Climate Change – the Costs of Inaction

Report to Friends of the Earth England, Wales and Northern Ireland

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October 11, 2006

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Executive Summary

This report examines the costs of inaction – the worsening damages that will result from allowing climate change to continue unabated. Economic models have estimated damages as great as US$74 trillion, but even these numbers fail to convey the multiple harms that lie in store for the world. In brief, we find that the first 2° of warming will have many harmful and costly impacts, outweighing the modest potential benefits, for northern countries such as the United Kingdom. Most developing countries will fare even worse, experiencing greater costs and no benefits at all. The first stages of warming already have begun to put essential ecosystems at risk, and will strain the ability of the world's economies and governments to respond.

Beyond 2°, in the second half of this century and later, the effects of further warming – which will certainly occur in the absence of ambitious mitigation efforts – will be much more dangerous, as all potential benefits vanish and all regions suffer steadily increasing harms. The risk of a global catastrophe will increase rapidly as temperatures continue to rise. If nothing is done to slow the process of warming, the grandchildren of today's young adults will inherit a world crippled by food and water shortages, extreme and variable weather, extinctions and other ecosystem damages, and a growing danger of an even more severe catastrophe.

The climate system, and our economic activities that affect it, have enormous momentum. It is not possible to wait until the world begins to get uncomfortably warm, and then suddenly decide to stop. Because of its momentum, a supertanker has to turn off its engines 25 km before it comes to a stop. Likewise, we have to achieve a drastic reduction in carbon emissions several decades before we can bring climate change under control. In other words, we have to take action long before we experience the full severity of the problem. The world as a whole can, just barely, cope with the impacts of the first 2° of warming, but only if there are immediate, large-scale, and creative approaches to international equity and cooperation. The challenge will be to understand the near term damages from climate change as a sign of much worse to come if nothing is done to stop it, while interpreting any limited benefits of the early stages of warming as a temporary windfall, soon to disappear.

Categorizing climate risks

In terms of the predictability of climate risks, the **changes in average conditions** are well understood and quite predictable:

- Higher maximum temperatures and more hot days, higher minimum temperatures and fewer cold days, and a narrower day/night range of temperatures worldwide.
- Higher humidity and more intense storms are expected around the world, and in the mid-latitudes, areas away from coastlines can expect increasingly dry summers.

Scientists' models of climate change predict not only increases in average temperature, but also **increased variability of weather conditions and more extreme events**, including more droughts and floods, more heat waves, more powerful storms:

- Recent climate change has already made extreme heat waves two to four times more likely, and over the next 40 years, extreme heat events will become 100 times more likely than in the late 20th century.
- Climate change is increasing the frequency and intensity of extreme weather, causing a sharp upswing in damages. In 2005, natural catastrophes caused US$220 billion worth of damage worldwide.
- In addition to property damages, there are losses of income for months or years after extreme weather events. The U.S. state of Louisiana, the area hardest hit by the extraordinary hurricanes of 2005, suffered a 15 percent loss of income for the post-hurricane months.

Lurking beyond the problem of extreme weather events is **the risk of a climate catastrophe**.

- Increasing temperatures raise the probability of collapse, followed by rapid melting, of gigantic ice sheets in Greenland and/or Antarctica, which could cause a devastating sea-level rise.
- Even more moderate melting in Greenland and the Arctic could potentially disrupt the circulation of ocean currents in the North Atlantic, which is responsible for the relatively mild temperatures of Northern Europe.
- In addition, there is a danger that gradual warming could lead to abrupt releases of large quantities of the methane – a greenhouse gas more powerful than carbon dioxide – that is currently stored in frozen, but quickly thawing, tundra; this would greatly accelerate the process of warming.

Table ES1 below summarizes the likely impacts of climate change by an incremental increase in average global temperature. It should be emphasized that all predictions of emissions scenarios and likely temperature changes are estimates, not exact figures. None of the temperatures and effects described in Table ES1 represent precise thresholds or discontinuities; rather, the effects become increasingly likely, and ominous, as temperatures and CO_2 levels rise.

Three types of benefits from moderate warming have been proposed, all of which are discussed in this report: slightly warmer weather and higher levels of CO_2 could increase yields in temperate agriculture; warmer weather could decrease total temperature-related mortality, particularly among the elderly in cold countries; and people in cold countries might simply enjoy life more if it were a little bit warmer. Even if we were to accept the existence of any of these benefits, the complacent conclusion that global warming might not be so bad is still unfounded for at least three reasons:

- The effects of variable and extreme weather events are bad for everyone, North and South – and outweigh any potential benefits.
- The average effects of even the earliest stages of warming are bad for developing countries.
- Beyond 2°, all regions will suffer from the worsening average effects of climate change, along with intensifying extremes and rising risks of catastrophe.

Table ES1. Likely Impacts of Climate Change

Temperature rise by 2100	**Likelihood**	**Effects**
0.6º	*Has already occurred*	• More frequent extreme weather events, more floods and more droughts, more heat waves; • A slow pole-ward migration of plant and animal species, with less mobile and less adaptable species increasingly at risk of extinction.
2º	*Will be exceeded unless there are immediate and vigorous efforts to reduce emissions*	• More tropical diseases over a wider geographical area; • Decreased crop yields in the developing world and, as a result, widespread hunger; • Many communities facing serious water stress and widespread droughts; • A total loss of arctic ice and the extinction of many arctic species; • A near total loss of coral reefs due to "bleaching;" • And perhaps the onset of the complete melting of the Greenland ice sheet, slowly but unstoppably raising sea levels by 7 m over the course of the next 3000 years.
3º	*Extremely likely without major efforts at reducing emissions*	• Decreasing crop yields in the developed world and decreasing world food supplies; • Widespread species extinctions and desertification; • The wholesale collapse of the Amazon ecosystem; • The complete loss of all boreal and alpine ecosystems.
4º	*Likely with no efforts at reducing emissions*	• Entire regions will have no agricultural production whatsoever and the melting of the West Antarctic ice sheet will gradually increase sea levels by 5 to 6 m (in addition to the increase from the loss of the Greenland ice sheet).
>4º		• There is a 50-50 chance that the ocean's circulation system will shut down, removing the crucial currents that warm and stabilize the climate of Northern Europe.

Source: (IPCC 2001b; IPCC 2001a; Watkiss et al. 2005). The climate change scenarios cited here are B1 (2.3º in 2100), B2 (3.0º), and A1F1 (4.8º) from IPCC 2001.

The UK in 2050: hot, and getting hotter

UK temperatures, as with most countries in the higher latitudes, are predicted to increase by slightly more than the global mean. Relative to early 20th century levels, average British temperatures have already increased by about 1º, and are expected to increase by a total of 3 to 4.5° by 2080.

- By 2020, twice as many days will exceed 25º in London each summer; by 2050, there will be three to five times as many hot days.
- Extreme storms and flooding in the UK are also likely to become more frequent and more severe. By 2080 the annual cost of flooding in the UK could be £22 billion, or fifteen times what it is today.
- If, as a result of warming trends, the UK matches the U.S. level of air conditioning use, another 56 billion kilowatt hours of electricity (a 16 percent increase in UK electricity generation) would be required, with a retail cost of about £5 billion per year.

Impacts of Climate Change

Agriculture

Agriculture is one of the few sectors in which some analysts have predicted short-term benefits to climate change. Both the scale and the duration of these benefits are debatable. But even the rosiest estimates show increased yields only in northern countries, lasting only during the first 2º of climate change. Even then, extreme weather events could reduce or eliminate any gains.

Many studies estimate that warmer temperatures and CO_2 fertilization will increase agricultural yields through 2050 or so. However, recent research suggests that even minute increases in ground-level ozone – a pollutant created by fossil fuel combustion – can reduce plant growth. Since increases in CO_2 levels, resulting from fossil fuel use, will be accompanied by increases in ozone, some or all of the benefits of CO_2 fertilization may be offset by the damages from ozone. This factor has not yet been incorporated into most agricultural forecasts.

- Some researchers predict a short-term global increase, while others estimate that global agricultural yields will decrease by 1 to 2 percent even before 2050.
- Predictions of gains in agricultural yields are best case scenarios, leaving out factors such as: increased variability of temperature and precipitation that will be bad for all crops; weeds, pests and diseases that are likely to expand their range as the world grows warmer; and farmers who may not adapt perfectly and rapidly to changing conditions.
- Much worse is in store beyond 2050, or beyond 2° warming, as any existing benefits start to disappear. As climate change continues, its effects on agriculture will turn negative everywhere, as rising temperatures and variable, extreme weather reduces crop yields, while the opportunities to adapt, to introduce new crop varieties, and to move agriculture into formerly colder areas, are progressively exhausted.

Industry and infrastructure

Climate change's most severe and costly impacts on industry and infrastructure will result from the rising tide of extreme weather events such as storms, floods, and heat waves. Worsening weather will place new strains on urban infrastructure, requiring expensive new investments.

- Estimates of the property damage caused by Hurricane Katrina in 2005 range as high as US$135 billion.
- Episodes of extreme temperatures, such as the recent European heat waves, will increase both the demand for energy and the cost of providing it.
- Increased electricity generation means an increased use of water resources, at exactly the time when other demands for water will peak. Both fossil fuel and nuclear power plants require huge quantities of cooling water, in many cases withdrawn from rivers and estuaries.

Fresh water

Climate change also has an impact on the quality and quantity of fresh water supplies sufficient for drinking, sanitation, agricultural, and industrial needs. Higher global average temperatures, and even larger increases to temperature in certain regions, will result in more rapid evaporation and the need for more intense irrigation. The most vulnerable areas will be those that are already water-stressed and the developing regions that lack water management systems that could act as buffers to increasing variability in water quality and quantity.

- In some areas, floods will increase in scale and frequency, while in other areas droughts will become more common and more prolonged. Shifting rain patterns will mean more stream-flow in the winter, just as summer demand for water is growing even larger.
- Since consumer demand for electricity in many regions is higher in summer (for cooling and refrigeration), a shift of peak stream-flow to winter will have an additional harmful effect in areas, including China, India, and the western U.S., that are heavily dependent on hydroelectric power. Reduced river flow in other seasons, caused by disappearing mountain snow-pack or rapidly shrinking glaciers, will increase the demand for electricity from other sources such as fossil fuel combustion.
- Water quality will decrease both with warmer water temperatures and with run-off caused by more precipitation or by extreme storms. Higher air and water temperatures are also associated with more frequent outbreaks of cholera and childhood diarrhea.
- Countries that are already experiencing water-stressed conditions will grow rapidly in population, from 1.8 billion in 1990 to 5 billion by 2025. Climate change will make this problem even worse, creating further stresses on water supplies, as water quality and quantity decrease.

Human health

Climate change is going to be increasingly bad for human health. Tropical diseases will spread northward, and heat waves and other extreme events will become more common. The short-term health consequences of warming will be increases in the impact of tropical diseases in the poorest and hottest countries. Meanwhile, extreme weather events will be harmful to human health everywhere.

- Some 50,000 people died in the 2003 heat wave in Europe. Some models now forecast that by the end of this century, typical summer temperatures in Europe will be at the level of the 2003 heat wave, i.e. 5° above 20th-century averages.
- Warmer, wetter conditions promote the spread of both the mosquitoes that transmit malaria and the pathogens that cause the most serious forms of diarrhea in developing countries. Global warming will allow these diseases to spread farther north and to higher altitudes. In Africa, a 4 degree global increase in temperature is predicted to cause an 8% increase in diarrhea.
- More deaths from malnutrition are expected as temperatures begin to rise, due to the forecast of a decline in crop yields in the tropics.

Ecosystems and extinctions

As climatic conditions change, certain species, or even entire ecosystems, may be unable to keep pace. In addition to the value of ecosystems in and of themselves, many ecosystems provide essential services on which human beings depend for their survival.

