Challenge Paper

The Challenge of Global Warming

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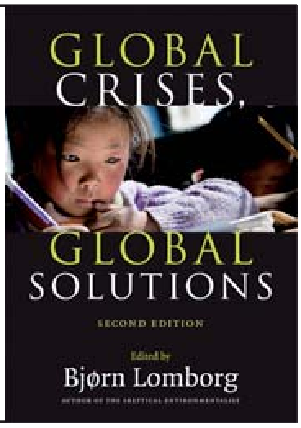

COPENHAGEN CONSENSUS 2008

GLOBAL WARMING

CHALLENGE PAPER

Copenhagen Consensus 2008 Challenge Paper

Global Warming

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Multiple changes are occurring simultaneously around the globe at an increasing pace. Energy and resource scarcities have emerged or intensified. Different trade regimes have evolved. New communication and information technologies have exploded into daily life. New human health issues have appeared, and old health issues have, in some cases, been exacerbated. Changes in global climate and associated patterns of extreme weather events must be added to this list, especially for the global poor whose very livelihoods depend directly in many instances on the use of specific natural resources.

The Intergovernmental Panel on Climate Change (IPCC), in its recently released Fourth Assessment Report (AR4), has concluded that a portfolio of mitigation and adaptation will prove to be the best option for dealing with climate change; see IPCC (2007b & 2007c). In this paper, we provide some additional evidence in support of such a multifaceted approach. In addition, it will become clear that ignoring climate change would mean that efforts which have been designed to ameliorate many of the other challenges contemplated in the Copenhagen Consensus exercise will ultimately be "swimming upstream" – i.e., expending effort unnecessarily simply to stay in place.

We begin in Section 1 by offering a brief overview of the state of knowledge about the risks of climate change. We rely heavily in this overview on the IPCC's AR4 (IPCC, 2007a and 2007b). Perhaps because many of the same authors were involved, the conclusions offered there (and here) are consistent with a parallel assessment conducted in support of Stern, *et al.* (2006). Both assessments build from the second assessment of the IPCC where the observation that global mean temperature is rising was statistically confirmed (IPCC, 1995). The IPCC concluded in its third assessment that increased concentrations of greenhouse gases (most notably carbon dioxide) were driving the warming and that climate impacts were beginning to be observed (IPCC, 2001). In its fourth assessment, the IPCC attributed observed impacts to anthropogenic sources (IPCC, 2007b) and the reported the statistical significance of anthropogenic sources of warming observed on continental scales (IPCC, 2007a).

Section 2 provides some insight into how two integrated assessment models (MERGE and FUND) were combined to produce emissions and impacts scenarios along which four alternative policy approaches are examined; two appendices provide more detail about the models themselves. The four approaches, described in our third section, including a "Business as Usual" baseline (alternatively viewed as a "No Climate Policy" Approach) as well as four more proactive approaches. All are consistent with the Copenhagen Consensus budget constraint both in the near term (the next four years) and the future (in monetary equivalence that recognizes the very long time horizon for any climate policy). We ultimately favor the fourth pro-active alternative, a combination of research and development, mitigation and adaptation, because it exploits the complementarity of straight mitigation efforts (enacted through economic mechanisms), enhanced investment in R&D for emissions saving and carbon sequestration technologies, and expanded adaptation to combat infectious disease.

Our results are presented in Section 4 where we report benefit-cost ratios using standard discounting practices that are well above the unity benchmark. Section 5 explores some caveats and extensions, most notably the significant value that would accrue if global policy over the next century or so could exploit cost minimizing flexibility over the timing of mitigation and investment efforts rather than adhering to the Copenhagen Consensus budget constraint each year. Concluding remarks in Section 6 bring our results into context with both the IPCC (2007a, 2007b and 2007c) assessments and the early contribution of Cline (2004) to the Copenhagen Consensus exercise.

1. Scoping the Problem

Section 1 summarizes briefly the state of knowledge about observed and anticipated climate change and associated impacts as reported in IPCC (2007a and 2007b). It begins with observed impacts, reviews anticipated climate trends and major sources of risk across sectors and continents, and concludes with a discussion of the value of pursuing mitigation and adaptation together in a portfolio approach designed to reduce risk.

Observed Climate Change through 2007.

A robust signal of anthropogenic climate change (particularly warming) has now been detected in every continent except Australia with strong statistical significance; and even there, the signal is quite evident. This signature conclusion of the Contribution of Working Group 1 to the AR4 is displayed in Figure 1.1 (Figure SPM.4, IPCC, 2007a). The result may be observed in the figure by noting that the bands of uncertainty for model simulations with and without anthropogenic forcing separate and that the pink bands (including anthropogenic forcing) capture observed trends in continental average temperature. This conclusion is important because it means that thinking about mitigation makes sense for every country, especially in the long run.

The manifestations of these observed changes have also been noted across the globe. The Tables 1.1 and 1.2, for example, provide the evidence with respect to transient trends in specific physical impacts and the incidence of extreme events (Tables 10.2 and 10.3, IPCC, 2007b). They focus on Asia, but they can easily be extended; the references listed can be tracked through Chapter 10 of IPCC (2007b). The take-home message for present purposes is that climate impacts have already been observed in precisely the regions where people are most vulnerable not only to climate-related stress, but also the other stresses captured in the Copenhagen Convention's list of challenges.

