.

Total endowment in the first period, $E_1 = \sum_{t=1}^{t_1} e_t$ and in the second period $E_2 = \sum_{t=t_1+1}^{300} e_t$. When $t_1 = 50$ years, average annual income in the first period is very close to current levels ($E_1/t_1 = 0.9985$). For the second period, average annual income is not heavily affected in the moderate state ($h = E_2/t_2 = 0.9787$) but in the severe state drops by just over 11% ($l = E_2/t_2 = 0.8885$) compared to the current level. In sensitivity analysis below we also consider the more draconian case when $l = 0.8$.

Since there are no within-period changes in information, this implies that the optimal consumption level remains constant within time periods, but will change from period 1 to period 2. We denote the annual consumption levels by c_1 and c_2, and note that the budget constraint is $t_1 c_1 + t_2 c_2 = E_1 + E_2$. The optimisation problem facing the agent is directly analogous to that described in the theoretical section above. In period 1, endowment is allocated between a risk-free zero interest rate bank account and consumption. The savings decision will be influenced by the signal received. Second period consumption is determined by the realisation of S and the savings decision taken in period 1. If we save \$$b$ in the bank each year in period 1, then period 2 consumption is raised by \$$bt_1/t_2$ in each year.

We report results for a utility function with constant relative risk aversion:

$$U\left(c_t\right) = \frac{c_t^{1-\gamma} - 1}{1 - \gamma}.$$

As the parameter γ increases, so does both the risk aversion, $A = \gamma/c_t$, and the prudence, $P = (\gamma + 1)/c_t$, of the agent. We set $\gamma = 3$. Results for other values of γ, and other classes of utility function, are available on request from the authors. In all cases that we have examined, these are consistent with the theoretical results of the paper and the numerical example presented here.

To determine the optimal level of consumption in the first time period, we use a numerical solver. We report results for $E_{1-\delta}\left[c_1\right] = 0.5\left(c_{1G}^* + c_{1B}^*\right)$ and $E_{1-\delta}\left[\Psi\right] = 0.5\left(\Psi_G + \Psi_B\right)$ where c_{1G}^* and c_{1B}^* represent optimal annual period 1 consumption levels contingent on receiving a good and bad signal respectively. Ψ_G and Ψ_B represent expected welfare contingent on these respective signals. We report $E_{1-\delta}\left[\Psi\right]$ in certainty equivalent consumption form, c_{CE}. This variable is defined by $300U\left(c_{CE}\right)$

18

$= 0.5 \left(\Psi_G + \Psi_B \right)$. If consumption were fixed at c_{CE} for the next 300 years, this would give the same welfare as we expect from our possible projected consumption paths. The benefit of a signal, ε, is then expressed in terms of the relative change in certainty equivalent consumption with a signal compared to the case of no signal: $c_{CE} \left(\varepsilon \right) / c_{CE} \left(\varepsilon = 0 \right) - 1$. If this number is positive, then welfare is increased since the agent always prefers more consumption to less.

5.1 Adaptation through consumption smoothing

Figure 5 reports results for $E_{1-\delta} \left[c_1 \right]$ and $c_{CE} \left(\varepsilon \right) / c_{CE} \left(\varepsilon = 0 \right) - 1$ as the strength of the signal changes when $t_1 = 50$ years. These results are consistent with the theoretical results described above. Expected welfare is improved by a stronger signal as it allows the agent to better smooth consumption between periods. The expected level of period 1 consumption also uniformly increases with the strength of the signal.

   [*Insert Figure 5 around here*]

   The effects are of considerable economic significance at the global level. Based on world GDP of \$87.25tn in 2013 (CIA World Factbook 2015), a fully informative good signal ($\varepsilon = 0.3$) compared to no signal increases global welfare by the certainty equivalent of \$16.7bn per year for the next 300 years. Let us stress again that this comes not from either changing future temperature levels, or by reducing our economic exposure to climate change, but instead just by learning something beforehand about the true level of the ECS which enables us to make better consumption and savings decisions.

5.2 Physical adaptation measures against the severe state

In the theoretical section above and the first set of numerical examples, savings were the sole mechanism by which agents are able to smooth consumption between the first and second periods. This subsection introduces a second option for moving resources to the second period. The agent can now choose, in addition to savings, to allocate money over the first t_1 years into a real investment project that partially protects against the severe outcome, but that offers no benefit should the state turn out to be moderate. Such a measure might be, for example, the Dutch enhancing their sea defences to protect against the possibility of very high sea level rises, or in any nation, placing factories in less convenient but more secure locations. Such

19

projects would not alter the evolution of T_t, but they would reduce the economic impact of severe climate change.

Denote by $y \geq 0$ the annual investment in the mitigation project over the first t_1 years. Then the average annual endowment over the second period is unchanged if the state is moderate, but equals l^* if the state is severe, where $l^* = h - (h - l) 0.5^{20y}$. Now $l^* = l$ as required if $y = 0$ and $l^* = h$ if $y = \infty$. Infinite investment – obviously impossible since period 1 has only a finite endowment – in this physical adaptation measure will bring the economic impact of severe temperature changes down to the moderate level. If we invest 1% / 5% / 10% / 20% of current income in the project for the next t_1 years, then we reduce the economic differential between the severe and moderate outcomes compared to the case when there is no physical adaptation by 13% / 50% / 75% / 94% respectively. The residual $b = e_1 - c_1 - y$ is saved in the bank at a zero interest rate.[6]

We again use a numerical solver to choose c_1 and y so as to maximise welfare at $t = 1$ dependent on the signal that we receive. We restrict the agent from borrowing resources against the future. In Figure 6 we report $E_{1-\delta}[y]$ and $E_{1-\delta}[b]$; the amount we expect to invest in physical adaptation and save in the bank respectively.

[Insert Figure 6 around here]

Interestingly, both these variables are non-montonic as the signal strengthens. With $\varepsilon = 0$ it is optimal to invest approximately 5% of time 1 endowment in the physical adaptation measure, with nothing saved in the bank. As the strength of the signal increases, physical adaptation declines or increases depending on whether the signal is good or bad. Initially the decline with a good signal outweighs the increase with a bad signal, so the expected level of adaptation investment decreases. However, once the signal reaches a certain strength (approximately $\varepsilon = 0.17$) the level of physical adaptation following a good signal falls to zero. Beyond this point, $E_{1-\delta}[y]$ increases along with the signal strength, driven entirely by higher levels of protective investment following a bad signal.