- As little as 1.0º warmer ocean temperatures can cause large sections of coral reefs to experience fatal “bleaching.” In some areas, an increase in water temperatures of just 0.5º is expected to cause annual large-scale bleaching, resulting in enough coral mortality to lead to the extinction of some species.
- Polar bears and other animals dependent on a sea-ice habitat are also extremely vulnerable to the effects of small increases in the average temperature. Specialists in Arctic and Antarctic ecosystems fear that extinction for some sea-ice dependent species is becoming more and more probable in the short-run.

Summary measures of the economic costs of climate change

Two recent modeling efforts rely on projections that average temperatures could reach 4° above the preindustrial level by 2100, enough to cause serious harm to agriculture, human health, and ecosystems worldwide, and to create some chance of a true catastrophe:

- One estimate, from the German Institute for Economic Research (DIW), is that if nothing is done to restrain greenhouse gas emissions, annual economic damages could reach US$20 trillion by 2100 (expressed in U.S. dollars at 2002 prices), or 6 to 8 percent of global economic output at that time. The same study found that immediate adoption of active climate protection policies could limit the temperature increase to 2° and eliminate more than half of the damages; by 2100 this would avoid $12 trillion in annual damages by spending $3 trillion per year on climate protection. If, however, climate protection efforts do not begin until 2025, the same model estimates that it will be impossible to limit warming to 2° by 2100 – and climate protection in general will be more expensive, the later it starts.

- Another estimate, from the PAGE model, was used in a study for the European Commission's Directorate General-Environment. It estimates that in the absence of new policies, the discounted present value of all cumulative climate damages from now through 2200 will amount to US$74 trillion (at 2000 prices). The average annual damages, from 2000 through 2200, will be $26 trillion, reasonably close to the DIW model estimate for 2100. Again, the PAGE model finds that more than half of those damages can be avoided by immediate adoption of active climate protection policies.

For purposes of policy analysis, many studies have estimated a measure of incremental damages, the "social cost of carbon" (SCC). The implication is that, if carbon emissions can be reduced at a cost per tonne less than or equal to the SCC, society as a whole is better off: the reduction in damages is worth more than the cost of reducing emissions.

- A 2005 review and analysis for the Department of Environment, Food, and Rural Affairs (DEFRA), produced "central guidance" estimates of the SCC, with many caveats, rising from £68 in 2010 to £143 in 2050.
- Of the 28 studies examined in the DEFRA review, most stick to the market impacts of predictable, average changes in climate. Only a few explore valuation of non-market impacts and/or extreme events; virtually none have considered the costs of a catastrophe, or socially contingent impacts. That is, all of the studies that estimate the social cost of carbon base their numbers on an incomplete picture of climate risks – often encompassing only the simplest and most predictable corner of the vast, troubling canvas that has been painted by climate science. In view of this serious incompleteness, SCC estimates are more useful for endorsing proposals than for rejecting them.

Estimates of climate damages rely on a host of hidden assumptions, which – once revealed – raise concerns about the essential plausibility and ethical significance of the resulting bottom line. When the values of ecosystems, human lives, and our enjoyment of our local climate are converted into monetary values in order to combine all costs and benefits into a single price tag for climate change, much of what is most meaningful in these predictions gets lost.

In most economic analyses, including those discussed here, future costs and benefits of climate change are "discounted" before they are summed up. Discounting reduces future costs and benefits, placing the greatest emphasis on present day effects: the farther into the future the predicted effect, the lower the weight it is given. The rate of discounting has a profound effect on estimates of both global costs and the social cost of carbon.

Conclusions and Policy Recommendations

Our common future is at risk from climate change. Behind the summary numbers lies a story of multiple, interacting, and worsening harms. The first 2º of climate change will be bad enough; the changes beyond that point become increasingly perilous. Vigorous action now, before these more severe impacts are visible, is essential in order to limit temperature increases to 2° and hold long-term damages to a survivable level. Even in the short run, the impact of climate change will be disproportionately bad for the countries that have had the least to do with adding carbon to the atmosphere. It is vital to create institutions to address equity and provide relief as quickly as possible, before food and water problems in the developing world reach critical levels.

The only way to turn the supertanker around, and to avoid the worst effects of climate change above 2º, is to act promptly and on a large scale. Waiting to see if things really turn out as badly as predicted will mean that we miss the last chance to ensure that our grandchildren, and their grandchildren, inherit a livable world.

Introduction

All of us, like it or not, are being dragged along on an unplanned journey with an unwelcome destination: human activity, particularly fossil fuel combustion, is causing large-scale, long-lasting changes in the earth's climate. The ultimate price of this journey will remain unknown until it is much too late to turn back; a recent study for the European Commission estimates that the cost of climate change could be as high as US$74 trillion (Watkiss et al. 2005).[1] As explained later in this report, even $74 trillion may be an underestimate of the enormous but uncertain costs.

Recognition of the climate problem is now widespread, as is the desire to find an effective solution. Yet an adequate response to the threat of climate change requires a complex, international mobilization of resources and policies, far beyond the limited scope of the Kyoto Protocol. In the absence of such a response, a resigned complacency has started to appear: if 2°, 3°, or 4° of warming are inevitable, some voices suggest, perhaps we can live with that.[2]

This report examines the costs of inaction – the worsening damages that will result from allowing climate change to continue unabated. In brief, it finds that the first 2° of warming will have many harmful and costly impacts, outweighing the modest potential benefits, for northern countries such as the United Kingdom. (This initial stage of warming refers to the first 2° increase above pre-industrial – or early 20th century – levels in the global mean temperature, of which 0.6° has already occurred.) Most developing countries will fare even worse, experiencing greater costs and no benefits at all. The first stages of warming already have begun to put essential ecosystems at risk, and will strain the ability of the world's economies and governments to respond.

Beyond 2°, in the second half of this century and later, the effects of further warming – which will certainly occur in the absence of ambitious mitigation efforts – will be much more dangerous, as all potential benefits vanish and all regions suffer steadily increasing harms. The risk of a global catastrophe will increase rapidly as temperatures continue to rise. If nothing is done to stop temperatures rising by more than 2º, the grandchildren of today's young adults will inherit a world crippled by food and water shortages, extreme and variable weather, extinctions and other ecosystem damages, and a growing danger of an even more severe catastrophe.

The climate system, and our economic activities that affect it, have enormous momentum. It is not possible to wait until the world begins to get uncomfortably warm, and then suddenly decide to stop. Because of its momentum, a supertanker has to turn off its engines 25 km before it comes to a stop. Likewise, we have to achieve a drastic reduction in carbon emissions several decades before we can bring climate change under control. In other words, we have to take action long before we experience the full severity of the problem. The world as a whole can cope

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[1] A trillion has 12 zeros; it is a million million. A billion has nine zeros; it is a thousand million.

[2] All temperatures in this report are in degrees Celsius. In most cases, temperatures are expressed as increases above the pre-industrial level, which is about the same as the temperature of the early decades of the 20th century. IPCC reports often measure temperatures relative to 1990, which is about 0.3° above the pre-industrial level; thus we have often added 0.3° to IPCC temperature change estimates for consistency.

with the effects of warming up to about 2°, but only if there are prompt, large-scale, and creative approaches to international equity and cooperation. The challenge will be to understand the near term damages from climate change as a sign of much worse to come if nothing is done to stop it, while interpreting any limited benefits of the early stages of warming as a temporary windfall, soon to disappear.

We begin with an overview of categories of climate risks, followed by a detailed examination of some of the major categories of impacts, which are often difficult to express in a single number. We then turn to a preview of the expected effects of climate change in the UK. Successive sections of the report address agriculture, industry and infrastructure, fresh water, human health, and ecosystem impacts.

A final chapter discusses economic issues that arise when measuring the effects of climate change: the meaning of global estimates of the monetary impact of climate change; interpretation of the estimates of the "social cost of carbon"; the problems of assigning monetary values to non-marketed health and environmental impacts; and the paradoxes associated with discounting costs and benefits that will occur in the future. As large as the estimates are – ranging up to US$74 trillion for global damages, and £70 or more for the "social cost" of a single tonne of carbon – they remain partial and inevitably incomplete measures of the manifold damages that can be expected if nothing is done about climate change.

Categorizing climate risks

The risks of future damages from climate change are sufficiently complex that a system is needed for cataloging them. One approach is to use a three-by-three "risk matrix," as shown in Figure 1 below. The risks associated with climate change vary both in predictability (the rows of the table) and in the type of impact (the columns).

In terms of predictability (the rows in Figure 1), the **changes in <u>average</u> conditions** are well understood and relatively predictable. Rising levels of CO_2 in the atmosphere lead to the greenhouse effect, causing a gradual, steady increase in average temperatures. Sea levels are already slowly rising, due to melting of polar ice and to the expansion of ocean water as it warms. Climate models are beginning to offer more detailed descriptions of the changes that we can expect: higher maximum temperatures and more hot days, higher minimum temperatures and fewer cold days, and a narrower day/night range of temperatures worldwide are predicted. Higher humidity and more intense storms are expected around the world, and in the mid-latitudes, areas away from coastlines can expect increasingly dry summers (IPCC 2001b, 575). If great efforts at carbon emission mitigation occur, by the year 2100 the world might see no more than about 2° warming and 20 cm sea-level rise (IPCC 2001a, 177). However, if nothing much is done to slow climate change over the next century, more uncomfortable and dangerous temperature levels will be in store for the end of the century and beyond. The changes in averages will be immediately harmful in many regions – but they may not be, in the short run, the world's most serious climate problems.

Figure 1. Matrix of climate risks

	Type of impact →	**Market impacts**	**Non-market physical impacts**	**Socially contingent impacts**
Predictability ↓	*Examples* → ↓	*Agricultural output, health costs, property loss*	*Deaths, extinctions, ecosystem damages*	*Migration, response to food & water shortages*
Averages	*Temperature, sea levels, atmospheric CO_2 are all steadily rising*	(Easiest to measure)		
Extremes	*Increased frequency and strength of heat waves, storms, droughts, floods*			
Catastrophes	*Polar ice sheets melting, "turning off" major ocean currents*			(Hardest to measure)

Source: Adapted, with changes in wording, from (Downing and Watkiss 2003).

Scientists' models of climate change predict not only increases in average temperature, but also **increased <u>variability</u> of weather conditions and more extreme events**: more droughts and floods, more heat waves, more powerful storms. Within the last few years, Europe has seen extraordinary floods and heat waves; in the same period, North America has experienced an increased severity of hurricanes, and other regions have been hit by extreme weather as well. According to one study, recent climate change has already made extreme heat waves two to four times more likely, and over the next 40 years, with no efforts to cut emissions extreme heat events will become 100 times more likely than in the late 20th century (Epstein and Mills 2005).

While increased variability in temperature, precipitation, and wind speeds is a virtual certainty, it is impossible to predict the exact details of when and how these extremes will manifest. No single weather event can be unambiguously linked to climate change, since there have always been climate fluctuations and occasional extremes. But climate change is increasing the frequency and intensity of extreme weather, causing a sharp upswing in damages. In 2005, natural catastrophes caused US$220 billion worth of damage (Swiss Re 2006, 5). According to the Association of British Insurers, a sea level rise of 1 m, which could occur by the end of this century if greenhouse gas emissions continue to rise, would increase the value of property at risk in a storm surge by $1.5 trillion (ABI 2005). Extreme weather is the source of some of the most important costs of climate change discussed below.

In addition to property damages, there are losses of income for months or years after extreme weather events. The U.S. state of Louisiana, the area hardest hit by the extraordinary hurricanes of 2005, was the only state in which gross state product (GSP; the state equivalent of GDP) declined in 2005. Louisiana experienced a loss of US$2 billion in GSP, whereas if it had grown at the same rate as the rest of the U.S. in 2005, it would instead have had a gain of $5 billion.[3] Thus it apparently suffered a loss of $7 billion, or 5 percent of state income for the year. Since this loss happened exclusively in the last third of the year – Katrina, the first and worst of the year's big hurricanes, struck on August 29 – it amounts to a 15 percent loss of income for the post-hurricane months. Louisiana includes many inland areas that suffered little or no damage; the percentage loss was much greater in New Orleans and other affected coastal communities.