Figure 1.1: Identifying the Signal of Anthropogenic Warming on Continental Scales

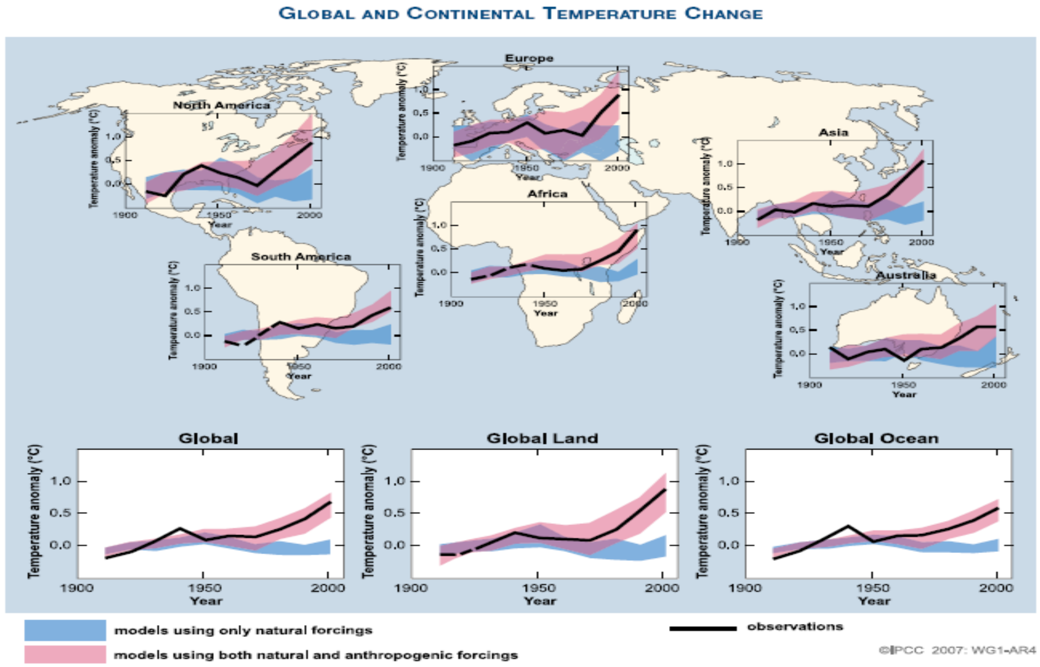


Figure SPM.4. *Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. {FAQ 9.2, Figure 1}*

Table 1.1: Observed Past and Present Trends in Climate and Climate Variability

Region	Country	Change in Temperature	Change in Precipitation	References
North Asia	Russia	2-3°C rise in past 90 years, more pronounced in spring and winter	Highly variable, decrease during 1951-95, increase in last decade	Savelieva, *et al.*, 2000; Peterson *et al.*, 2002; Gruza & Rankova, 2004
	Mongolia	1.8°C rise in last 60 years, most pronounced in winter	7.5% decrease in summer and 9% increase in winter	Natragdorj *et al.*, 2005; Batima *et al.*, 2005a
Central Asia	Regional mean	1-2°C rise in temperature per century	No clear trend during 1900-96.	Peterson *et al.*, 2002
	Northwest China	0.7°C increase in mean annual temperature from 1961 to 2000	Between 22% and 33% increase in rainfall	Shi *et al.*, 2002
Tibetan Plateau	Regional mean	0.16 and 0.32°C per decade increase in annual and winter temperatures, respectively	Generally increasing in northeast region	Liu and Chen, 2001; Yao *et al.*, 2000; Cai *et al.*, 2003; Liu *et al.*, 1998; Zhao *et al.*, 2004; Du and Ma, 2004
West Asia (Middle East)	Iran	During 1951- 2003 several stations in different climatological zones of Iran reported significant decrease in frost days due to rise in surface temperature	Some stations show a decreasing trend in precipitation (Anzali, Tabriz, Zahedan) while others (Mashad, Shiraz) have reported increasing trends.	Rahimzadeh, 2006, IRIMO, 2006a, b
East Asia	China	Warming during last 50 years, more pronounced in winter than summer, rate of increase pronounced in minimum than in maximum temperature	Annual rain declined in past decade in Northeast and North China, increase in Western China, Changjiang River and along southeast coast	Hu *et al.*, 2003; Zhai *et al.*, 1999; Zhai and Pan, 2003
	Japan	About 1.0°C rise in 20th century, 2 to 3°C rise in large cities	No significant trend in the 20th century although fluctuations increased	Japan Meteorological Agency, 2005; Ichikawa, 2004