With no signal, there is no savings; monies are more profitably deployed investing in the physical adaptation measure. The same priorities apply when the signal is bad. However, when the signal is good and once investment in mitigation approaches zero, then savings yield value. For certain moderate signals money is both saved in the bank and invested in the physical adaptation measure, but then the risk-free savings absorb everything invested on behalf of period 2. This savings level then

---

[6]In sensitivity analysis below, we consider the case when $t_1 = 100$ years. We then change the expression for l^* so that we need to invest 2% of income per year over this horizon to halve the impact of severe climate change compared to the moderate outcome.

drops as the signal gets stronger still, as there is less need to smooth consumption between the two time periods. In all cases, investment in the physical adaptation measure is expected to be higher than the level of bank savings as it is, in general, a much more effective way of promoting welfare.

Figure 7 is analogous to Figure 5, addressing the case when physical adaptation is a possible investment.

[*Insert Figure 7 around here*]

Consumption now takes a more complex, non-linear, form compared to when there is no opportunity to invest in physical adaptation. $E_{1-\delta}(c_1)$ initially increases as the signal strengthens, but then declines once ε is greater than approximately 0.08. This result is again driven by behaviour following a bad signal, when the desire to move endowment away from consumption and into the self insurance mechanism gets very strong for greater ε.

As intuition would suggest, expected welfare remains monotonic increasing in the strength of the signal. The effect is an order of magnitude greater in the presence of a physical adaptation measure compared to when there is no project that partly protects against the economic consequences of severe temperature change. Now the expected annual gain at the global level in consumption equivalent terms when going from no signal to a full good signal is approximately \$500bn. The value of early information increases substantially if we can directly protect ourselves against severe outcomes.

5.3   Heterogeneous outcomes

We now incorporate the possibility that not everyone will be equally affected by a severe outcome. If the state of the world is moderate, then the total endowment over the period $t \in [t_1 + 1, 300]$ is $E_2/t_2 = h$ with certainty. However, if climate change is severe then, with 5% probability, $E_2/t_2 = 0.7l$. This reflects the fact that some members of the population are likely to be much more severely affected by extreme climate change than others and we are currently unable to determine whether or not we are in the high-risk group. Alternatively, we might posit that individuals are saving or self insuring for the next generation, and care about all its members equally. For the 95% of the population who are not affected, $E_2/t_2 = 1.0158l$. This keeps the economy-wide average income level in the severe state the same as in the homogeneous agent example. l^* takes the same form as before for both the 95% and 5% groups. Thus, a 5% endowment spend over the next $t_1 = 50$ years will halve the

21

difference in income between the moderate and severe states when compared to the no insurance case.

Both in the presence and absence of a protective project, the broad shapes of expected consumption, welfare and savings follow the patterns described in Figures 5-7. When physical adaptation is not possible, $t = 1$ expected consumption increases as the signal gets stronger and expected welfare increases in signal strength. Further, the relative benefit of the full good signal when compared to no signal also now rises. The annual certainty equivalent consumption level globally rises from \$16.7bn for the homogeneous agent model to \$23.4bn when there are unequal outcomes.

In the presence of a physical adaptation measure, expected consumption at $t = 1$ decreases slightly compared to the homogeneous agent model. The reduced consumption is primarily transferred into the protective project. We invest more in physical adaptation with stronger good signals than in the homogeneous agent case, resulting in the turning points in expected insurance investment and expected consumption being slightly further to the right than in Figures 6 and 7.

With the potential to self insure, the annual certainty equivalent benefit from a full good signal rises from \$499bn when all individuals are equally affected by climate change to \$528bn in a heterogeneous agent environment. This is clearly a major societal gain, and it comes even though there is no reduction in future climate change itself.

Table 1 summarises the gains in welfare, $c_{CE}(\varepsilon)/c_{CE}(\varepsilon = 0) - 1$, for sixteen models when receiving the full good signal versus no signal. These are unit combinations of four different frameworks: (i) $t_1 = 50$ years and $t_1 = 100$ years; (ii) l calibrated as described above and $l = 0.8$, or average income is 80% per year of current endowment in the second period if the state is severe; (iii) homogenous and heterogeneous agent models, and; (iv) bank savings only and bank savings plus the potential to employ the physical adaptation measure.

[*Insert Table 1 around here*]

In all cases, the signal improves welfare, as expected. In general, welfare is improved more when physical adaptation measures are available, income levels are low in the severe state, and agents have heterogeneous incomes and do not know whether they will be rich or poor.

6   Conclusion

Climate scientists have good reason to feel discouraged. Policy makers may pay strong lip service to their warnings, but they take modest actions in response. Advances in the science have also disappointed: findings have gained little precision in decades, and while experts agree on certain aspects of the climate science, such as predictions of global averages, wide variation and occasionally strong disagreement remains about other aspects of the climate change problem. Localised climate predictions, the relationship between emissions and climate, the pathway of emissions, the damages that emissions cause; all of these are subject to huge uncertainty and disagreement. While some of these uncertainties are likely to be irreducible, fortunately, in key areas, some are likely to be significantly reduced. As long as scientific research continues, some of Nature's secrets will inevitably be revealed, uncertainties at least partially resolved, along with the potential for disagreement. Yet, what would be the value of such an advance in the science if policy makers do not respond?

This article addresses this question and provides a different and supplementary justification for a vigorous climate science research effort: better predictions on the consequences of climate change will lead to better decisions on adaptation.

The intuition behind this result is as follows. If future climate change will be severe, GDP will be significantly impaired and major capital losses will be incurred. If climate change is only moderate, the losses will be much less. The welfare that we can expect when confronted by such uncertainty depends on the information we have about the likelihood of severe and moderate climate change, and how we use this information in making our adaptation decisions. Our welfare will therefore also depend on how flexible our adaptation strategies are. Those we consider are saving for an impaired tomorrow and physical adaptation measures, such as building seawalls or locating facilities in less desirable but less vulnerable locations.

Better predictions on the probabilities of severe and moderate consequences will raise expected welfare by improving adaptation decisions. Even when we are in a constrained world in which the only adaptation decision concerns saving for an uncertain future, better predictions raise expected welfare by allowing more effective consumption smoothing. When physical adaptation measures are also available, the prospect of improved signals is valued even higher. In essence, a better signal allows us to find the correct balance between damage limitation investments, consumption smoothing and saving, and tailor the adaptation to the effects of climate change in different future states of the world.

Given the renewed prominence of adaptation in the high-level negotiations on climate change, this is at the very least a morale boosting result for climate scientists.