Lurking beyond the problem of extreme weather events is **the risk of a climate catastrophe**. Increasing temperatures raise the probability of collapse, followed by rapid melting, of gigantic ice sheets in Greenland and/or Antarctica, which could cause a devastating sea-level rise. Even more moderate melting in Greenland and the Arctic could potentially disrupt the circulation of ocean currents in the North Atlantic, which is responsible for the relatively mild temperatures of Northern Europe (all of the UK is farther north than virtually all of the population of Canada). In addition, there is a danger that gradual warming could lead to abrupt releases of large quantities of the methane – a greenhouse gas more powerful than carbon dioxide – that is currently stored in frozen, but quickly thawing, tundra; this would greatly accelerate the process of warming. All of these dangers are just possibilities, of unknown probability. No one is saying that they are definitely expected to occur in the near term. But there is a real risk of these disaster scenarios occurring that is directly dependent on how much carbon we continue to emit (Epstein and Mills 2005; Lenton et al. 2006; Schellnhuber et al. 2006).

Table1 below summarizes the likely impacts of climate change by an incremental increase in average global temperature. It should be emphasized that all predictions of emissions scenarios and likely temperature changes are estimates, not exact figures. None of the temperatures and effects described in Table 1 represent precise thresholds or discontinuities; rather, the effects become increasingly likely, and ominous, as temperatures and CO_2 levels rise.

The IPCC has classified nine categories of scenarios for models of climate change, which include detailed information on rates of emissions, population growth, economic growth, and technological change. One-third of the IPCC scenario categories reach 2° increase in global mean temperature by 2050; these are the A1 scenarios that model rapid economic growth with the introduction of new, more efficient technologies, and a global population peaking at 8.7 billion in 2050 and then declining. All of the central estimates of IPCC scenario categories reach 2° by 2100, even the most “optimistic” B1 scenarios, which model the same level of population growth as the A1 scenarios along with slower economic growth and “rapid change in economic structures toward a service and information economy, reductions in material intensity, and introduction of clean technologies.”(IPCC 2001a, 176) The question is whether they reach 2° and continue to accelerate toward higher and more threatening temperatures, or glide to a halt with little or no momentum toward temperatures beyond 2°.[4]

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[3] Our calculations from GSP data in U.S. Comerce Department, Bureau of Economic Analysis press release, June 6, 2006, http://www.bea.gov/bea/newsrel/GSPNewsRelease.htm. All amounts in this paragraph are measured at 2000 prices. Both the neighboring state of Texas and the Southeast region of the U.S. as a whole grew faster than the national average in 2005, as did Louisiana in 2004; thus it seems likely that Louisiana would have grown at least as fast as the national average in the absence of the hurricanes.

[4] A marked deceleration and leveling off of temperature increases by 2100 can be seen in the IPCC’s B1 and A1T scenarions, in contrast to several of the others; see (IPCC 2001b, 14).

Table 1. Likely Impacts of Climate Change

Temperature rise by 2100	**Likelihood**	**Effects**
0.6º	*Has already occurred*	• More frequent extreme weather events, more floods and more droughts, more heat waves; • A slow pole-ward migration of plant and animal species, with less mobile and less adaptable species increasingly at risk of extinction.
2º	*Will be exceeded unless there are immediate and vigorous efforts to reduce emissions*	• More tropical diseases over a wider geographical area; • Decreased crop yields in the developing world and, as a result, widespread hunger; • Many communities facing serious water stress and widespread droughts; • A total loss of arctic ice and the extinction of many arctic species; • A near total loss of coral reefs due to “bleaching;” • And perhaps the onset of the complete melting of the Greenland ice sheet, slowly but unstoppably raising sea levels by 7 m over the course of the next 3000 years.
3º	*Extremely likely without major efforts at reducing emissions*	• Decreasing crop yields in the developed world and decreasing world food supplies; • Widespread species extinctions and desertification; • The wholesale collapse of the Amazon ecosystem; • The complete loss of all boreal and alpine ecosystems.
4º	*Likely with no efforts at reducing emissions*	• Entire regions will have no agricultural production whatsoever and the melting of the West Antarctic ice sheet will gradually increase sea levels by 5 to 6 m (in addition to the increase from the loss of the Greenland ice sheet).
>4º		• There is a 50-50 chance that the ocean’s circulation system will shut down, removing the crucial currents that warm and stabilize the climate of Northern Europe.

Source: (IPCC 2001b; IPCC 2001a; Watkiss et al. 2005). The climate change scenarios cited here are B1 (2.3º by 2100), B2 (3.0º), and A1F1 (4.8º) from IPCC 2001.

The difficulty of prediction and the danger of abrupt catastrophe are connected to the problem of positive feedback. Small changes can, in some cases, lead directly to bigger changes in the same direction. Perhaps the most important feedback mechanism is the role of water vapor in the atmosphere, which is an important greenhouse gas: the warmer it gets, the more water vapor the atmosphere can hold, leading to even more global warming. This effect alone leads to double the amount of warming that would occur if there was only a fixed amount of water in the atmosphere (IPCC 2001b). There are other natural causes of positive feedback: ice and snow are more reflective, and absorb less heat than other surfaces; so as warming leads to more melting of ice and snow, the earth's surface absorbs more heat and becomes warmer, which leads to even faster melting. As the Greenland ice sheet begins to melt, the increased flow of meltwater may seep into and under the remaining ice, accelerating the melting process – and creating the possibility of a very abrupt change at some point in the future (Hansen 2004). As hotter and drier conditions lead to shrinkage of tropical rainforests in the Amazon and elsewhere, the massive amounts of carbon formerly sequestered in these forests is at least partially released to the atmosphere, causing additional warming.

Some feedback loops, however, are caused by human activities: as greenhouse gases lead to higher temperatures, more people install and use air-conditioning, which increases the demand for electricity, which – if generated from fossil fuel-burning plants – leads to more emissions of greenhouse gases and even higher temperatures. Any attempt to adapt to climate change by using more energy will create this type of feedback, as the energy used for adaptation worsens the underlying problem and requires even more adaptation in the future.When, as in these examples, a problem is self-amplifying, the danger of runaway change cannot be dismissed. The natural processes involved are inherently difficult to predict, and are not yet completely understood, although it is clear that feedback mechanisms increase overall vulnerability and risks of abrupt change (Rial et al. 2004).

Turning to the types of impacts (the columns in Figure 1), discussion of the “costs” of climate change begins with **market impacts** such as changes in farm output, public health expenditures, and property losses, and other cases where the effects of climate change have well-defined prices. Many of the important impacts of climate change, however, involve **physical damages that have no prices** attached, such as human deaths, extinctions of other species, and numerous forms of environmental damage. Economists could, in theory, estimate the monetary value of some of these impacts, but this is a controversial and difficult undertaking, as discussed in our final chapter. Finally, some impacts are “**socially contingent**,” i.e. dependent on how society responds to physical changes. Will large-scale migration occur out of the most severely affected areas? How will societies respond to food and water shortages that result from climate change? Answers to questions like these are critical to an assessment of the impact of climate change – and obviously impossible to value in monetary terms. Thus whatever the estimates of monetary impacts, there will be many severe consequences of climate change that cannot be priced.

The (mistaken) case for complacency derives from using a narrow assessment which considers only one element of the risk matrix: the predictable, average changes associated with the first 2° of warming may create some benefits as well as many types of costs for developed countries. Although there is no consensus on these issues, three types of benefits from moderate warming have been proposed: slightly warmer weather and higher levels of CO_2 could increase yields in temperate agriculture; warmer weather could decrease total temperature-related mortality, particularly among the elderly in cold countries; and people in cold countries might simply enjoy life more if it were a little bit warmer.

The change in agricultural yields is the most important and most widely accepted benefit. Many analysts believe that if farmers adapt rapidly to changing conditions, global food production could increase as a result of the early stages of warming; we discuss this, and rival perspectives, in the section on agriculture, below. On the other hand, the recent projections of reduced mortality from warmer weather appear to be mistaken, as we discuss in the section on health. Finally, the hypothesized subjective benefit of increased warmth to cold northerners is described and critiqued in the discussion of valuation problems, in our final section on economic issues in climate analysis.

Even if we accept the existence of any of these benefits, particularly the increased agricultural yields, the complacent conclusion that climate change might not be so bad is still unfounded for at least three reasons. First, the effects of variable and extreme weather events are bad for everyone, North and South – and outweigh any potential benefits; second, even the average effects of the initial 2° will be bad for agriculture in developing countries; and finally, beyond 2°, all regions will suffer from the worsening average effects of climate change, along with intensifying extremes and rising risks of catastrophe. Complacent inaction, based on exaggeration of the benefits of the early stages of warming, will only hasten the time when those benefits melt away forever in the growing heat of the day.

The UK in 2050: hot, and getting hotter

Climate change has already begun to have negative impacts throughout the UK, and worse is in store in the decades to come. On average UK temperatures, as with most countries in the higher latitudes, are predicted to increase by even more than the global mean. Relative to early 20th century levels, average British temperatures have already increased by nearly 1º, which is higher than the corresponding global increase. Most of the expected annual mean increase of 1.5 to 2.5º by 2050 will manifest as warmer summers and autumns, with much less change in spring and winter temperatures[5]. The southeast can expect the UK's greatest summer warming (Hulme et al. 2002; EEA 2004, 24-25).

By the middle of this century, London will be 1 to 2º warmer in winter and 2 to 3.5º warmer in summer than it was at the beginning of the 20th century. By 2020, twice as many days will exceed 25º in London each summer; by 2050, there will be three to five times as many hot days. In central London, the urban heat island effect can add 6º to the highest temperatures, making a hot day in the suburbs an unbearable day at Charing Cross. The number of really hot days, higher than 30º, is also expected to increase: heat waves, reminiscent of the summer of 2003, will soon be Londoners' common fare (GLA September 2005, 5-6).

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[5] The climate impacts in this section are dependent on future emissions and range from the central estimate of the low emission B1 IPCC scenarios to the central estimate of the high emission A1F1 scenarios.

A shift in rainfall patterns, which is already underway, will compound unprecedented heat with severe drought. Dependent on future emissions, summer rains in southern England are expected to decrease by 20 to 40 percent, while rains in winter (when fresh water is in less demand) are expected to increase only by 10 to 30 percent. Extreme storms and flooding in the UK are also likely to become more frequent and more severe: floods in recent years in Carlisle, Cornwall, and Yorkshire may be a taste of what is to come. The biggest changes in precipitation are likely to occur in the UK's Eastern and Southern regions (Hulme et al. 2002; EEA 2004, 24-25; GLA 2005a). The Association of British Insurers predicts that by 2080 the annual cost of flooding in the UK could be £22 billion, or fifteen times what it is today, for high-temperature increase scenarios (ABI 2005, 7).

Climate change will also have costly effects on public transportation systems. Hot temperatures slow down train travel, due both to safety issues with high speeds on hot tracks, and with buckling tracks and other physical damages. In the summer of 2003, heat-related train delays cost London £750,000 – not including the expense of repairing four damaged tracks. The Underground may need to be retrofitted for improved flood drainage, air conditioning, and ventilation. Temperatures can be over 10° hotter in underground tunnels than they are at the street level. In 2003, maximum recorded temperatures in the Underground were 41.5° on a train and 36.2° in a station. By the 2050s, each summer will have 28 to 45 days hotter than 25° on the surface, hotter than 30° on most trains, and hotter than 35° on the worst trains and platforms. No simple or inexpensive solution has as yet been discovered: when the Mayor's office offered a £100,000 prize for a plan for cooling the Underground, all 3500 entries were rejected as impracticable (GLA 2005a, 15-21).