Table 1.1 continued

Region	Country	Change in Temperature	Change in Precipitation	References
	Korea	0.23°C rise in annual mean temperature per decade, Increase in diurnal range	More frequent heavy rain in recent years	Jung *et al.*, 2002; Ho *et al.*, 2003
South Asia	India	0.68°C increase per century, increasing trends in annual mean temperature, warming pronounced during post monsoon and winter	Increase in extreme rains in northwest during summer monsoon in recent decades, lower number of rainy days along east coast	Lal, 2003; Lal *et al.*, 2001; Lal *et al.*, 1996; Kripalani *et al.*, 1996; Singh and Sontakke, 2002
	Nepal	0.09°C per year in Himalayas and 0.04°C in Terai region, more in winter	No distinct long-term trends in precipitation records for 1948-1994	Shrestha *et al.*, 2000; Bhadra, 2002; Shrestha, 2004
	Pakistan	0.6 to 1.0°C rise in mean temperature in coastal areas since early 1900s	10 to15% decrease in coastal belt and hyper arid plains, increase in summer and winter precipitation over the last 40 years in northern Pakistan	Farooq and Khan, 2004
	Bangladesh	An increasing trend of about 1°C in May and 0.5°C in November during the 14-year period from 1985–1998	Decadal rain anomalies above long term averages since 1960s	Mirza and Dixit, 1997; Khan *et al.*, 2000; Mirza, 2002
	Sri Lanka	0.016°C increase per year between 1961-90 over entire country, 2°C increase per year in central highlands	Increase trend in February and decrease trend in June	Chandrapala and Fernando, 1995; Chandrapala, 1996
SE Asia	General	0.1-0.3°C increase per decade reported between 1951-2000	Decreasing trend between 1961 and 1998; Number of rainy days have declined throughout SE Asia.	Manton *et al.*, 2001
	Indonesia	Homogeneous temperature data were not available	Decline in rainfall in southern and increase in northern region.	Manton *et al.*, 2001; Boer and Faqih, 2004
	Philippines	Increase in mean annual, maximum and minimum temperatures by 0.14°C between 1971-2000	Increase in annual mean rainfall since 1980s and in number of rainy days since 1990s, increase in inter-annual variability of onset of rainfall	Cruz *et al.*, 2005, PAGASA, 2001,

Table 1.2: Observed Changes in Extreme Events and Severe Climate Anomalies

Country/Region	Key Trend	Reference
Intense Rains and Floods		
Russia	Increase in heavy rains in western Russia and decrease in Siberia; Increase in number of days with more than 10mm rain; 50 to 70% increase in surface runoff in Siberia	Gruza *et al.*, 1999; Gruza and Rankova, 2004; Izrael and Anokhin, 2001; Ruosteenoja *et al.*, 2003
China	Increasing frequency of extreme rains in western and southern parts including Changjiang river, and decrease in northern regions; More floods in Changjiang river in past decade; More frequent floods in Northeast China since 1990s; More intense summer rains in East China; Severe flood in 1999; 7-fold increase in frequency of floods since 1950s.	Zhai and Pan, 2003; Zhai, 2004; Zhai *et al.*, 1999; Ding and Pan, 2002
Japan	Increasing frequency of extreme rains in past 100 years attributed to frontal systems and typhoons; Serious flood in 2004 due to heavy rains brought by 10 typhoons; Increase in maximum rainfall during 1961-2000 based on records from 120 stations.	Kajiwara *et al.*, 2003; Isobe, 2002; Kawahara and Yamazaki 1999; Kanai *et al.*, 2004
South Asia	Serious and recurrent floods in Bangladesh, Nepal and Northeast states of India during 2002, 2003 and 2004; A record 944 mm of rainfall in Mumbai, India on 26-27 July 2005 led to loss of over 1000 lives with loss of more than US$250 millions; Floods in Surat, Barmer and in Srinagar during summer monsoon season of 2006; May 17, 2003 floods in southern province of Sri Lanka were triggered by 730 mm rain	India Meteorological Department, Reports, 2002-06; Department of Meteorology, Sri Lanka, 2003
Southeast Asia	Increased occurrence of extreme rains causing flash floods in Vietnam; landslides and floods in 1990 and 2004 in the Philippines, and floods in Cambodia in 2000	FAO, 2004a; Tran Viet Lien *et al.*, 2005; Cruz *et al.*, 2005; FAO/WFP, 2000; Environment News Service, 2002
Droughts		
Russia	Decreasing rain and increasing temperature by over 1°C have caused droughts; 27 major droughts in 20th century have been reported.	Golubev and Dronin, 2003; Izrael and Sirotenko,2003
Mongolia	Increase in frequency and intensity of droughts in recent years; Droughts in 1999-2002 affected 70% of grassland and killed 12 million livestocks	Natsagdorj *et al.*, 2005; Batima, 2003
China	Increase in area affected by drought has exceeded 6.7 M ha since 2000 in Beijing, Hebei Province, Shanxi Province, inner Mongolia and North China; Increase in dust storms affected area	Zhou, 2003; Chen *et al.*, 2001; Yoshino, 2000,2002
South Asia	50% of droughts associated with El Niño; Consecutive droughts in 1999 and 2000 in Pakistan and NW-India led to sharp decline in water tables; Consecutive droughts between 2000 and 2002 caused crop failures, mass starvation and affected ~11 million people in Orissa; Droughts in NE-India during summer monsoon of 2006	Webster *et al.*, 1998; Lal, 2003; India Meteorological Department Report, 2006
Southeast Asia	Droughts normally associated with ENSO years in Myanmar, Laos, Philippines, Indonesia and Vietnam; Droughts in 1997-98 caused massive crop failures and water shortages and forest fires in various parts of Philippines, Laos and Indonesia	Duong Lien Chau, 2000; PAGASA, 2001; Kelly *et al.*, 2000; Glantz, 2001
Cyclones/ Typhoons		
Philippines	On an average 20 cyclones cross the Philippines Area of Responsibility with about 8-9 land fall each year; with an increase of 4.2 in the frequency of cyclones entering PAR during the period 1990-2003	PAGASA, 2001
China	Number and intensity of strong cyclones increased since 1950s; 21 extreme storm surges in 1950-2004 of which 14 occurred during 1986-2004	Fan and Li, 2005
South Asia	Frequency of monsoon depressions and cyclones formation in Bay of Bengal and Arabian Sea on the decline since 1970 but intensity is increasing causing severe floods in terms of damages to life and property	Lal, 2001; Lal, 2003
Japan	Number of tropical storms has two peaks, one in mid 1960s and another in early 1990s, average after 1990 and often lower than historical average	Japan Meteorological Agency, 2005