There is good reason to provide more refined scientific information about climate change at the level of those who inevitably must adapt.

funding. We have received no funding for this work.

conflict. We have no conflicts of interest.

References

[1] IPCC 2014. Summary for policymakers. In *Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field CB, Barros VR, Dokken DJ, Mach KJ Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, and White LL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and NewYork, NY, USA, 1−32.

[2] IPCC 2013. *Intergovernmental Panel on Climate Change Fifth Assessment Report, Final Synthesis Report for Policy Makers.*

[3] IPCC 2007. *Intergovernmental Panel on Climate Change Fourth Assessment Report, Working Group I.* http://www.ipcc.ch/index.htm.

[4] Copenhagen Accord 2009. FCCC/CP/2009/11/Add.1 See http:/unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf.

[5] Pielke Jr R, Prins G, Rayner S, Sareqitz D 2007. Lifting the taboo on adaptation, *Nature*, **445**, 8.

[6] Barrett S 2003. *Environment and Statecraft: The Strategy of Environmental Treaty-Making*, Oxford University Press, Oxford.

[7] Barrett S 2005. The theory of international environmental agreements, in: Maler KG and Vincent J (Eds.), *Handbook of Environmental Economics*, vol. 3, Elsevier, Amsterdam, 1457−1516.

[8] Finus M 2001. *Game Theory and International Environmental Cooperation*, Edward Elgar, Cheltenham, UK.

[9] Wagner UJ 2001. The design of stable international environmental agreements: economic theory and political economy, *Journal of Economic Surveys,* **15**, 377−411.

[10] Barrett S 2013. Climate treaties and approaching catastrophes, *Journal of Environmental Economics and Management*, **66**, 235–250.

[11] Groom B, Gatti JRJ, Goeschl T, Swanson T 2012. Bargaining over global public goods. Chapter 12 In: *Global Environmental Commons: Analytical and Political Challenges in Building Governance Mechanisms*, Edited by Brousseau E, Dedeurwaerdere T, Jouvet P-A and Willinger M, Oxford University Press, Oxford, UK.

[12] Kahn M 2014. Climate change adaptation: Lessons from urban economics. NBER Working Paper 20716, National Bureau of Economic Research http://www.nber.org/papers/w20716

[13] Wolfram C, Shelef O, Gertler PJ 2012. How will energy demand develop in the developing world?. NBER working paper 17747. National Bureau of Economic Research.

[14] Moss RH, Meehl GA, Lemos MC, Smith JB, Arnold JR, Arnott JC, Behar D, Brasseur GP, Broomell SB, Busalacchi AJ, Dessai S, Ebi KL, Edmonds JA, Furlow J, Goddard L, Hartmann HC, Hurrell JW, Katzenberger JW, Liverman DM, Mote PW, Moser SC, Kumar A, Pulwarty RS, Seyller EA, Turner II BL, Washington WM, Wilbanks TJ, 2013. Hell and high water: Practice-relevant adaptation science, *Science*, **342**, 696−698.

[15] Roy D, Zeckhauser R 2015. Grappling with ignorance: Frameworks from decision theory, lessons from literature, *Journal of Benefit Cost Analysis*, forthcoming.

[16] Millner A 2012. Climate prediction for adaptation: Who needs what?, *Climatic Change*, **110**, 143−167

[17] Roe GH, Baker MB 2007. Why is climate sensitivity So unpredictable?, *Science*, **318,** 629−33.

[18] Seo NJ, Mendelsohn R 2012. An analysis of crop choice: Adapting to climate change in South American farms, *Ecological Economics,* **67**, 109−116.

[19] Patrinos A, Bamzai A. 2005. Policy needs robust climate science, *Nature,* **438**, 285.

[20] Epstein LG 1980. Decision making and the temporal resolution of uncertainty, *International Economic Review*, **21**, 269−83.

[21] Gollier C, Jullien B, Treich N 2000. Scientific progress and irreversibility: an economic interpretation of the Precautionary Principle, *Journal of Public Economics*, **75**, 229−253.

[22] Kelly DL, Kolstad CD 1999. Bayesian learning, growth, and pollution, *Journal of Economic Dynamics and Control,* **23**, 491−518.

[23] Dessai S, Hulme M, Lempert R, Pielke Jr R 2007. Climate prediction: a limit to adaptation? Ch 5 in *Adapting to Climate Change: Thresholds, Values, Governance*, eds. Adger WN, Lorenzoni I and O'Brien KL. Cambridge University Press, Cambridge.

[24] Millner A, Dietz S, Heal G 2013. Scientific ambiguity and climate policy. *Environmental and Resource Economics,* **55,** 21−46.

[25] Hall JW, Fu G, Lawry J 2007. Imprecise probabilities of climate change: aggregation of fuzzy scenarios and model uncertainties, *Climatic Change,* **81**, 265−281.

[26] Weitzman ML 2010. What is the damages function for global warming, and what difference might it make?. *Climate Change Economics,* **1**, 57−69.

[27] Pindyck RS 2013. The climate policy dilemma. *Review of Environmental Economics and Policy,* **7**, 219−237.

[28] Nordhaus W 2008. *A Question of Balance.* Princeton Press.

[29] Freeman MC, Wagner G, Zeckhauser R 2015. Uncertainty, Scientific advances o n Climate Change, and Consumption Decisions, *Philosophical Transactions of the Royal Society A.* This issue of the journal.

[30] Wagner G, Weitzman ML 2015. *Climate Shock: the Economic Consequences of a Hotter Planet.* Princeton University Press.

[31] Thomas R K, Arguez A, Huang B, Lawrimore JH, McMahon JH, Menne MJ, Peterson TC, Vose RS, Zhang HM, 2015. Possible artifacts of data biases in the recent global surface warming hiatus, *Science* **348**, 6242, 1469−1472.

[32] Meehl GA, Arblaster JM, Fasulio JT, Hu A, Trenberth KE 2011. Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. *Nature Climate Change*, **1**, 360−364.

[33] Risbey JS, Lewandowsky S, Langlais C, Monselesan DP, O'Kane TJ, Oreskes N 2014. Well-estimated global surface warming in climate projections selected for ENSO phase. *Nature Climate Change*, **4**, 835−840.

[34] Millner A 2011. Do probabilistic expert elicitations capture scientists' uncertainty about climate change?, *Climatic Change*, **116**, 427−436.

[35] Smith LA 2007. *Chaos: A Very Short Introduction*, Oxford University Press, Oxford, UK.