Higher temperatures and changes in the rainfall patterns will also have a negative impact on the UK's natural ecosystems. A study by the UK Climate Impacts Programme predicts that 42 percent of the combined area of the UK and Ireland will experience widespread ecosystem changes between now and 2050; the largest changes are expected in the central Highlands, Kent, Lanarkshire, Snowdonia, the South Essex coast, and Sussex (UKCIP 2006b, 8). Fish species, like Atlantic cod, herring, and sandeels, have already begun moving northwards away from the British Isles as ocean waters approach the lethal temperature for their eggs. British populations of terns and wading birds are also at risk as rising sea levels engulf nests and food sources – like sandeels – become scarce. As climate change continues, populations of grey seals and fin whales are likely to decline along with the fish on which they prey (WWF Scotland 2005).

The UK will also suffer the effects of increased variability in weather conditions. Table 2 reports the likely increase in extreme weather – heat waves and violent storms – using an IPCC scenario with medium to high emissions (A2), which predicts a change in global mean temperature of 1.7° by 2050 and 4.1° by 2100. By 2080, in the UK every year will be as warm as 1999, one of the warmest years on record at the time that the Department of Environment, Food, and Rural Affairs (DEFRA) study was completed; nearly two-thirds of all years will have average summer that are at least 3.4° warmer and half of all years will summers that are 37 percent drier than the 1961-1990 average (Hulme et al. 2002).

Serious weather events can cause storm surges that are a danger, not only to infrastructure, but to human lives in coastal areas and river deltas. In London, the net effect of subsidence (the ground beneath London and many other areas of the UK is settling) and rising sea levels will increase the net sea level by 8 to 18cm in 2020, 13 to 42cm in 2050, and 17 to 77cm by 2080, depending on the level of ongoing greenhouse gas emissions (UKCIP 2006a). Table 3 below shows the predicted net sea level change for the UK by region. When storm surges combine with higher net sea levels, the results may begin to challenge the capacity of the Thames Barrier, the UK's largest and most important flood defense.

Table 2: Predicted Percentage of Years with Extreme Weather in the UK

	2020s	**2050s**	**2080s**
Temperature			
A hot '1995-type' August (+3.4º)	1	20	63
A warm '1999-type' year (+1.2º)	28	73	100
Precipitation			
A dry "1995-type" summer (37 percent drier than average)	10	29	50
A wet "1994/95-type" winter (66 percent wetter than average)	1	3	7

Source: Adapted from Hulme et al. 2002, Table 6, p.39.

With high temperatures, floods, and droughts all likely to be common features of London's weather in the not too distant future, the Mayor's office has issued recommendations for protecting new buildings against the ravages of climate change that include air conditioning systems; building methods and materials resilient to floods, subsidence, coastal erosion, landslides, storm surges, and sea-level rise; and careful attention to the use of increasingly scarce water resources (GLA 2005b, 17-18).

Existing homes and businesses may need to be retrofitted for climate change, especially with regard to ventilation systems and air conditioning. Only about 2 percent of UK homes had air conditioning in 2005 (compared to 76 percent in the U.S. in 2001), but in the summer of 2006, UK retailers were selling 10 times more air conditioning units than in previous years (EIA 2001; Morley 2005; Shreeve 2006). A DEFRA study predicts a change in "cooling degree days"[6] (over 22º) for southeast England from 320 per year to 570 to 620 per year by the 2080s (Hulme et al. 2002).

In the U.S., air conditioning accounts for 16 percent of domestic electricity use and 26 percent of office and commercial electricity use, compared to the very small share in the UK until now. If, as a result of warming trends, the UK matches the U.S. level of residential, office, and commercial air conditioning, another 56 billion kilowatt hours of electricity would be required, with a retail cost of about £5 billion per year (see Appendix I for details and sources). This would amount to a 16 percent increase in UK electricity generation. But it would not be distributed uniformly throughout the year; rather, it would all be needed in the summer months, primarily in the daytime, and particularly on the hottest days. Less than half of this increased

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[6] "cooling degree days" measure both the number of days when air-conditioning might be used, and how hot those days are. With a 22 degree threshold, as in this case, a day at 23 degrees represents one cooling degree day; a day at 25 degrees represents three cooling degree days, etc. The season total of cooling degree days thus measures how hot it is, for how long, which determines the annual total demand for air conditioning.

demand could be supplied by existing plants; a massive wave of new plant construction would be required to power the nation's new air conditioners. The new plants would sit idle at all but the hottest times of the year. If, as seems likely, many of the plants would burn fossil fuels, they would ironically contribute to worsening climate change, in order to help people cope with its effects.

Table 3: Sea-level Change by UK Region, including Subsidence

	Net Sea-level Change 2080s (cm) Relative to 1961-90	
	Low Emissions scenario	**High Emissions scenario**
NE Scotland	1	61
SE Scotland	0	60
NE England	6	66
Yorkshire	15	75
East Midlands	20	80
Eastern England	22	82
London	26	86
SE England	19	79
SW England	16	76
Wales	11	71
Northern Ireland	9	69
NW England	7	67
SW Scotland	-2	58
NW Scotland	-1	59
Orkney & Shetland	9	69
Global average	**9**	**69**

Source: Adapted from Hulme et al. 2002, Table 12, p.75; net sea level change includes uplift and subsidence (geological rise and fall of land with respect to sea level).

Changes in average conditions and increased variability in the form of extreme storms and heat waves are those most predictable effects of climate change. The UK is also at some risk of experiencing the effects of a (much less predictable) climate catastrophe. In the event of the disruption of the circulation of ocean currents in the North Atlantic, British temperatures could approach those of Canada, which lies at a similar latitude.

Rapid changes to natural ecosystems, flood and heat damage to public infrastructure, installation and operation of cooling systems in homes and businesses, deadly droughts and heat waves, and rising sea waters and storm surges all add up to bad news for UK residents. Climate change will be deadly for some, uncomfortable for most, and expensive for everyone in the UK. But as bad as this seems, worse news is still to come: in the near term, the UK is actually getting off relatively lightly. In most of the developing world, climate change will be much more deadly and much more expensive. Without the benefit of the UK's billions of pounds for flood protection equipment, small islands and many coastal areas in the developing world will quickly become uninhabitable. Whole regions will experience long-term droughts, agricultural productivity throughout most of the tropical regions will be severely reduced, and many developing countries will experience an increase to their already substantial burden of infectious disease.

Growing numbers of refugees will flee from areas of food and water shortages, including many parts of Africa and southern Asia. In Bangladesh, where half the population lives in areas less than five meters above sea level, one estimate indicates that a one percent increase in average global temperatures will cause a loss of 10 percent of all land area. With permanent flooding and shortages of drinking water, climate change could result in 30 to 40 million Bangladeshi refugees (Ahmed 2006).

The developed world will inevitably face higher costs of absorbing and providing for the new, environmentally driven immigration. Today, 75 million people around the world live in areas subject to coastal flooding, and a global average sea level rise of 0.4 meters by 2080 (an estimate for a medium emissions scenario or around 3º temperature increase by 2100) would increase this number to 200 million people (Edwards 2005; Schubert et al. 2006). Environmental refugees, already numbering in the tens of millions worldwide, could reach 50 million by the end of this decade and 150 million by 2050, as climate change continues to worsen the conditions that drive many people from their homes (Edwards 2005, Myers 1993). In the UK alone, the number of people at risk of coastal flooding is expect to increase from 0.9 million in 2002 to 1.8 million in 2080 (an estimate for a high emissions scenario or around 4º temperature increase by 2100) (Schubert et al. 2006). In addition to costs related to refugees, financial costs to the UK may include larger expenditures on humanitarian aid, higher prices for tropical products (for example, tea and coffee), and lower profits for UK businesses located abroad.

Impacts of Climate Change

We now turn to the more detailed impacts of climate change on human and natural systems, examining the expected effects on agriculture, industry and infrastructure, water supplies, human health, and natural ecosystems. Extensive research, summarized in the periodic reports from the Intergovernmental Panel on Climate Change (IPCC) and elsewhere, makes it increasingly clear that there are ominous threats in each of these areas. In many cases, there is a threshold around 2° of warming, beyond which the risks become much greater.

Agriculture

Agriculture is one of the few sectors in which some analysts have predicted short-term benefits to climate change. Both the scale and the duration of these benefits are debatable. But even the rosiest estimates show increased yields only in northern countries, lasting only during the first 2º of climate change. Even then, extreme weather events and other negative trends could reduce or eliminate any gains. Indeed, in the heat waves of 2003 many European countries, including the UK, saw their crop yields decline sharply (EEA 2004, 67).

Agriculture appears to be a case where climate impacts have a well-defined value, based on losses or gains in marketed output. There is, however, an economic paradox which makes it difficult to interpret monetary estimates of the value of climate damages (or benefits) in agriculture.

Consumer demand for food is relatively insensitive to price changes. Most people do not eat much more than usual when food is cheap, or much less when it is expensive. Economists say that the market for food exhibits “inelastic demand” – meaning that a 1 percent decrease in the supply of food causes a more than 1 percent increase in the price. Thus if crop yields decrease as a result of climate change, prices will increase more than proportionately, and gross agricultural revenue will increase. Conversely, if yields increase, agricultural revenue will decrease. Declining agricultural revenue could paradoxically be evidence of the adequacy of food supplies, while growth of revenue might reflect scarcity.

The paradox results from a clash between equity and efficiency concerns: decreased agricultural production means less food for the world, and more risk of hunger; but hungry people will pay more for food, a “success” if judged purely by the market value of agricultural output. Thanks to inelastic demand, the physical volume and the market value of the global food supply tend to move in opposite directions. It is simpler and clearer, therefore, to discuss changes in crop yields directly, rather than estimating their market value.

A common conclusion is that the first 2° or more of warming, or the next 50 years or more, will see increased yields in temperate agriculture and decreased yields in tropical agriculture. This is the finding, for example, of the massive literature review in the IPCC 2001 report (IPCC 2001a, 252-270). Eventually, as temperatures and CO_2 levels rise and precipitation patterns change, most analysts expect that climate change will harm agriculture everywhere; but many studies put the turning point after 2050.

The predictable, average changes due to climate change include increases in both temperature and CO_2 concentration, and regional changes in rainfall patterns. Warmer temperatures will be bad for crops that are already near the top of their natural temperature range; this is one reason why tropical agriculture will suffer decreased yields from the initial stages of climate change. On the other hand, warmer temperatures will allow crops to expand into areas that were previously too cold, and will create longer growing seasons in cold areas. If farmers in temperate climates adapt correctly to these changes, they may be able to benefit. Long-term changes in precipitation will complicate the process of adaptation, as some areas will become too dry for agriculture, or will require more irrigation, while others will become wetter.

More CO_2 is also helpful to plant growth, at least up to a point.[7] Plants absorb CO_2 and use it in the process of photosynthesis, so “feeding” them more CO_2 functions somewhat like fertilization. Different plants respond differently to CO_2 fertilization: maize, sugarcane, and sorghum are less affected than most other crops. The increase in yields is not quite as valuable as it looks; some

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[7] This paragraph is largely based on the review of expected impacts on agriculture, in (IPCC 2001a), section 5.3.

studies have found that CO_2 fertilization decreases protein content in wheat and rice, and produces wheat that makes lower quality bread. However, on balance many studies estimate that warmer temperatures and CO_2 fertilization will increase temperate agricultural yields through 2050 or so; a 17 percent yield increase is a plausible average estimate.[8] An increase in atmospheric CO_2 also reduces some plants' need for water.