Anticipated Climate Change Impacts.

Warming is generally anticipated across the globe, but it will be unevenly distributed. The general trajectory will depend on global emissions scenarios, to be sure, but impacts will depend critically on local manifestations. Figure 1.2, for example, displays results across a collection of global circulation models in terms of global averages and the associated global distributions for three SRES scenarios (IPCC, 2000) for the 2020's and the 2090's (Figure SPM.6, IPCC, 2007a). Significant warming is expected everywhere, but especially in the northern latitudes. The 2 to 5 degree warming patterns expected across Asia and Africa by the 2080's along the higher emissions scenarios A1B and A2 are, perhaps, most troubling because they will impact the very people who experience stress from the other challenges. Indeed, even the B1 scenario would push temperatures 2.5 degrees higher toward the end of this century.

Figure 1.2: Projections of Surface Temperatures for the 2020's and the 2090's.

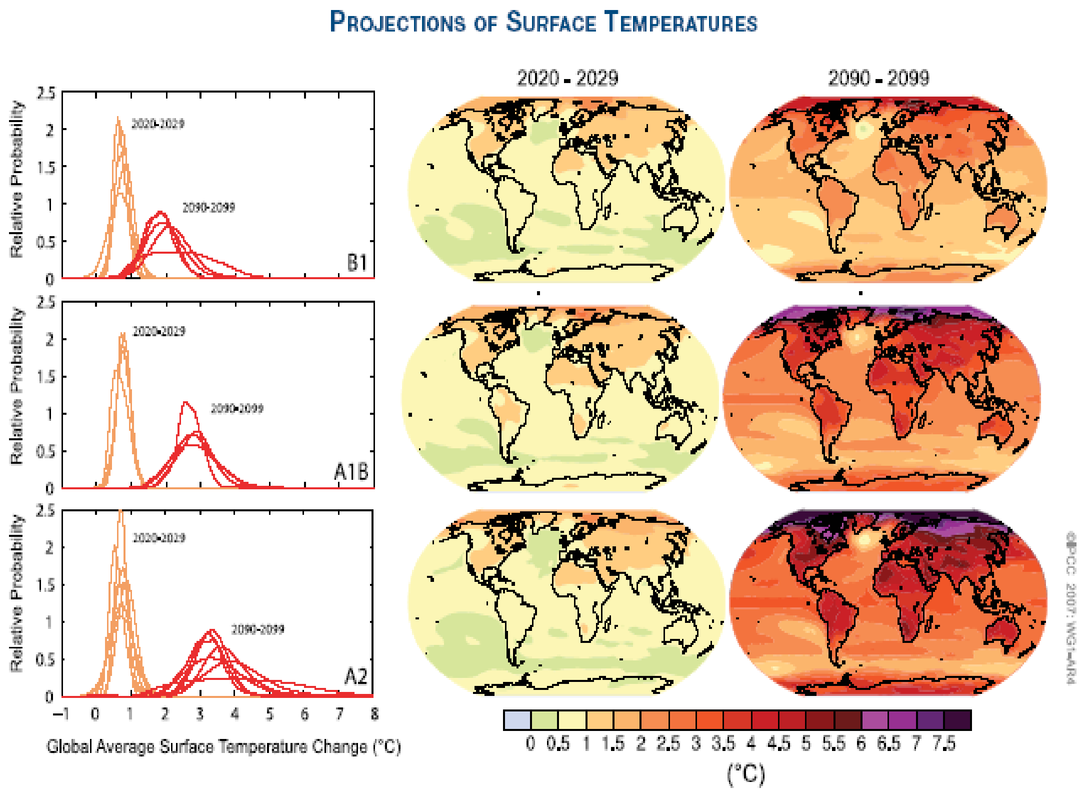


Figure SPM.6. *Projected surface temperature changes for the early and late 21st century relative to the period 1980–1999. The central and right panels show the AOGCM multi-model average projections for the B1 (top), A1B (middle) and A2 (bottom) SRES scenarios averaged over the decades 2020– 2029 (centre) and 2090–2099 (right). The left panels show corresponding uncertainties as the relative probabilities of estimated global average warming from several different AOGCM and Earth System Model of Intermediate Complexity studies for the same periods. Some studies present results only for a subset of the SRES scenarios, or for various model versions. Therefore the difference in the number of curves shown in the left-hand panels is due only to differences in the availability of results. {Figures 10.8 and 10.28}*