[36] Zickfeld K, Morgan MG, Frame DJ, Keith DW 2010. Expert judgments about transient climate response to alternative future trajectories of radiative forcing. *Proceedings of the National Academy of Sciences*, **107**, 12451−12456.

[37] Vogel C, O'Brien K 2006. Who can eat information? Examining the effectiveness of seasonal climate forecasts and regional climate-risk management strategies. *Climate Research*, **33**, 111−122.

[38] Botzen WJW, Aerts JCJH, van den Bergh JCJM 2009. Willingness of homeowners to mitigate climate risk through insurance. *Ecological Economics*, **68,** 2265−2277.

[39] Huppert HE, Sparks RSJ 2006. Extreme natural hazards: population growth, globalization and environmental change. *Philosophical Transactions of the Royal Society A,* **364**, 1875−1888.

[40] Stern N 2007. *The Stern Review of the Economics of Climate Change*, Cambridge University Press, Cambridge, UK.

[41] Adger NW, Paavola J, Huq S, Mace MJ 2008. *Fairness in Adaptation to Climate Change*. MIT Press, Cambridge, Massachusetts.

[42] Huq S, Rahman A, Konate M, Sokona Y, Reid H 2004. Mainstreaming adaptation to climate change in Least Developed Countries (LDCs). *Climate Policy*, **4**, 25−43.

[43] CAF 2007. The Cancun Adaptation Framework, http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf

[44] Fankhauser S, Smith J, Tol R 1999. Weathering climate change: some simple rules to guide adaptation decisions, *Ecological Economics,* **30**, 67−78.

[45] Konrad, KA, Thum MP 2012. The role of economic policy in climate change adaptation. Working Paper of the Max Planck Institute for Tax Law and Public Finance No. 2012−08,http://ssrn.com/abstract=2158578

[46] Gorst A, Groom B, Dehlavi A 2015. Crop productivity and adaptation to climate change in Pakistan. Grantham Research Institute on Climate Change and the Environment Working paper No. 189.

[47] Di Falco S, Veronesi M, Yesuf M 2011. Does adaptation to climate change provide food security? Micro evidence from Ethiopia. *American Journal of Agricultural. Economics,* **93**, 829−846.

[48] Ridgwell A, Freeman C, Lampitt R (eds) 2012. *Geoengineering: taking control of our planet's climate?, Philosophical Transactions of the Royal Society A,* **370**, 1974, HREF

[49] Leland HE 1968. Saving and uncertainty: The precautionary demand for saving, *Quarterly Journal of Economics,* **82**, 465−473.

[50] Kimball MS 1990. Precautionary saving in the small and in the large, *Econometrica,* **58**, 53−73.

[51] Pindyck RS 2012. Uncertain outcomes and climate change policy. *Journal of Environmental Economics and Management,* **63**, 289−303.

[52] Jawitz JW 2004. Moments of truncated continuous univariate distributions. *Advances in Water Resources,* **27**, 269−281.

[53] Weitzman ML 2009. On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics,* **91**, 1−19.

[54] Pindyck RS 2013. The climate policy dilemma. *Review of Environmental Economics and Policy,* **7**, 219−237.

[55] Marshak J 1971. Economics of Information Systems, *Journal of the American Statistical Association,* **66**, 192−219.

[56] Hirshleifer J, Riley JG 1979. The analytics of uncertainty and information - An expository survey. *Journal of Economic Literature,* **17**, 1375−1421.

7   Appendix

In this appendix we prove Results 1 and 2.

7.1   Result 1

If we receive the full signal at $t = 1$, then future endowment is fully known. In this case, given that the utility function is concave, it is optimal to perfectly smooth consumption across time: $c_t = (e_1 + e_2)/2$ for $t = 1, 2$. Therefore the expected welfare at time $t = 1 - \delta$ is:

$$E_{1-\delta}[\Psi] = E_{1-\delta}\left[2U\left(\frac{e_1 + e_2}{2}\right)\right].$$

With no signal, $E_{1-\delta}[\Psi] = \Psi$, since there is no new information. Expectations are the same whether taken at time $t = 1 - \delta$ or $t = 1$. Therefore:

$$E_{1-\delta}[\Psi] = \max_{c_1} U(c_1) + E_{1-\delta}U(e_2 + e_1 - c_1).$$

Undertaking the optimisation gives:

$$U'(c_1^*) = E_{1-\delta}U'(e_2 + e_1 - c_1^*),$$

where c_1^* denotes the optimal consumption level. By Jensen's inequality

$$E_{1-\delta}U'(e_2 + e_1 - c_1^*) \geq U'(E_{1-\delta}[e_2 + e_1] - c_1^*) \qquad U'''(\cdot) \geq 0,$$

where the inequality is strict if and only if $U'''(\cdot) = 0$. Then

$$U'(c_1^*) \geq U'(E_{1-\delta}[e_2 + e_1] - c_1^*) \qquad U'''(\cdot) \geq 0. \tag{1}$$

Now notice that if

$$c_1^* = E_{1-\delta}\left[\frac{e_2 + e_1}{2}\right], \tag{2}$$

then the left- and right-hand sides of equation (1) are equal. This is the expected level of time 1 consumption under a full signal. When equation (1) is an inequality, c_1^* must be less than the right hand side of equation (2) because $U''(\cdot) < 0$. This proves Result 1.2.

To establish Result 1.1, note that c_1^* cannot be equal to both $(e_1 + l)/2$ and $(e_1 + h)/2$, the optimal consumption levels at time $t = 1$ following the receipt of a bad and good signal respectively. Since consumption decisions under no signal do not optimise expected welfare in the presence of a signal, the result follows immediately. This is also a special case of Result A2.4 below.

7.2   Result 2

We prove four sub-results.   From them Result 2 in the body of the text follows immediately

Result A2.   If we receive a partial signal in the interval $[1 - \delta, 1]$, then:

A2.1 Let σ_1^2 denote the volatility of time 2 endowment, e_2, as calculated at time 1. Let $\sigma_1^2 = \sigma_G^2$ if the signal received is good and $\sigma_1^2 = \sigma_B^2$ if the signal received is bad.   Then $\sigma_G^2 < \sigma^2$ if $\varepsilon_G > 1 - 2p$ and $\sigma_B^2 < \sigma^2$ if $\varepsilon_B > 2p - 1$, where σ^2 is the volatility of time 2 endowment calculated at time $1 - \delta$.   In addition, the expectation of σ_1^2 as calculated at time $1 - \delta$, $\pi\sigma_G^2 + (1 - \pi)\sigma_B^2$, is monotonic decreasing in the strength of the signal, ε_G.