However, recent research suggests that even minute increases in ground-level ozone – a pollutant created by fossil fuel combustion – can reduce plant growth. Since increases in CO_2 levels, resulting from fossil fuel use, will be accompanied by increases in ozone, some or all of the benefits of CO_2 fertilization may be offset by the damages from ozone. This factor has not yet been incorporated into most agricultural forecasts. Additional research is needed to understand the effects on agriculture of joint increases in CO_2 and ozone (Long et al. 2006).

This is the best possible case for agriculture; several negative factors could complicate the picture and limit the short run increase in yields. Increased variability of temperature and precipitation will be bad for all crops, as suggested by the experience of the European heat wave of 2003. Many plants are particularly sensitive to temperature at key stages of their development, and can be harmed by excessive heat at those critical points; with worsening climate variability, yields may drop when heat waves occur at the wrong time in the growing season – even if average temperatures have not yet exceeded the level that crops can withstand (Peng et al. 2004). Increased variability in rainfall, forecast for many regions by climate models, will also be bad for agriculture.

A detailed analysis of the expected effects of climate change on agriculture in ten locations in the U.S. Midwest reveals the effects of variable weather (Southworth et al. 2000). It projects that maize yields could increase in the northernmost locations, where the benefits of warming could outweigh the costs of increased variability, assuming that farmers adopt the correct maize varieties for the changed conditions. In the central and southern locations, however, both the effects of increased average temperature and of increased variability are negative, causing yield decreases. For soybeans and wheat, which respond more strongly to CO_2 fertilization than maize, the same researchers found a similar north-south gradient – climate change will be more helpful to the northernmost farming regions within the U.S. – with yield increases expected in most or all locations through 2050 to 2059, the endpoint of the study (Southworth et al. 2002a; Southworth et al. 2002b).

An additional problem, excluded from almost all of the studies predicting increasing yields in northern climates, is that weeds, pests and diseases are likely to expand their range as the world grows warmer. If tropical plant-eating insects and plant diseases move farther north, some of the yield increases will be lost. Some studies have projected that U.S. crop losses to pests, already significant, could increase dramatically (Yudelman et al. 1998; Rosenzweig et al. 2000).

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[8] More precisely, a review of open-air experimental evidence in developed, temperate countries finds that atmospheric CO2 levels of 550 ppm – roughly the level expected by mid-century – would increase average yields by 20 percent for crops other than maize, sorghum, and sugarcane. The latter crops would have smaller if any yield increases, with insufficient data to support numerical estimates (Long et al. 2004). The 17 percent figure is a guess, adjusting the 20 percent average down to reflect the importance of lower impacts for maize.

Most of the optimistic projections about agricultural yield assume rapid adaptation to changed conditions. Growing seasons and optimum planting times will change; new varieties or crops adapted to the new weather may be required; old irrigation facilities may be wholly or partly unneeded in some areas, while new ones will have to be constructed in other areas; in some cases, farmers will need to move into formerly colder areas. Year-to-year variability in weather conditions, which has always been substantial and will be increasing with climate change, will make it difficult for farmers to identify the change in average conditions to which they should adapt. If farmers adapt imperfectly, or with a long lag, the potential benefits will be reduced.

It seems unfortunately likely that developing-country farmers will have much less ability to make these adaptations than their rich-country counterparts. This will add to the disadvantage of developing countries: climate change is worse for them because they are in many cases located in warmer, more tropical areas; and in addition, the adaptations required to manage the impacts of climate change will be more difficult for them (Fischer et al. 2002). Lower agricultural yields in developing countries will also make it increasing difficult to meet UN Millennium Development Goals, like halving the share of people who suffer from hunger by 2015 (UN-DESA 2006). If the world's total food supply increases, it will be because production gains in the North outweigh losses in the South. Some researchers, however, estimate that global agricultural yields will decrease by 1 to 2 percent even before 2050 (Arnell et al. 2002; Parry et al. 2004).

At the same time, the world's population will be increasing through about 2050, even in the scenarios with the lowest growth rates. In fact, population growth will outpace the growth of agricultural yields attributable to climate change; more intensive and/or extensive cultivation will be required to feed the more numerous human race of 2050. A serious question of equity and distribution will arise: almost all of the population growth will be in the global South, while food production will shift heavily toward the global North. There is no guarantee that any increased food supply will be delivered to those in need. It is all too easy to imagine a “business as usual” scenario in which people in the tropics have less food than they need, while northern countries grow more and more grain, and feed it to their cows (or to their cars, if ethanol production catches on). Only with imaginative and generous new provisions for aid and trade, recognizing the changing shape of agriculture in a warming world, will it be possible to prevent widespread hunger.

All this will be required to cope with the early stages of warming as it affects agriculture, the area where climate change brings the greatest “benefits.” Much worse is in store beyond 2050, or beyond 2° warming, as any existing benefits start to disappear. As climate change continues, its effects on agriculture will turn decisively negative everywhere, as rising temperatures and variable, extreme weather reduces crop yields, while the opportunities to adapt, to introduce new crop varieties, and to move agriculture into formerly colder areas, are progressively exhausted. With at least 9 billion mouths to feed, a declining food supply will indeed be a crisis.[9]

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[9] In the UN's medium scenario, with population growth below the replacement rate everywhere, the world will stabilize at about 9 billion people for the late 21st century (United Nations Department of Economic and Social Affairs 2004).

Industry and infrastructure

Climate change will affect economic activity in numerous areas beyond agriculture. Modest impacts will result from the changes in average conditions, but most industries, with the exception of some outdoor, temperature-related activities, will be able to adapt to the gradual warming of the next few decades. Much more severe and costly impacts will result from the rising tide of extreme weather events such as storms, floods, and heat waves. Damages from such events are growing rapidly, as the insurance industry and others have begun to observe. Worsening weather will place new strains on urban infrastructure, requiring expensive new investments; the problems will be worst in the cities of the developing world, where virtually all of the world's population growth of the 21st century will occur.[10]

Monetary costs are difficult to forecast, since they result primarily from unpredictable extreme events. The costs, however, can be large even from a single event: estimates of the property damage caused by Hurricane Katrina in 2005 range as high as US$135 billion, according to Swiss Re. One-third of that amount, $45 billion, was covered by insurance; failure to anticipate such costs, and to set appropriate (i.e., higher) premiums, can swiftly drive insurance companies into bankruptcy (Swiss Re 2006, 5). Timely defense against, and adaptation to, worsening weather can also be expensive: the costs of building both the Thames Barrier and similar Dutch storm surge barriers added up to billions of pounds. Seawalls of up to 13 m in height, protecting much of the Netherlands, have been built up over time at substantial cost. Other low-lying countries, such as Bangladesh, simply lack the resources to follow the Dutch example. (The southern coastal regions of the United States presumably had the resources but lacked the political will and foresight to construct adequate defenses; while the problem is worst for developing countries, it is not confined to them alone.)

Even the near-term changes in average conditions will affect some industries. Tourism is often uniquely dependent on weather and aesthetics; loss of natural assets such as beaches, coral reefs, or reliable snow cover for winter sports, could be devastating in some regions. Industries directly dependent on inputs from agriculture and forestry, such as food processing, and pulp and paper, will be affected along with their suppliers. Increasingly stormy weather, far below the level of major hurricanes, can cause accidents and delays in transportation and construction.

Benefits of warming for industry are largely confined to the coldest, northernmost regions, and are problematical even there. For example, increased melting of Arctic ice is an ominous development in ecological terms, raising sea levels, diminishing habitats for species such as polar bears, and threatening to alter the vital, large-scale circulation of ocean currents that regulates global temperatures. However, there are also increased opportunities for shipping, since more of the Arctic Ocean is ice-free for more months of the year. While urban settlements in the far north might welcome some of the amenities of warmer weather, the loss of year-round permafrost conditions may require expensive reconstruction of roads and other infrastructure (IPCC 2001a, chapter 16).

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[10] Among other sources, see the UN Population Fund web site, http://www.unfpa.org/pds/urbanization.htm.

Some of the largest impacts on industry and infrastructure involve the supply of water (treated in the next section) and energy. Episodes of extreme temperatures, such as the recent European heat waves, will increase both the demand for energy and the cost of providing it. Like tropical diseases, the desire for air conditioning will spread farther north as peak summer temperatures rise. Costs to manufacture and install air-conditioning equipment will be incurred relatively quickly, while any offsetting capital cost savings due to reduced heating requirements will occur only slowly as buildings or their heating systems are replaced. (Changes in fuel costs – on average, more for cooling, less for heating – will occur immediately when temperatures change.)

U.S. experience shows that in areas with heavy air-conditioning use, the demand for electricity exhibits a sharp peak on the hottest days of the summer (Sailor 2001). Electricity use for refrigeration also increases as temperatures rise. In order to supply peak summer demand, additional power plant capacity must be available, beyond what is needed at any other time of the year. The more extreme the peak temperatures and air-conditioning demand become, the greater will be the cost of peak electricity generation capacity, which must be maintained but sit idle all the rest of the year. Thus more extreme weather leads to a need for more power plant capacity, and to higher average costs for electricity.

Increased electricity generation means an increased use of water resources, at exactly the time when other demands for water will peak. Both fossil fuel and nuclear power plants require huge quantities of cooling water, in many cases withdrawn from rivers and estuaries. The cooling process is less efficient when the incoming water temperature is higher, as it will be during a heat wave. Yet other demands for water, for household use, irrigation, and other purposes, will also increase when it is hotter. During the 2003 heat wave, when "cooling water" taken from rivers was quite warm, French nuclear plants came within 2^o of the temperature requiring emergency shutdown; plant managers resorted to spraying water on the walls of nuclear reactors that were most exposed to sunlight, in order to keep them cool enough to operate.[11] Even in the most affluent countries, more extreme summer peak temperatures could lead to a joint crisis of energy and water supplies.

A similar pattern could emerge in other sectors. For example, the 2003 European heat wave revealed the need for stronger year-round emergency medical services. Maintaining emergency medical capacity that is used only a few times a year is expensive, just like maintaining peak power plant capacity. Intensifying extremes of weather will thus redirect the resources of developed countries, into building seawalls and storm barriers, peak power generation capacity, and emergency services. Jobs and incomes will be created, but an increasing share of them will be devoted to protecting ourselves from harms of our own making, providing services and defenses that nature once offered for free. For developing countries, where resources may not be available to provide the same level of protection, the economic and human costs of worsening weather extremes will be much starker.

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[11] "Europe swelters under heat wave," CNN.com, August 6, 2003, http://www.cnn.com/2003/WORLD/europe/08/05/heatwave/ .

Fresh water

Climate change also has an impact on the quality and quantity of fresh water supplies sufficient for drinking, sanitation, agricultural, and industrial needs. Higher global average temperatures, and even larger increases to temperature in certain regions, will result in more rapid evaporation and the need for more intense irrigation. The most vulnerable areas will be those that are already water-stressed and the developing regions that lack water managements systems that could act as buffers to increasing variability in water quality and quantity (IPCC 2001a, 193-226).

Regions that in the past have had snow-pack and glaciers (which act as natural storage systems for winter's accumulation of precipitation and then gradually release it throughout the spring and summer) will begin to experience their peak stream-flow in winter, instead of spring when there is a greater need for irrigation water. In the short run, flooding from rapidly melting glaciers is anticipated, but as glaciers begin to shrink and small glaciers disappear altogether, some rivers and streams are already beginning to dry up in summer (IPCC 2001a).

In some areas, floods will increase in scale and frequency, while in other areas droughts will become more common and more prolonged. Stream-flow is expected to increase in the higher latitudes and in southeast Asia, but a decrease is expected in central Asia, the Mediterranean, southern Africa, and Australia. Average precipitation levels do not, however, tell the whole story: more extreme weather events, more floods, and more resulting property and ecosystem damage are expected world-wide (IPCC 2001a).