The discussion thus far has focused attention on what we know about the physical manifestations of climate change with only passing mention to the activities that support human welfare. Tables 1.3 and 1.4 correct this omission by replicating the summary tables for major sectors and major regions, respectively, from AR4 (Tables 20.8 and 20.9, IPCC, 2007b). All of the entries in both tables were selected by the author teams of the respective chapters to illustrate impacts that are important for human welfare; references back to those chapters are indicated in the table notes.[1] The criteria used in the selection process included magnitude, rate, timing and persistence. Where possible, the entries identify both a threshold calibrated to change in global mean temperature and a

[1] The various chapters of the Working Group II report are available before their publication by Cambridge University Press on the IPCC website: http://www.ipcc-wg2.org/index.html.

quantitative measure calibrated in the most appropriate metric. The time dimension along different scenarios, including mitigation scenarios, is reflected by the bars on the top of Table 1.3. The real message to be drawn from these bars is one of uncertainty. No temperature threshold that might be subjectively judged as the lower bound of "dangerous climate change" can be guaranteed by even the most stringent of mitigation policies; adaptation is thus an imperative. Moreover, we are currently committed to roughly another 0.6 degrees C of warming regardless of efforts to reduce future greenhouse gas emissions.

Many of the bars in Tables 1.3 and 1.4 highlight risks that will be born by the planet's most vulnerable – those who face declining opportunities to sustain subsistence born of higher temperatures and increased water stress. Tables 1.5 and 1.6 translate these vulnerabilities into global and regional estimates along representative scenarios for the 2080's; they replicate Tables 20.4 and 20.5 in IPCC (2007b). While the precise numbers depend on climate futures and assumptions about adaptation and carbon dioxide fertilization (not to mention the specific global circulation model employed to represent future climate change), it is clear that future impacts depend most critically upon future development choices. For example, impacts calibrated in human lives are greatest along the A2 scenario not because climate change would be most severe in that case, but because there would be more people on the planet.

Anticipated Climate Change Impacts on Agriculture.

As can be gleaned from Tables 1.3 through 1.6, vulnerability to climate risk is not uniform across the planet. Two explanations come to mind. On the one hand, as displayed in Figure 1.2, climate change itself is not uniformly distributed. In addition, vulnerability depends on socio-economic factors that determine exposure, sensitivity, and adaptive capacity on a site-by site basis. To explore the ramifications of this diversity, consider the impact of climate change on cereals. Parry, *et al.* (2005) superimposed these yield relationships onto geographically explicit representations of climate change to produce maps that display the relative changes in yield across the globe. Their findings for cereal yields in the 2080's are reflected here in Figure 1.3 (Figure 5, Parry, *et al.*, 2005). Unmitigated climate change produces significant yield reductions across Africa and much of southern Asia even though gains are anticipated elsewhere. It follows that measures of global aggregates might show modest changes in overall productivity and thereby mask significant geographic dispersion. This disparity can, as well, be amplified by local climate factors that are not adequately captured in climate model outputs.