A2.2 If prudence is zero, then the expectation at time $t = 1 - \delta$ of time 1 consumption, $E_{1-\delta}[c_1]$, is unaffected by the anticipation of any signal.

A2.3 If prudence is positive, then the stronger the signal that we will receive (the greater is ε_G), the higher is our expectation of time 1 consumption, $E_{1-\delta}[c_1]$.

A2.4 For all monotonic increasing and concave utility functions, the stronger the signal that we will receive, the larger is the expected welfare as calculated at time $t = 1 - \delta$; $E_{1-\delta}[\Psi]$

Proof. Use the notation $\mu = ph + (1 - p)l$ and $\sigma^2 = p(h - \mu)^2 + (1 - p)(l - \mu)^2$ to denote the mean and variance of time 2 endowment conditional on the information available at $t = 1 - \delta$.   It is straightforward to verify that $\sigma^2 = p(1 - p)(h - l)^2$. Similarly, let $\mu_G = (p + \varepsilon_G)h + (1 - p - \varepsilon_G)l$, $\mu_B = (p - \varepsilon_B)h + (1 - p + \varepsilon_B)l$, $\sigma_G^2 = (p + \varepsilon_G)(h - \mu_G)^2 + (1 - p - \varepsilon_G)(l - \mu_G)^2$, and $\sigma_B^2 = (p - \varepsilon_B)(h - \mu_B)^2 + (1 - p + \varepsilon_B)(l - \mu_B)^2$ denote the means and variances of time 2 endowment conditional on receiving the good (G) and bad (B) signal in the interval $[1 - \delta, 1]$.   It is again straightforward to verify that, for $\theta_G = \varepsilon_G(h - l)$ and $\theta_B = \varepsilon_B(h - l)$:

$$
\begin{aligned}
\mu_G &= \mu + \theta_G \\
\mu_B &= \mu - \theta_B \\
\sigma_G^2 &= \sigma^2 + \varepsilon_G(1 - 2p - \varepsilon_G)(h - l)^2 \\
\sigma_B^2 &= \sigma^2 - \varepsilon_B(1 - 2p + \varepsilon_B)(h - l)^2.
\end{aligned}
$$

$\sigma_G^2 < \sigma^2$ if and only if $1 - 2p - \varepsilon_G < 0$.   For $\sigma_B^2 < \sigma^2$, $1 - 2p + \varepsilon_B > 0$.   It is also straightforward to verify that:

$$
\pi\sigma_G^2 + (1 - \pi)\sigma_B^2 = \sigma^2 - \frac{\pi}{1 - \pi}\varepsilon_G^2(h - l)^2,
$$

30

which decreases as ε_G increases. This proves Result A2.1.

Now consider the welfare function at time 1 conditional on receiving the good signal, Ψ_G. Again, $E_G[\cdot]$ denotes the expectation taken at time $t = 1$ conditional on the good signal.

$$\Psi_G = \max_{c_1} U(c_1) + E_G[U(e_1 + e_2 - c_1)].$$

Define the variable υ as follows. Let $e_2 = \mu_G + \upsilon = \mu + \theta_G + \upsilon$ for $\upsilon = h - \theta_G - \mu$ or $\upsilon = l - \theta_G - \mu$ depending on which state of the world occurs at $t = 2$. Undertaking the optimisation and using c_{1G}^* to denote optimal consumption at time 1 conditional on receiving the good signal:

$$U'(c_{1G}^*) = E_G[U'(e_1 + \mu + \theta_G + \upsilon - c_{1G}^*)]. \tag{3}$$

First consider the case when $U'''(\cdot) = 0$. Then, by Jensen's inequality:

$$U'(c_{1G}^*) = U'(e_1 + \mu + \theta_G - c_{1G}^*),$$

showing immediately that $c_{1G}^* = (e_1 + \mu + \theta_G)/2$. By an analogous argument, if we receive the bad signal, $c_{1B}^* = (e_1 + \mu - \theta_B)/2$. This results in

$$
\begin{aligned}
E_{1-\delta}[c_1] &= \pi c_{1G}^* + (1 - \pi) c_{1B}^* \\
&= \frac{e_1 + \mu}{2} + \frac{\pi \theta_G - (1 - \pi) \theta_B}{2} \\
&= \frac{e_1 + \mu}{2} + \frac{\pi \varepsilon_G - (1 - \pi) \varepsilon_B}{2} (h - l),
\end{aligned}
$$

and, through the relation between ε_G and ε_B, this is equal to $(e_1 + \mu)/2$ for any potential signal that we might receive. This proves Result A2.2.

With $U'''(\cdot) > 0$, we can view $U'(\cdot)$ as a pseudo-utility function that is monotonic decreasing and convex. Again, suppose that we have received the good signal at $t = 1$. Note that $Var(\upsilon) = \sigma_G^2$ and, as usual, $c_{2G} = e_1 + e_2 - c_{1G} = e_1 + \mu + \theta_G + \upsilon - c_{1G}$. Using a standard Pratt-Arrow approach, we can replace this stochastic consumption with the expected consumption level $e_1 + \mu + \theta_G - c_{1G}$ minus a prudence adjustment ψ_G:

$$
\begin{aligned}
E_G[U'(e_1 + \mu + \theta_G + \upsilon - c_{1G})] &= U'(e_1 + \mu + \theta_G - c_{1G} - \psi_G) \\
\psi_G &\approx -\frac{1}{2}\sigma_G^2 \frac{U'''(e_1 + \mu + \theta_G - c_{1G})}{U''(e_1 + \mu + \theta_G - c_{1G})} \\
&= \frac{1}{2}\sigma_G^2 P_G,
\end{aligned}
$$

31

where $P_G = -U''' \left(e_1 + \mu + \theta_G - c_{1G} \right) / U'' \left(e_1 + \mu + \theta_G - c_{1G} \right)$ is the prudence of consumption at time 2 in the good state if endowment equals the expected value at this time conditional on the signal received at $t = 1$.