The shift of peak stream-flow to winter will have an additional effect in areas, like China, India and the western U.S., that are heavily dependent on hydroelectric power generated by rivers flowing from winter snow-pack or glaciers. When stream-flow peaks in winter, so too will electricity generation – at exactly the wrong time to meet high summer demands for air conditioning and refrigeration in homes and businesses. Indeed, as the global climate warms, the summer peak in demand for power will grow even higher, just as summer supplies of power dry up.

The quality of water is also likely to suffer. Water quality will decrease both with warmer water temperatures and with run-off caused by more precipitation or by extreme storms. An increase in water temperatures will lead to faster growth of microbes and algae. Warmer water temperatures together with more storm run-off have the effect of lowering water levels in lakes and streams, thereby introducing higher concentrations of agricultural chemicals and heavy metals. Heavy rainfall results in saturated soils, through which the microbes responsible for diarrheal diseases are transported more easily. Higher air and water temperatures are also associated with more frequent outbreaks of cholera and childhood diarrhea. Run-off is also likely to be more polluted with human sewage as well as agricultural wastes and chemicals. In areas close to coastlines, rising sea levels cause an increase in saltwater intrusion into natural fresh water bodies and into fresh water delivery systems (Epstein and Mills 2005).

Countries that are already experiencing water-stressed conditions will grow rapidly in population, from 1.8 billion in 1990 to 5 billion by 2025. Climate change will make this problem even worse, creating further stresses on water supplies (Arnell, 1999). The Millennium

Development Goal of halving the number of people without sustainable access to safe drinking water and basic sanitation by 2015 is already an enormous challenge; with climate change, this goal will be even more difficult to meet (UN-DESA 2006).

Again, developing countries bear the brunt of the impacts from climate change. Today, most of the current water-stressed areas are in the South; many people living in the South have limited access to health care systems, at least in comparison to their Northern counterparts; and many urban and most rural communities in the South have little or no access to safe, clean drinking water because of a lack of water treatment, water delivery, and sanitation systems. The developing world's ability to meet the challenges posed by less water, worse water, and occasional flooding will be severely constrained by its existing poor or absent infrastructure for water, sanitation, and healthcare. At the same time, variations in rainfall and the disappearance of snow-pack and glacier-fed streams will place an added burden on developing countries' agricultural systems, already stressed by higher average temperatures and more frequent heat waves.

Human health

Most people would imagine – quite correctly – that climate change is going to be increasingly bad for human health. Tropical diseases will spread northward, and heat waves and other extreme events will become more common. The effects on developing countries will make it difficult or impossible to meet the Millennium Development Goals for health improvement. Some researchers, however, have claimed to find large health benefits from the early stages of climate change.

The supposed health benefits of climate change are based on a misunderstanding of the relationship between mortality and short-term temperature variation. Deaths from cardiovascular and respiratory diseases among the elderly are quite sensitive to daily temperature changes. Virtually all studies have found a "minimum mortality temperature", with more deaths at either lower or higher temperatures (Martens 1997). That is, a graph of death rates versus temperature is V-shaped, with the point of the V representing the minimum mortality temperature.

Some researchers have used this V-shaped relationship to estimate global changes in mortality due to gradual warming, assuming that the minimum mortality temperature remains fixed. In some studies, this has led to the surprising prediction that the early stages of warming will lead to fewer deaths worldwide (Tol 2002; Bosello et al. 2006).[12] It is a mistake, however, to assume that the minimum mortality temperature is a constant. It varies widely from place to place; it is 16.5° in Amsterdam, but may be as high as 29° in Taiwan (Martens 1997). In the U.S., the minimum mortality temperature is 9° warmer in Miami than in Chicago (Curriero et al. 2002). Although the process is not well understood, it appears that the minimum mortality temperature adapts, at least partially, to prevailing local conditions (Martens 1997). Thus it is not reasonable to make sweeping global projections on the basis of a fixed minimum mortality temperature, as some economists have done. One of the most dramatic projections of fewer deaths from near-

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[12] Other studies of the same effect have predicted roughly no net change due to warming (McMichael et al. 2003).

term warming also makes the assumption that no rural deaths are caused by excessive heat, an unsupported notion that appears to be contradicted by the evidence on heat waves in India (Bosello et al. 2006).[13]

In general, there are only limited health effects associated with moderate increases in average temperature in developed countries. Some studies have found decreasing sensitivity to temperature variation in developed countries, possibly related to the spread of air-conditioning and adequate health services (Davis et al. 2003; Carson et al. 2006). The short-term health consequences of warming will be increases in the impact of tropical diseases in the poorest and hottest countries. Meanwhile, extreme weather events will be harmful to human health everywhere.

In the extreme, it is clear that climate change can kill you. As many as 50,000 people may have died in the 2003 heat wave in Europe (Brücker 2005). This was an unusually high toll, in part reflecting a lack of preparation which has since been corrected. But it was not completely unique; extreme weather events routinely cause large numbers of deaths. The U.S. suffered 1800 deaths from Hurricane Katrina in 2005,[14]and more than 700 fatalities from a 1995 heat wave in Chicago (Klinenberg 2002). The heat waves of summer 2006 killed at least 1000 in the Netherlands and 200 in the U.S.[15] Heat waves in India, in which temperatures sometimes reach 49°, have killed more than a thousand people on several occasions in recent years (De et al. 2005).

In the long run, if climate change is not brought under control, changes in average conditions will be much more severe. Some models now forecast that by the end of this century, typical summer temperatures in Europe will be at the level of the 2003 heat wave, i.e. 5° above 20th-century averages. But the near-term health effects of warming will be concentrated among those living in hotter climates, and/or those who are particularly vulnerable to disease (Schär et al. 2004).

Table 4 below summarizes the likely increase in risk of diarrhea, death from flooding, and malaria by region. In developing, tropical countries, people continue to die in large numbers from diseases that are rare – or at least rarely fatal – in richer, temperate countries. More than a million people a year die from malaria, almost all in Africa; in addition, 2 million annual deaths result from diarrhea, almost all in Africa and Asia (WHO 2004). A conservative, carefully calculated estimate by the World Health Organisation suggests that in 2000, worldwide deaths attributable to climate change included at least 77,000 due to malnutrition, 47,000 due to diarrhea, 27,000 due to malaria, and 2,000 due to flooding (McMichael et al. 2004). While these are small fractions of total deaths from these conditions, climate-related deaths will increase (unlike many other causes of disease), both because the population is growing in the hardest-hit regions, and because the risks will increase in future, as shown in Table 4. Warmer, wetter

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[13] For a detailed critique, see (Ackerman and Stanton 2006).

[14] As of August 2, 2006, the Louisiana Department of Health and Hospitals reported 1464 deaths in Louisiana, and 346 deaths in other states, due to Hurricane Katrina, http://www.dhh.louisiana.gov/offices/page.asp?ID=192&Detail=5248.

[15] Heidi Cullen, "Heat Wave Death Toll Numbers Trickling In," http://www.weather.com/blog/weather/8_10348.html.

conditions promote the spread of both the mosquitoes that transmit malaria and the pathogens that cause the most serious forms of diarrhea in developing countries. The relationship of both diseases to temperature is well established; even gradual warming is likely to worsen both, except where limited by declining precipitation. Droughts will limit both diseases, but storms and floods will help them to spread. Although there is debate about the extent of the effect, it is now recognized that climate change will allow malaria to spread farther north, and to higher altitudes (Hales et al. 2003; Epstein and Mills 2005).

More deaths from malnutrition are also expected as temperatures begin to rise, due to the forecast of a decline in crop yields in the tropics (discussed in the agriculture section above). This could be mitigated by aid and trade, but in the absence of major policy changes, the regions of the world with the fastest growing populations will also be the ones with declining food supplies in the next few decades. Of course, malnutrition, malaria, and diarrhea interact with each other, and with other diseases such as HIV-AIDS; people weakened by one disease are more likely to be harmed by another one.

Table 5. Percentage increase in health risks in 2030 due to climate change

Health impact	**Diarrhea**			**Death in coastal floods**			**Death in inland floods**			**Malaria**		
Temperature change	*>2º*	*>3º*	*>4º*	*>2º*	*>3º*	*>4º*	*>2º*	*>3º*	*>4º*	*>2º*	*>3º*	*>4º*
Africa - D	5%	6%	8%	44%	48%	64%	130%	99%	66%	1%	1%	2%
Africa - E	5%	6%	8%	12%	13%	18%	130%	99%	86%	7%	9%	14%
Americas - A	0%	0%	0%	13%	14%	19%	1050%	866%	699%	27%	33%	51%
Americas - B	0%	0%	0%	90%	96%	127%	160%	218%	203%	8%	10%	15%
Americas - D	2%	2%	2%	258%	276%	364%	192%	126%	140%	4%	5%	8%
Middle East/Central Asia - B	0%	0%	0%	53%	57%	75%	220%	304%	304%	0%	0%	0%
Middle East/Central Asia - D	6%	6%	9%	201%	218%	291%	429%	356%	368%	15%	19%	29%
Europe - A	0%	0%	0%	9%	10%	14%	430%	427%	453%	0%	0%	0%
Europe - B	1%	1%	1%	378%	402%	531%	132%	216%	146%	0%	0%	0%
Europe - C	0%	0%	0%	3%	3%	4%	145%	331%	245%	25%	31%	48%
Southeast Asia - B	0%	0%	0%	28%	30%	39%	151%	257%	139%	0%	0%	0%
Southeast Asia - D	6%	7%	9%	3%	3%	4%	73%	39%	21%	0%	1%	1%
East Asia/Oceania - A	0%	0%	0%	3%	3%	4%	191%	104%	132%	25%	30%	48%
East Asia/Oceania - B	0%	0%	1%	4%	4%	5%	88%	100%	130%	22%	26%	42%

Source: McMichael, 2004. Data refer to McMichael's middle scenario for 2030.
Temperature changes correspond to stabilization of CO2 levels at 550 ppm, 750 ppm, and no stabilization.
Regions are subdivided by mortality levels (the UK is in Europe - A):

	child mortality	*adult mortality*
A	*very low*	*very low*
B	*low*	*low*
C	*low*	*high*
D	*high*	*high*
E	*high*	*very high*

These worsening disease conditions in developing countries fly in the face of the Millennium Development Goals, which set out an ambitious agenda for improvements in health. The goals include reducing under-5 mortality by two-thirds and maternal mortality by three-quarters between 1990 and 2015, and halting and beginning to reverse the spread of malaria and other major diseases by 2015 (UN-DESA 2006). These goals will be all but impossible to achieve as long as climate change, largely caused by greenhouse gas emissions in developed countries, is worsening the conditions of life and promoting the spread of life-threatening diseases in the poorest countries of the world.

Ecosystems and extinctions

Human beings are extremely adaptable. We live in very nearly every climate on Earth, at both ends of every extreme: temperature, elevation, precipitation. We can quickly accustom ourselves to new climates, and we can use technology to make unpleasant climates more livable. During the first 2º of climate change, and even for some time beyond that, the human species as a whole is resilient enough to adapt and survive; the risk of our extinction is negligible. When extreme events, like floods or heat waves, outpace our ability to adapt, then tragically it is very often the most vulnerable people – especially the elderly, the infirm, small children, and those whose economic or social marginalization impedes their ability to relocate or use technology as a buffer – that are injured, made ill, or die. At great social and economic cost, others survive, adapt, and rebuild.

Many natural ecosystems lack the resilience of the human species: as climatic conditions change, certain species, or even entire ecosystems, may be unable to keep pace. In addition to the value of ecosystems in and of themselves, many ecosystems provide essential services on which human beings depend for their survival. Even those human beings who have the means to successfully adapt to a warmer climate would find it very difficult to survive without vital ecosystem services like oxygen production, carbon storage, the hydrological cycle, and protection of coasts from waves and wind.

Ecosystems have differential sensitivities: some are more resilient to changes in average temperature and precipitation, and the effects of extreme weather than others. Those ecosystems or particular species that are currently at the top of their temperature range or at the extreme of their precipitation range may not be able to weather even 2º of warming.