Figure 1.3: Potential Changes in Cereal Yields in the 2080's

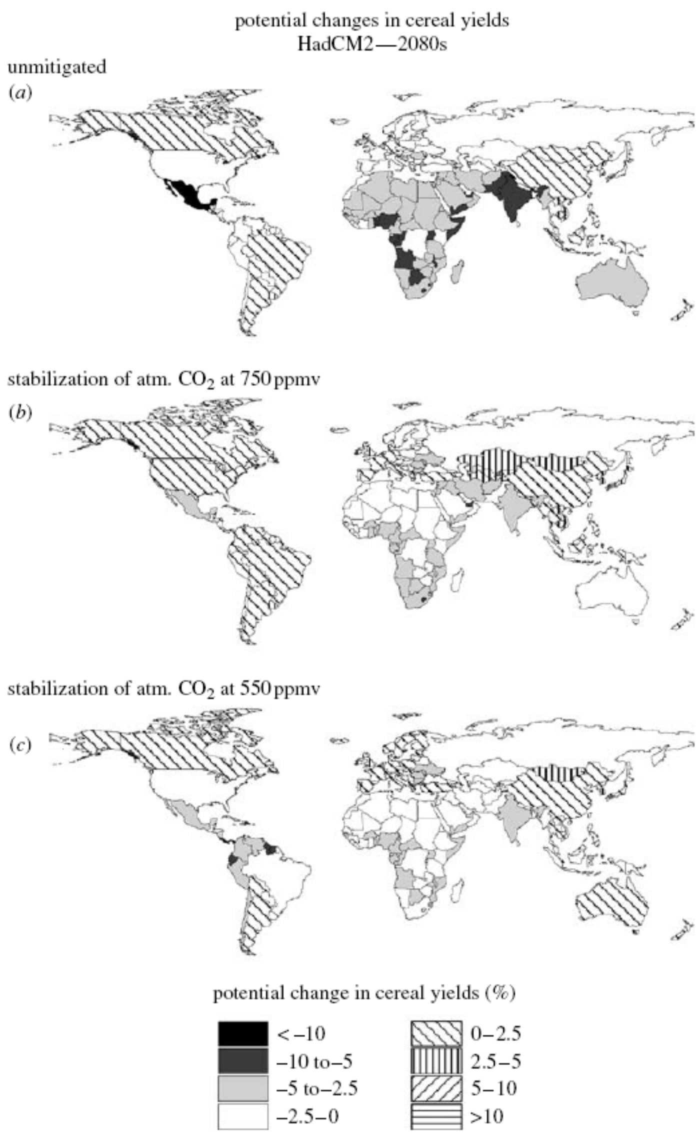


Figure 5. Changes in national cereal crop yields by the 2080s under three different emissions scenarios—(*a*) unmitigated (IS92a), (*b*) S750 and (*c*) S550 (Arnell *et al.* 2001).

Comparing Adaptation and Mitigation.

It is now widely accepted that mitigation alone is not enough to solve the climate problem; that was one of the major messages of Tables 1.3 and 1.4. Nor will adaptation alone be sufficient. Even together, they may not be sufficient to avoid dangerous interference and associated significant damages. These points are illustrated in Figure 1.4 and 1.5 for 2050 and 2100. Replicated from Yohe, *et al.* (2006), both figures are based on the intermediate A2 SRES emissions scenario assuming climate sensitivity turns out to be high. The regional distributions reflect climate impacts, calibrated in temperature change, for each country averaged across results derived from a collection of global circulation models. The top right panels depict the global distribution of a vulnerability index without any specific climate policy intervention. The top right panels display the implications of improving adaptive capacity so that, by 2100, developing countries achieve levels that are typical of developed countries at the turn of the 21st century. Notice the improvement almost everywhere, but particularly in China, in 2050; notice, as well, that climate change overwhelms even enhanced adaptive capacity by 2100.

The bottom two panels bring mitigation into the mix by tracing the implications of pursuing a least cost path to limiting atmospheric concentrations of greenhouse gases to 550 parts per million in carbon dioxide (and so less restrictive than restricting to 550 ppmv in carbon dioxide equivalents). The left panel captures only the effects of mitigation. Some improvement is observed in 2050, but the capacity to adapt is overwhelmed in most regions by 2100, despite mitigation effort. Comparing these results with the middle panel of Figure 1.3 is also instructive. Parry, *et al.* (2005) show mitigation having significant benefit for cereal yields in the 2080's. Their results do not, however, reflect the high climate sensitivity embodied in the current figures. Nor do they aggregate multiple climate stresses felt across multiple sectors. Finally, the right panels of Figures 1.3 and 1.4 add enhanced adaptive capacity to the mix. Again, there is some additional improvement in 2050, and the combination of the two approaches is most effective. Unfortunately, vulnerability to climate change remains nearly everywhere by 2100.