Given this, from equation 3:

$$c_{1G}^* = \frac{e_1 + \mu + \theta_G - \psi_G}{2}.$$

Similarly,

$$c_{1B}^* = \frac{e_1 + \mu - \theta_B - \psi_B}{2}$$

$$\psi_B = \frac{1}{2}\sigma_B^2 P_B.$$

Therefore, under the assumption that prudence is approximately constant at value P over the range of interest:

$$
\begin{aligned}
E_{1-\delta}\left[c_1\right] &= \pi c_{1G}^* + (1 - \pi) c_{1B}^* \\
&= \frac{e_1 + \mu}{2} + \frac{\pi \varepsilon_G - (1 - \pi) \varepsilon_B}{2} (h - l) - \frac{\pi \sigma_G^2 + (1 - \pi) \sigma_B^2}{4} P \\
&= \frac{e_1 + \mu}{2} - \left(\sigma^2 - \frac{\pi}{1 - \pi} \varepsilon_G^2 (h - l)^2 \right) \frac{P}{4}.
\end{aligned}
$$

The final term gets less negative the stronger is the signal ε_G. A more powerful signal increases expected time 1 consumption provided the agent is prudent. This proves Result A2.3.

Result A2.4 follows immediately from, for example, [55] and [56]. A less clear signal can be treated as a "garbled" interpretation of a stronger signal. As an example, consider a world where unconditionally the moderate and severe outcomes at $t = 2$ are equally likely. Assume that, if we receive the stronger good (bad) signal at $t = 1$, then the probability of having the moderate outcome is revised to 70% (30%). A good (bad) weaker signal instead revises these probabilities to 60% (40%).

The weak signal can be imaged as a world where we receive the strong signal, but where it may be misread or "garbled". In the example, imagine that there is a 25% chance that we will mis-read a true good (bad) strong signal as being bad (good) instead. Then on receiving a truly good strong signal, there is a 75% probability that this will be interpreted correctly as a good strong signal and a 25% that it will be mistakenly read as a bad strong signal. The estimated probability of the moderate state occurring at time 2 is 75%*70% +25%*30% = 60% conditional on receiving

32

this garbled signal. Similarly, on receipt of a bad signal, the estimated probability of the moderate state occurring at time 2 is 75%*30% +25%*70% = 40%. The probabilities are identical to those we assign under the weaker signal in the absence of garbling. As the probabilities of the stronger signal bracket the probabilities of the weaker signal, it is generally true that weaker signals can be interpreted as garbled stronger signals.

Under these conditions, as argued by [56] (p. 1397), the stronger signal "must lead to higher utility so long as there is any change in best conditional action under either message". As shown above, optimal consumption levels at $t = 1$ depend on the value of ε_G, so conditional action does depend on the strength of the message. This completes the proof of Result A2.4

8   Figures & Tables

	Savings only		Savings and physical adaptation	
	l calibrated	$l = 0.8$	l calibrated	$l = 0.8$
		$t_1 = 50$ and $t_2 = 250$		
Homogeneous	1.92	9.08	57.21	97.66
Heterogeneous	2.68	10.75	60.60	98.50
		$t_1 = 100$ and $t_2 = 200$		
Homogeneous	3.17	13.52	49.62	80.18
Heterogeneous	4.35	15.90	52.12	80.73

Table 1. Certainty Equivalent Gains in Annual Consumption from a Full Signal (measured in basis points). For the sixteen calibrations considered, this table presents the basis point increase in the certainty equivalent annual consumption level that arises as a consequence of having a full signal rather than no signal at the start of $t = 1$; $c_{CE}(\varepsilon)/c_{CE}(\varepsilon = 0) - 1$. l is the average annual income in the severe state, and is either calibrated as described in the body of the text or is set equal to 80% of current endowment.
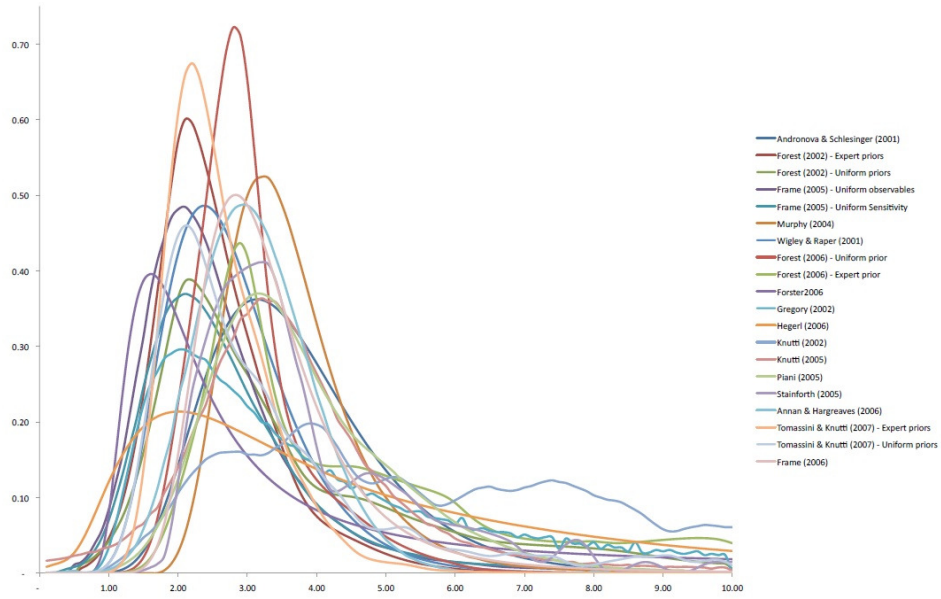
Figure 1. Estimates of Climate Sensitivity Probability Densities. [24]
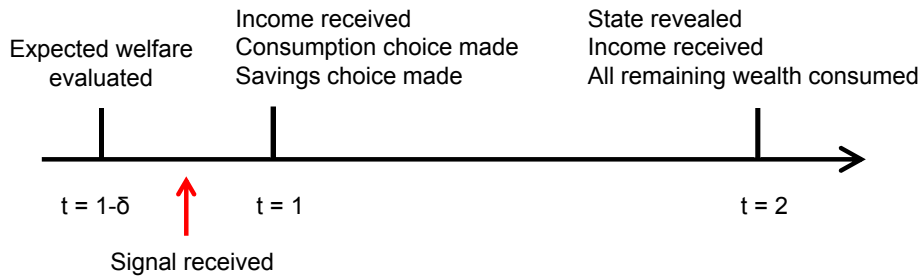
Legend:
- Andronova & Schlesinger (2001)
- Forest (2002) - Expert priors
- Forest (2002) - Uniform priors
- Frame (2005) - Uniform observables
- Frame (2005) - Uniform Sensitivity
- Murphy (2004)
- Wigley & Raper (2001)
- Forest (2006) - Uniform prior
- Forest (2006) - Expert prior
- Forster2006
- Gregory (2002)
- Hegerl (2006)
- Knutti (2002)
- Knutti (2005)
- Piani (2005)
- Stainforth (2005)
- Annan & Hargreaves (2006)
- Tomassini & Knutti (2007) - Expert priors
- Tomassini & Knutti (2007) - Uniform priors
- Frame (2006)