One of the ecosystems most vulnerable to warming is that of coral reefs, in which one-third of all marine species live. Coral reefs provide important ecosystem services, like coastline protection, and several forms of human industry utilize them, for example, fisheries and tourism. In many reefs, coral is already living at the top of its temperature range. As little as 1.0º warmer ocean temperatures are expected to have dramatic and irreversible effects on coral populations. In water that is too warm, large sections of reefs can experience fatal "bleaching." In some areas, an increase in water temperatures of just 0.5º is expected to cause annual large-scale bleaching, resulting in enough coral mortality to lead to the extinction of some species (IPCC 2001a, 361, 858-859).

Polar bears and other animals dependent on a sea-ice habitat are also extremely vulnerable to the effects of small increases in the average temperature. Already sea ice is melting several weeks earlier in the spring than it did a few decades ago, and the Arctic is expected to experience a greater degree of climate change-related warming then the change in global average temperature. Specialists in Arctic and Antarctic ecosystems fear that extinction for some sea-ice dependent species is becoming more and more probable in the short-run (IPCC 2001a, 311-315).

Other types of ecosystems exist at the extremes of tolerance for precipitation, too much and too little. Desert ecosystems, for example, tend to be very delicate and vulnerable to any change in precipitation. In those arid areas where rainfall will increase with climate change, causing deserts and their ecosystems to shrink, the likely result will be the extinction of as much as one-half of all plant and animal species. With neither established ecosystem services nor built infrastructure to protect them, human communities that live in desert ecosystems are also vulnerable to flooding caused by annual precipitation increases and by large storms. In addition, in those deserts likely to experience a reduction in annual rainfall, ecosystems that currently have just enough water to survive will begin die off: in these areas, deserts will expand, but desert ecosystems will shrink (IPCC 2001a, 280-286).

Those ecosystems that can – with or without human efforts at conservation – adapt quickly enough to keep pace with the initial average effects of climate change may still be at the mercy of changing weather patterns. Increased variability in temperature and precipitation, as well as extreme storms, floods and heat waves, may be more than many natural ecosystems can withstand. In some cases, hardier species (the plant and animal equivalents of the rat or the cockroach that exist at the margins of every ecosystem) will begin to out-compete the species prized for their usefulness or their beauty by human beings.

As temperatures rise beyond the initial 2º change, more ecosystems will reach the limits of their ability to adapt. As climates zones push pole-ward, the least mobile species – often trees or other plants that need many years to reach maturity and reproduce – will be unable to keep pace. In some cases, ecosystems are robust enough to adapt to the loss of one or more species. But often ecosystem well-being is extremely dependent on the survival of a small number of “keystone” species. In the case of forests, trees provide food, shelter, and water to the entire ecosystem, as well as creating a micro-climate of lower temperatures and higher humidity. If key tree species cannot keep up with climate change than whole forest ecosystems will cease to exist (IPCC 2001a, 286-295). With climate change, meeting the Millennium Development Goal of integrating the principles of sustainable development into country policies and programs, and reversing the loss of environmental resources is even more critical, and also much more challenging (UN-DESA 2006).

Summary measures of the economic costs of climate change

The costs of climate change, described in the previous sections, will have profound effects on many aspects of life. Some are relatively predictable, well-defined monetary costs; others are uncertain and/or hard to express in financial terms. In terms of the risk matrix in Figure 1, many crucial impacts of climate change fall outside the easily measured, upper left-hand corner of the matrix.

Nonetheless, there is a continual demand for a summary, “bottom line” numerical estimate of climate costs as a whole. Two types of estimates can be found in the discussion of climate change: global estimates of total costs in the future, or over a long span of years; and estimates of the costs imposed on society by an additional tonne of carbon emissions, or the “social cost of carbon.” Both produce impressively large numbers, but both are incomplete – and cannot easily be completed, for reasons that we address in the following sections.

Global cost estimates

How much, in total, will climate change cost over the next 100 to 200 years? Economic forecasts over such vast stretches of time are inevitably uncertain. The numerous varieties of harm caused by the changing climate, discussed in this report, will interact in ways that are not precisely predictable – and become rapidly less predictable as we look farther into the future. Moreover, the effort to collapse the vast breadth of information about climate impacts into a single number inevitably loses important details and runs the risk of oversimplification.

Two recent modeling efforts, using similar assumptions reflecting the dangers of unrestrained emissions, have produced roughly similar results. Both rely on projections that, in the absence of mitigation efforts including new climate protection policies, average temperatures could reach 4° above the preindustrial level by 2100.[16] As discussed earlier, 4° of warming is enough to cause serious harm to agriculture, human health, and ecosystems worldwide, and to create some chance of a true catastrophe. Thus it is not surprising that the models produce large numbers for the resulting damages.

One estimate, from the World Integrated Assessment General Equilibrium Model (WIAGEM), operated by the German Institute for Economic Research (Deutsches Institut für Wirtschaftsforschung, DIW), is that if nothing is done to restrain greenhouse gas emissions,

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[16] Specifically, they rely on the A2 scenario from the 2001 IPCC report, which projects 4.1° of warming by 2100 in the absence of new policy initiatives.

annual economic damages could reach US$20 trillion by 2100 (expressed in U.S. dollars at 2002 prices), or 6 to 8 percent of global economic output at that time (Kemfert 2005).[17] The same study found that immediate adoption of active climate protection policies could limit the temperature increase to 2° and eliminate more than half of the damages; by 2100 this would avoid $12 trillion in annual damages by spending $3 trillion per year on climate protection. If, however, climate protection efforts do not begin until 2025, the same model estimates that it will be impossible to limit warming to 2° by 2100 – and climate protection in general will be more expensive, the later it starts.

WIAGEM is innovative in its integrative structure; its detailed cost figures rest on estimates of climate damages published by other researchers. In particular, it incorporates the partial calculations of monetary costs of climate change that are available in the economics literature. In terms of the risk matrix (Figure 1, above), it includes market impacts of average changes, plus partial estimates of non-market damages and extreme weather impacts. That is, it encompasses only parts of the risk matrix. Its estimates of future damages, as large as they are, represent only a fraction of the full range of risks and harms that will be caused by climate change.

Another estimate, from the PAGE model run by University of Cambridge researcher Chris Hope, was used in a study for the European Commission's DG-Environment (Watkiss et al. 2005). It estimates that in the absence of new policies, the discounted present value of all cumulative climate damages from now through 2200 will amount to US$74 trillion (at 2000 prices). The average annual damages, from 2000 through 2200, will be $26 trillion, reasonably close to the WIAGEM estimate for 2100 (Hope 2003).[18] Like WIAGEM, the PAGE model finds that more than half of those damages can be avoided by immediate adoption of active climate protection policies.

The description of PAGE (Hope 2003) suggests that its treatment of climate damages, although thorough in many areas, and impressive in its careful approach to uncertainty, is potentially incomplete in other respects. It relies on earlier consensus estimates, as presented in the 2001 IPCC report, of the magnitude of economic damages attributable to a specified degree of warming; thus it is limited by the scope of the available economics literature, just as WIAGEM is; and it does not reflect the extensive newer research which has continued to find more serious problems even from small temperature increases. It includes a growing chance of catastrophe as temperatures rise, but the catastrophe amounts to a loss of roughly 10 percent of global income. This can be compared to the estimated 15 percent loss of income in Louisiana following Hurricane Katrina in 2005, as explained above.

The incompleteness of these models reflects the inescapable limitations of economic forecasting. Both offer ambitious, extensive attempts at comprehensive cost calculations. But both models, like any such model, cannot assign meaningful dollar values to all of the non-market and socially contingent impacts of climate change, nor to the uncertain but growing risks of true catastrophe. The models' enormous damage estimates, reaching unimaginable levels of trillions of dollars (or pounds), still necessarily omit some of the most troubling potential consequences of climate change.

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[17] Confirmed by personal communication from Claudia Kemfert, September 2006.

[18] On the compatibility of the two models, see also Appendix II.

The social cost of carbon

Global modeling of climate damages is an expensive and time-consuming process, and the resulting global estimates are difficult to apply to the evaluation of multiple policy options. For purposes of policy analysis, many studies have estimated a measure of incremental damages, the “social cost of carbon” (SCC). In the words of a recent review of the subject, the SCC is the “value of climate change impacts... [caused by] one additional tonne of carbon emitted to the atmosphere today. It is the marginal global damage costs of carbon emissions.”(DEFRA 2006, ii) The implication is that, if carbon emissions can be reduced at a cost per tonne less than or equal to the SCC, society as a whole is better off: the reduction in damages is worth more than the cost of reducing emissions.

In 2002, the UK Government Economic Service recommended the use of £70 per tonne of carbon as an estimate of the SCC, with a range of £35 to 140. A review of these values, commissioned by the DEFRA in 2005, confirmed that £35 was a reasonable lower bound on the SCC, but was reluctant to endorse a best guess or upper bound (DEFRA 2006). The proliferating estimates of the SCC range from zero or even slightly negative values, to several hundred pounds per tonne of carbon. With many reservations and qualifications, the DEFRA review proposed “central guidance” estimates of the SCC, rising from £68 in 2010 to £143 in 2050. The principal qualification was that these values “should only be used as part of a wider framework that considers additional effects of non-quantifiable impacts across the full risk matrix.”(DEFRA 2006, xi)

This qualification is important because so many studies of the SCC include only very partial treatment of climate change impacts. Of the 28 studies examined in the DEFRA review, most stick to the market impacts of predictable, average changes in climate (i.e., the upper left-hand cell of the risk matrix, labeled “easiest to measure” in Figure 1). Only a few explore valuation of non-market impacts and/or extreme events; virtually none have considered the costs of a catastrophe, or socially contingent impacts. Drawing on the same research literature as the models discussed above, the SCC studies have similar limitations in scope.

That is, all of the studies that estimate the social cost of carbon base their numbers on an incomplete picture of climate risks – often encompassing only the simplest and most predictable corner of the vast, troubling canvas that has been painted by climate science. There is, of course, no way to assign monetary values to the global response to the possibility of widespread droughts across large parts of Asia, or an increase in the probability of a sudden change in ocean currents that would make the UK as cold as Canada. But in the understandable absence of such impossible monetary values, it is important to remember the disclaimer from the DEFRA review: all estimates of the SCC omit some of the most important, unpriced risks of climate change. The same disclaimer applies to virtually any quantitative economic estimate of climate impacts.

In view of this serious incompleteness, SCC estimates are more useful for endorsing proposals than for rejecting them. Any opportunity to reduce carbon emissions at a cost lower than the SCC is surely worthwhile, because the benefit to society from reduced emissions is worth more than the SCC. But the reverse is not true: carbon reduction strategies should not be ruled out just because their costs exceed the SCC, since the substantial unpriced benefits of reducing emissions might still justify the additional cost.

Valuation

A huge and growing research effort has gone into estimating both global damages and the SCC, as described in the preceding sections. The resulting estimates have underscored the seriousness of the problem, providing valuable numerical measures of the costs of inaction on climate change. But no matter how far this research goes, it will remain intrinsically incomplete. Like other economic analyses of health and environmental impacts, estimates of climate damages rely on a host of hidden assumptions, which – once revealed – raise concerns about the essential plausibility and ethical significance of the resulting bottom line. When the values of ecosystems, human lives, and our enjoyment of our local climate are converted into monetary values in order to combine all costs and benefits into a single price tag for climate change, much of what is most meaningful in these predictions gets lost.