Table 1.3: Examples of Projected Impacts by Sector

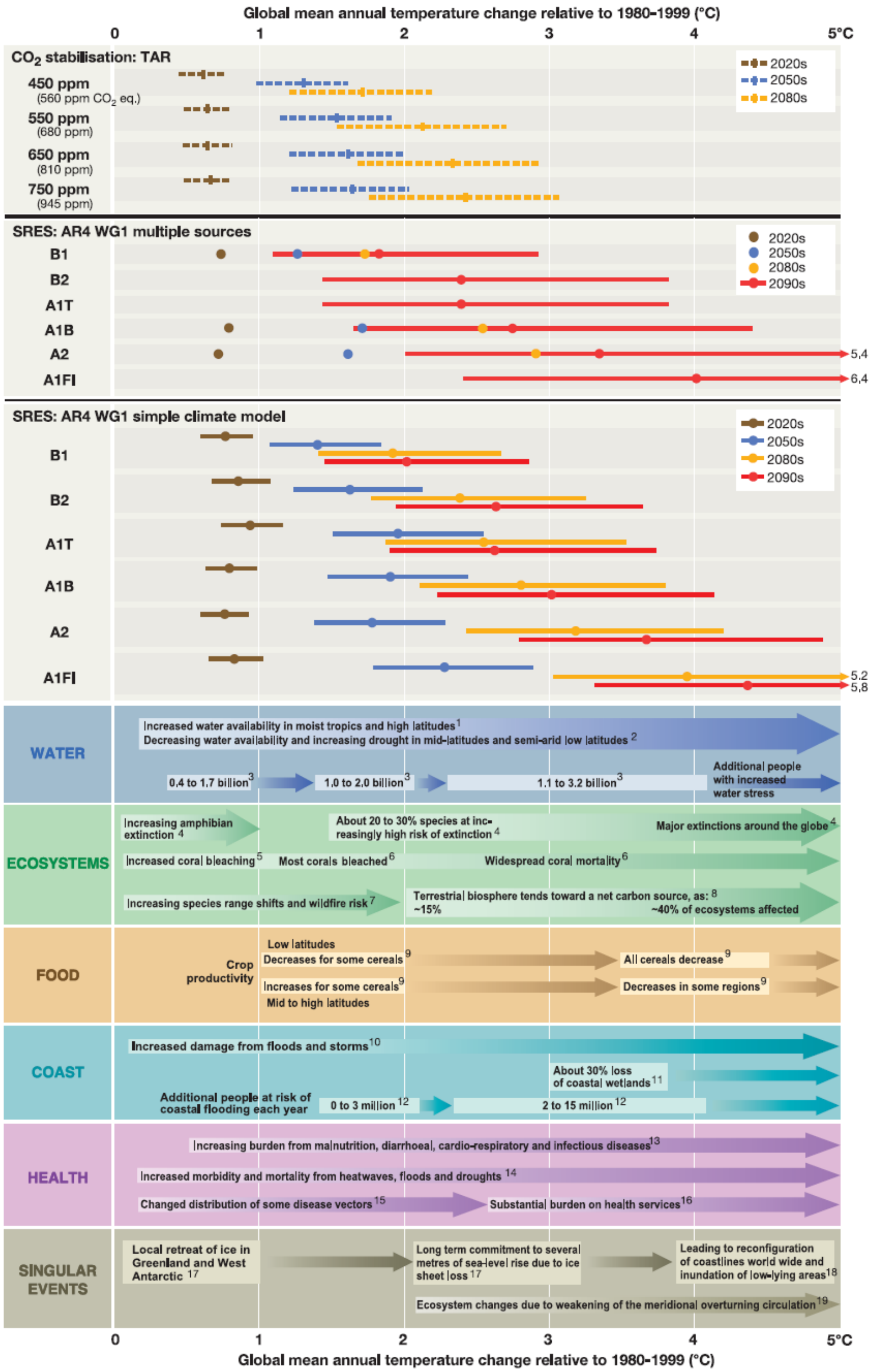


Table 20.8. *Examples of global impacts projected for changes in climate (and sea level and atmospheric CO_2 where relevant) associated with different amounts of increase in global average surface temperature in the 21st century. This is a selection of some estimates currently available. All entries are from published studies in the chapters of the Assessment. (Continues below Table 20.9)*