Figure 2. Timeline for Valuation, Decision and Realisation of Uncertainty.
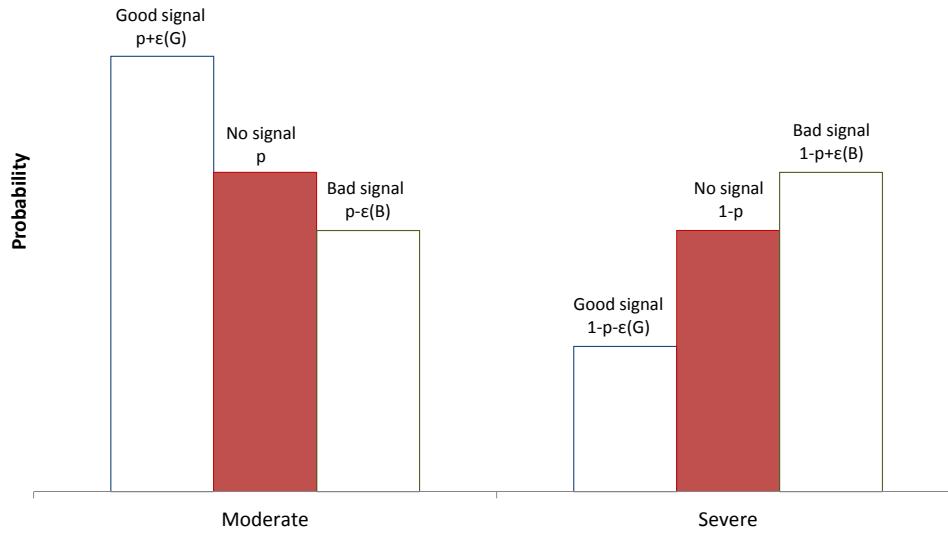
Figure 3. **Illustration of 'Good' signals and 'Bad' signals.** Following the arrival of a good or bad signal prior to $t = 1$, this illustrates the probability of the moderate and severe states occurring at $t = 2$.
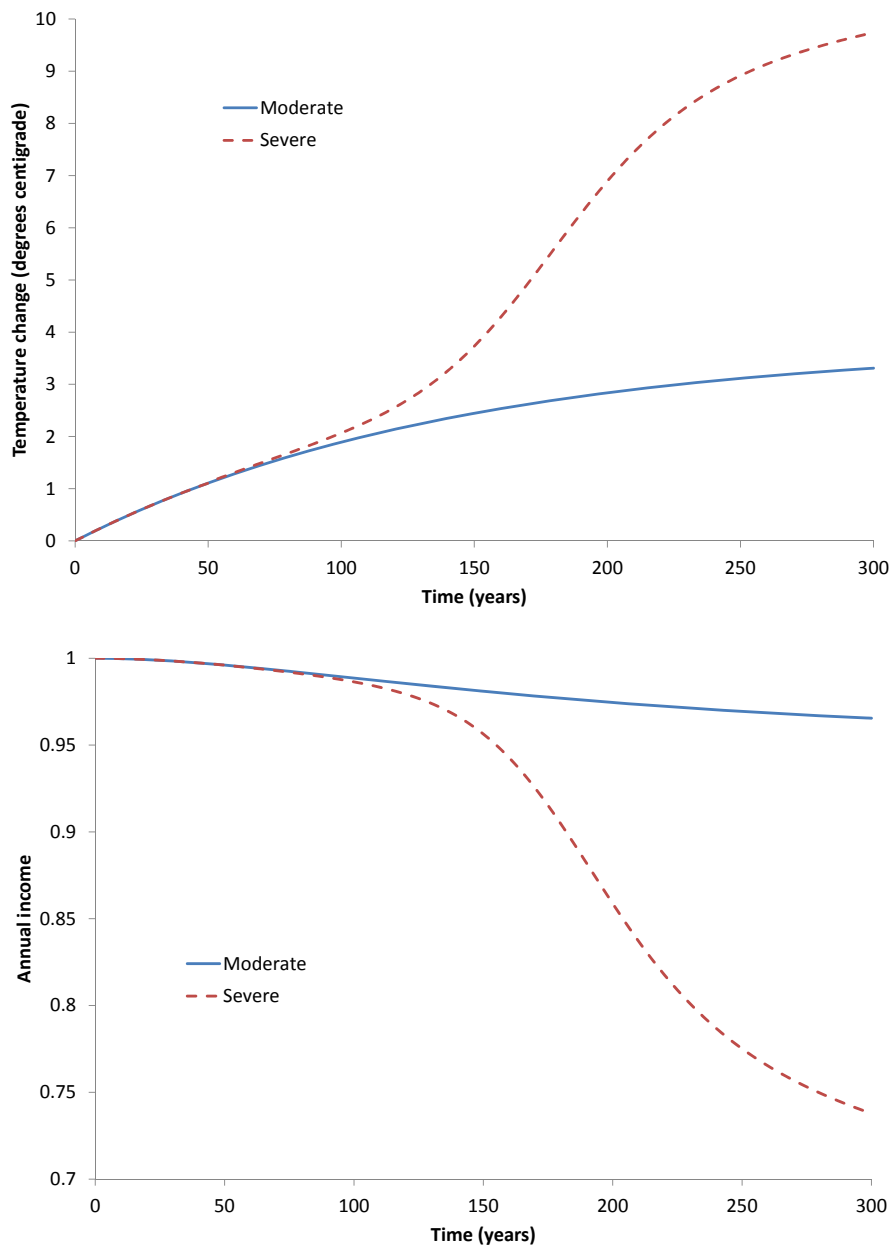
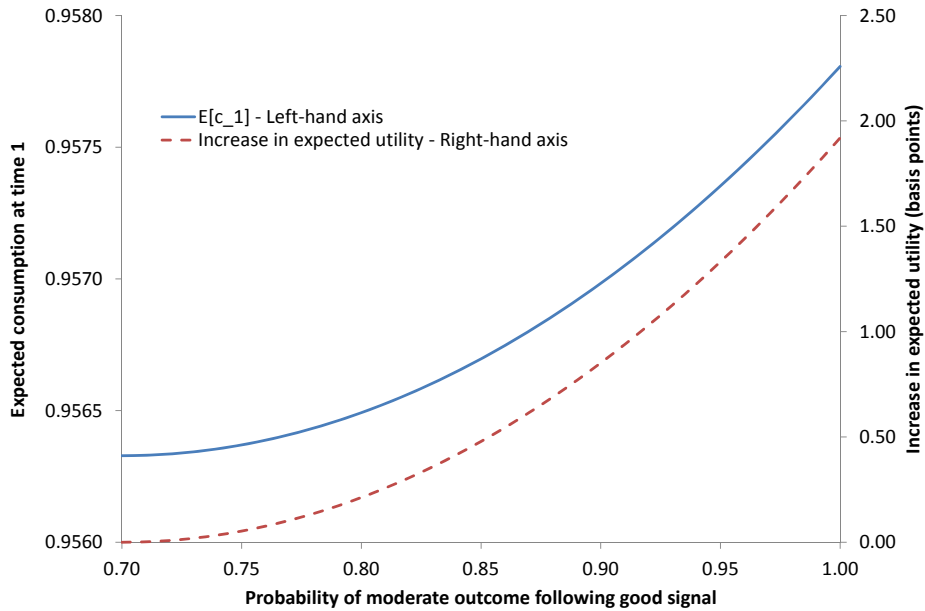**Figure 4.** The Evolution of Temperature Change and Annual Income Under the Moderate and Severe Scenarios.