Ecosystem damages and the extinction of species can in theory be monetized by adding together the projected value of building and operating replacements for lost ecosystems services – think of the costs of water purification, replacing once-clean rivers that have become polluted – plus the subjective value that humans place on the existence of these ecosystems (as estimated by "contingent valuation" surveys). But the values that current generations place on an ecosystem, even if accurately estimated, may not sum up to the true worth of that ecosystem, even when narrowly defined as its worth to human beings. Ecosystems may provide services and share interdependencies that are not yet fully understood. For this, among other reasons, future generations may place a higher value both on ecosystems services and on the existence of certain ecosystems. Another liability of this method is that surveys estimating values of ecosystems have only been carried out in a few locations, but these results are applied to ecosystems around the world – often with valuations weighted in proportion to the local per capita income.[19] Endangered species that have the foresight to live in rich countries are thus declared to be "worth" more than those who have only low income human neighbors.

Human lives lost as a result of climate change can be monetized by assigning a – necessarily arbitrary – value to each life. In recent U.S. EPA cost benefit analyses, for example, this was often equivalent to £3.2 million under the Clinton administration, or £2.0 million under the Bush administration (Ackerman and Heinzerling 2004). But once a monetized value of lost lives has been added together with property damage, clean-up costs, and reduced production, what is the meaning of the resulting sum? If we use it, as in SCC, to compare the cost of damages due to climate change to the cost of mitigation, what do trade-offs at the margin imply? This is really about deciding whether or not the research and development of an alternative fuel, for example, will cost too much in comparison to the amount of carbon that it can offset at £70 per tonne. How is the quality of decisions like this improved by lumping goods and services that can be bought and sold in a market – like steel girders or labor hours – together with human lives, which

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[19] See (Tol 2002)

both legal and moral codes prevent us from trading? The dubious ethical import of monetizing human lives is further compounded when, as in some SCC estimates, the value of a life is made proportional to the income per capita in each country, so that the cost of a lost human life ranges from £20,000 to £6 million depending on the country.[20] Developing countries have, needless to say, reacted badly to the idea that their citizens' lives are "worth less" than those in rich countries.

The mischief that can be done by casually assigning prices to priceless values is visible in a study by William Nordhaus, a well-known American economist (Nordhaus 1999; Nordhaus and Boyer 2000). Despite careful work in many areas of analysis, the study undoes itself with one silly assumption. Based on the fact that Americans spend more on summer than on winter outdoor recreation, Nordhaus concludes that there is a huge subjective desire, and willingness to pay, for hotter weather in rich northern countries. In his view, people worldwide feel that the optimal temperature is a year-round average of 20° – the temperature of Houston or New Orleans in the U.S., or Tripoli in Libya. His monetization of the assumed craving for heat is weighed against real damages caused by climate change in his cost-benefit analysis; on this basis, he finds that there will be no net damages until the world has become quite a bit warmer.[21] Any useful details found in other aspects of Nordhaus' research are obscured, not clarified, by his attempt to put a price on the subjective experience of heat (Ackerman and Finlayson 2006).

Discounting

If the causes of climate change remain unmitigated, some of the most severe effects will not begin in earnest for another 50 years or more. Even if we stop or drastically reduce carbon emissions immediately, the effects of climate change will be felt nonetheless for a century or more. How can we add up all of the future effects of climate change in a way that takes account of how each new generation will be impacted? In most economic analyses, including those discussed here, future costs and benefits of climate change are "discounted" before they are summed up. Discounting reduces future costs and benefits, placing the greatest emphasis on present day effects: the farther into the future the predicted effect, the lower the weight it is given. The pace of this shrinkage of the future is governed by the "discount rate," measuring the percentage loss of value for every year that passes. Thus a larger discount rate means that a smaller weight is given to future costs and benefits (Ackerman and Finlayson 2006).

A high or moderate discount rate implies that even the most serious far-future outcomes don't matter much to the present generation. At a 4 percent discount rate, often used in recent European Commission analyses, a benefit of £1 million, occurring 200 years from now, has a present value of about £400. Thus unless the discount rate is very low, the benefits of climate change mitigation in future centuries are almost worthless in present value terms, and many short-term preventive expenditures are "too expensive" relative to their discounted benefits. The PAGE model, discussed above, used a discount rate of about 4 percent, and summed up 200

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[20] See (Tol 2002)

[21] Other survey research, examining actual attitudes toward temperature, has produced far smaller estimates of the psychological benefits of warming, suggesting that only a few of the northernmost countries will enjoy even the next few decades of climate change (Rehdanz and Maddison 2005).

years of damages, averaging £26 trillion per year, to a present value total of only £74 trillion. Alternatively, using the discount rate schedule recommended by the UK Treasury Green Book, the present value of climate damages might almost double, as illustrated in Appendix II.

It is a well-known finding in climate economics that the choice of the discount rate dominates the results: with exactly the same facts and assumptions about present and future costs and benefits, a low discount rate implies a high SCC and a strong rationale for active mitigation efforts – while a high discount rate implies a low SCC and almost seems to justify inaction. But the choice of the discount rate for long-run climate studies is not a matter of objective scientific analysis. Rather, it is an expression of concern (or lack thereof) about the welfare of the generations that will follow us.

Conclusions and Policy Recommendations

Our common future is at risk from climate change. Behind the summary numbers – £74 trillion of cumulative global damages, the social cost of carbon at £70 per tonne and rising – lies a story of multiple, interacting, and worsening harms. The first 2º of climate change will be costly in terms of economic disruption, lives lost or shortened, ecosystems damages, and species extinctions. Even with gradual average changes, the variability of temperatures and rainfall, as well as extreme storms, will have enormous costs. Before 2050, this will very likely be bad for developed countries, which have already begun to experience more severe hurricanes and heat waves. It will be much worse for developing countries, which will suffer greater losses and will have more limited resources to respond and adapt.

If nothing is done to reduce emissions, after 2050 average temperatures will continue rising into the much more dangerous zone beyond 2°. Agricultural losses, disruption of essential water supplies, health impacts, and ecosystem damages will rapidly worsen in every region, as will the likelihood of a global climate catastrophe. Vigorous action now, before these more severe impacts are visible, is essential in order to limit temperature increases to 2° and hold long-term damages to a survivable level.

While a certain amount of climate change is now inevitable, the impact of these changes will be disproportionately bad for the countries that have had the least to do with adding carbon to the atmosphere. It is vital that institutions address equity and provide relief as quickly as possible, before food and water problems in the developing world reach critical levels.

The only way to turn the supertanker around, and to avoid the worst effects of climate change above 2º, is to act promptly and on a large scale. Small adjustments to the amount of carbon released each year are insufficient to the task; the short-term targets of the Kyoto Protocol amount to only a gesture in the right direction. Waiting a while, in order to see if things really turn out as badly as predicted, will mean that we miss the last chance to ensure that our grandchildren, and their grandchildren, inherit a livable world.

Appendix I: Estimates of electricity required for air conditioning

This appendix explains and documents the calculations presented in the text, estimating what would happen if the UK moved to the U.S. level of air conditioning as a result of warming. This is not based on a particular temperature scenario that would trigger precisely the U.S. level of air-conditioning use. Rather, U.S. data provide a plausible, available example of the demand for air conditioning in an industrial country with hotter summers. Due to lags in data collection, the latest available U.S. data refer to 1999 to 2001; with several hot summers since that time, it is possible that current U.S. air-conditioning use is even higher than estimated here. Also, due to lack of data, no estimates are included for air-conditioning use in industry.

US electricity used for air conditioning. The 2001 Residential Energy Consumption Survey found that 16 percent of residential electricity use is for air conditioning. (http://www.eia.doe.gov/emeu/recs/recs2001/enduse2001/enduse2001.html). The 1999 Commercial Buildings Energy Consumption Survey implies that 26 percent of commercial electricity use is for air conditioning (our calculation, from http://www.eia.doe.gov/emeu/cbecs/enduse_consumption/intro.html). In these U.S. statistics, "commercial" includes offices and public administration; electricity users are classified as either residential, commercial, or industrial.

These percentages are applied to UK data to produce the estimates in the text. Note that we have used the U.S. *proportion* of electricity devoted to air-conditioning, not the absolute amount per capita. If the UK reached the U.S. level of per capita electricity use devoted to air-conditioning, the additional demand would be much greater than our estimates.

UK electricity use, extrapolated to "US levels" of air-conditioning demand. In 2005, total electricity consumption in the UK was 345,000 gigawatt hours (GWh; a gigawatt is a million kilowatts), of which 117,000 GWh went to domestic users, and 97,000 GWh to public administration and commercial users (http://www.dtistats.net/energystats/dukes5_2.xls). Our calculation assumes that these quantities include only a negligible percentage of air-conditioning demand. An increase of 22,000 GWh for residential air-conditioning, added to the actual 2005 usage, would make air-conditioning amount to 16 percent of residential electricity usage. An increase of 34,000 GWh for public administration and commercial users, added to the actual 2005 usage, would make air-conditioning amount to 26 percent of those customers' electricity usage. The combined effect for the two sectors is 56,000 GWh, or a 16 percent increase in total UK electricity consumption.

Price of electricity. A press release from the Department of Trade and Industry estimates an average electricity bill of £285 for 3300 kWh of electricity in 2005 (http://www.gnn.gov.uk/environment/detail.asp?ReleaseID=210961&NewsAreaID=2). This implies an average retail price of £0.086 per kWh. Applying this price to 56,000 GWh produces an estimated total cost of £4.8 billion.

Seasonal variation and need for new plants. UK electricity consumption currently peaks in the winter. In 2005, monthly consumption in both January and December was just over 33,000 GWh, while the monthly average for May through September – the period when virtually all air-conditioning demand will occur – was 27,000 GWh (our calculation from http://www.dtistats.net/energystats/et5_5.xls). Assuming that the plants that supply the winter peak are available from May through September, they can supply an additional average of 6,000 GWh per month for these five months, or a seasonal total of 30,000 GWh. Since we have estimated that moving the UK to the U.S. level of air-conditioning would add 56,000 GWh of demand, the idle capacity in the summer could in theory supply just over half of the additional demand.

However, air-conditioning usage is extremely temperature dependent, and is unlikely to be evenly distributed through the five-month stretch from May through September in exactly the same pattern as the available capacity. Thus it seems likely that the current capacity to increase summer generation would be exhausted, and new plants would be required, well before the UK reached half of the U.S. level of air-conditioning demand. These new plants would be idle for the rest of the year, outside of the air-conditioning season, unless other seasonal demands for electricity emerge in cooler weather.

Appendix II: Two approaches to long-term discounting

The PAGE model, as discussed in the text, projects damages over 200 years. On the assumption of no new mitigation efforts, it finds average damages of US$26 trillion, and a present value, at a constant discount rate of almost 4 percent, of $74 trillion (Hope 2003). It seems clear that damages will increase more than linearly over time; that is, damages will accelerate as time goes on. The simplest way to represent this algebraically is with a quadratic function: assume that annual damages are kT^2, where k is a constant and T is years since 2000. With k = $1.96 billion and a constant discount rate of 3.8 percent, this simple damage function matches the reported summary results of the PAGE model: the unweighted, undiscounted annual average damages for 2001 to 2200 are $26.3 trillion, while the present value over the same time period is $74.0 trillion. (Using this damage function, annual damages in 2100 are $19.6 trillion, thus also matching the result for the DIW model discussed in the text.)

The UK Treasury Green Book recommends a different approach to long-term discounting, where the discount rate declines over time, due to increasing uncertainty about the future (HM Treasury 2003). Specifically, it recommends a discount rate of 3.5 percent for years 1-30 into the future, followed by 3.0 percent for years 31-75, 2.5 percent for years 76-125, and 2.0 percent for years 126-200 (as well as further declines beyond year 200). Applying this schedule of discount rates to the quadratic damage function described above yields a present value, over 200 years, of US$137.2 trillion, or 85 percent more than the present value obtained with a fixed 3.8 percent rate. That is, with the same description of damages in each of the 200 years, the summary measure of the total cost can be changed from $74 trillion to $137 trillion, simply by switching from one to another widely used approach to discounting.

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