Figure 5. Gains in Consumption and Expected Utility as Signal Strength Increases. This shows the expectation, as calculated at $t = 1 - \delta$, of $t = 1$ consumption and expected future welfare expressed as a basis point $(1/100^{th}\%)$ increase in the certainty equivalent consumption level (compared to the no signal case) as the strength of a partial signal changes. Endowment over the first t_1 years must be either consumed or saved in a risk-free asset with a zero interest rate.
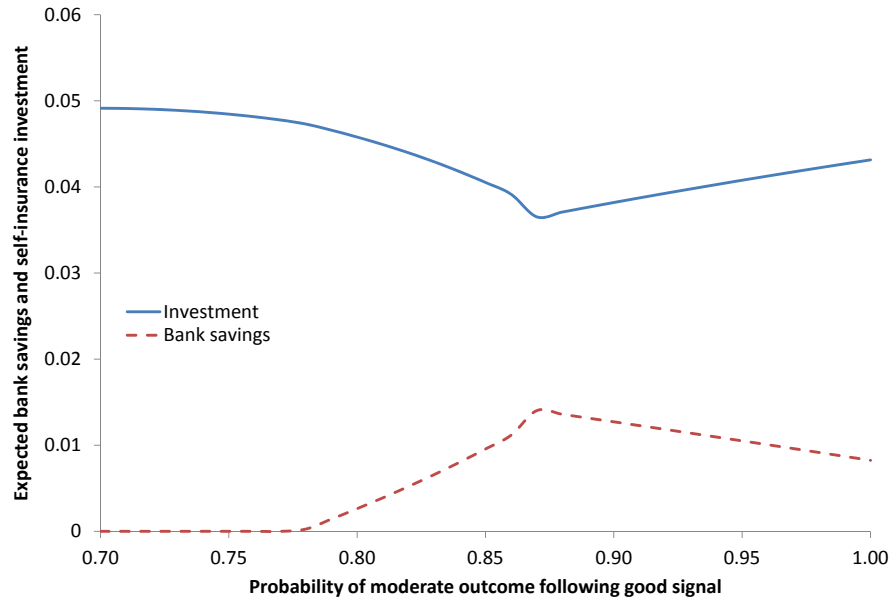
Figure 6. **Investment in Physical Adaptation and Savings as Signal Strength Increases.** This shows the expectation, as calculated at $t = 1 - \delta$, of the levels of investment in the self insurance policy and the risk-free savings opportunity. Endowment at $t = 1$ can be either consumed, saved in a risk-free asset with a zero interest rate, or invested in a physical adaptation project that partially protects against the severe outcome.
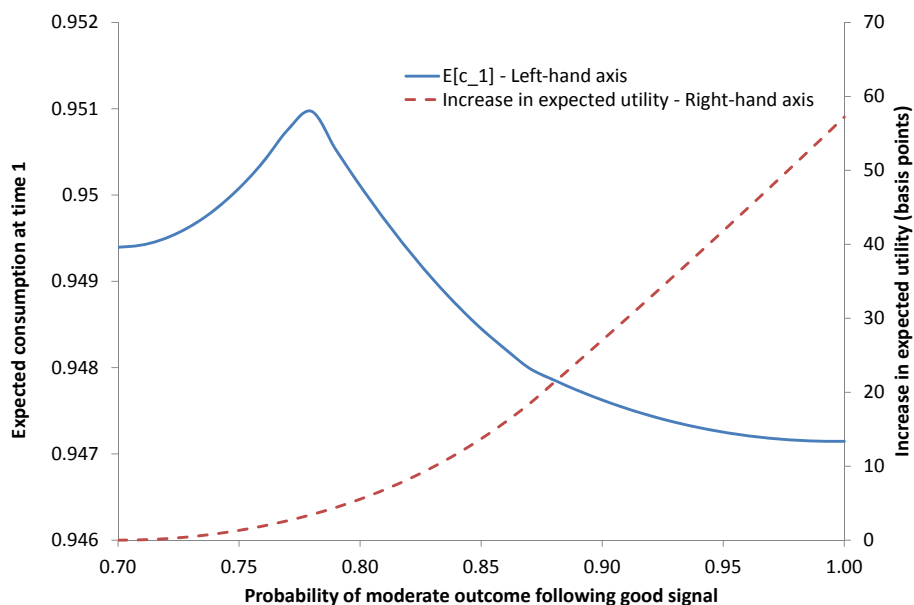
Figure 7. Gains in Consumption and Expected Utility with Physical Adaptation as Signal Strength Increases. Following Figure 5, this shows the expectation, as calculated at $t = 1 - \delta$, of $t = 1$ consumption and expected future welfare expressed as a basis point $(1/100^{th}\%)$ increase in the certainty equivalent consumption level (compared to the no signal case) as the strength of a partial signal changes. Endowment at $t = 1$ can be either consumed, saved in a risk-free asset with a zero interest rate, or invested in a physical adaptation measure that partially protects against the severe outcome.