Table 1.4: Examples of Projected Impacts by Region

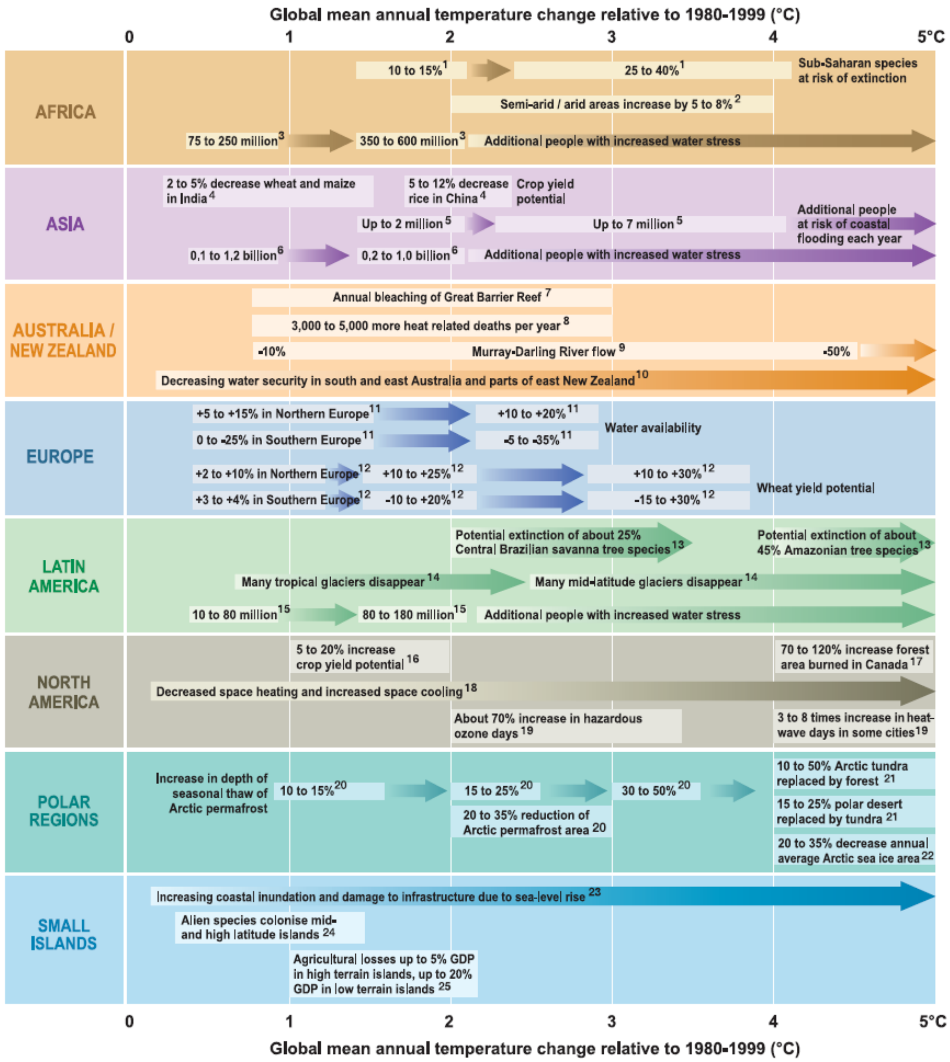


Table 20.9. *Examples of regional impacts. See caption for Table 20.8.*

Table 20.8. (cont.) *Edges of boxes and placing of text indicate the range of temperature change to which the impacts relate. Arrows between boxes indicate increasing levels of impacts between estimations. Other arrows indicate trends in impacts. All entries for water stress and flooding represent the additional impacts of climate change relative to the conditions projected across the range of SRES scenarios A1FI, A2, B1 and B2. Adaptation to climate change is not included in these estimations. For extinctions, 'major' means ~40 to ~70% of assessed species.*

The table also shows global temperature changes for selected time periods, relative to 1980-1999, projected for SRES and stabilisation scenarios. To express the temperature change relative to 1850-1899, add 0.5°C. More detail is provided in Chapter 2 [Box 2.8]. Estimates are for the 2020s, 2050s and 2080s, (the time periods used by the IPCC Data Distribution Centre and therefore in many impact studies) and for the 2090s. SRES-based projections are shown using two different approaches. ***Middle panel:*** *projections from the WGI AR4 SPM based on multiple sources. Best estimates are based on AOGCMs (coloured dots). Uncertainty ranges, available only for the 2090s, are based on models, observational constraints and expert judgement.* ***Lower panel:*** *best estimates and uncertainty ranges based on a simple climate model (SCM), also from WGI AR4 (Chapter 10).* ***Upper panel:*** *best estimates and uncertainty ranges for four CO_2-stabilisation scenarios using an SCM. Results are from the TAR because comparable projections for the 21st century are not available in the AR4. However, estimates of equilibrium warming are reported in the WGI AR4 for CO_2-equivalent stabilisation*[a]*. Note that equilibrium temperatures would not be reached until decades or centuries after greenhouse gas stabilisation.*

Table 20.8. Sources: **1,** 3.4.1; **2,** 3.4.1, 3.4.3; **3,** 3.5.1; **4,** 4.4.11; **5,** 4.4.9, 4.4.11, 6.2.5, 6.4.1; **6,** 4.4.9, 4.4.11, 6.4.1; **7,** 4.2.2, 4.4.1, 4.4.4 to 4.4.6, 4.4.10; **8,** 4.4.1, 4.4.11; **9,** 5.4.2; **10,** 6.3.2, 6.4.1, 6.4.2; **11,** 6.4.1; **12,** 6.4.2; **13,** 8.4, 8.7; **14,** 8.2, 8.4, 8.7; **15,** 8.2, 8.4, 8.7; **16,** 8.6.1; **17,** 19.3.1; **18,** 19.3.1, 19.3.5; **19,** 19.3.5
Table 20.9. Sources: **1,** 9.4.5; **2,** 9.4.4; **3,** 9.4.1; **4,** 10.4.1; **5,** 6.4.2; **6,** 10.4.2; **7,** 11.6; **8,** 11.4.12; **9,** 11.4.1, 11.4.12; **10,** 11.4.1, 11.4.12; **11,** 12.4.1; 12, 12.4.7; **13,** 13.4.1; **14,** 13.2.4; **15,** 13.4.3; **16,** 14.4.4; **17,** 5.4.5, 14.4.4; **18,** 14.4.8; **19,** 14.4.5; **20,** 15.3.4, **21,** 15.4.2; **22,** 15.3.3; **23,** 16.4.7; **24,** 16.4.4; **25,** 16.4.3

[a] Best estimate and likely range of equilibrium warming for seven levels of CO_2-equivalent stabilisation from WGI AR4 are: 350 ppm, 1.0°C [0.6–1.4]; 450 ppm, 2.1°C [1.4–3.1]; 550 ppm, 2.9°C [1.9–4.4]; 650 ppm, 3.6°C [2.4–5.5]; 750 ppm, 4.3°C [2.8–6.4]; 1,000 ppm, 5.5°C [3.7–8.3] and 1,200 ppm, 6.3°C [4.2–9.4].

Table 1.5: Global Scale Climate Impacts by 2080

Table 20.4. *Global-scale impacts of climate change by 2080.*

	Climate and socio-economic scenario			
	A1FI	A2	B1	B2
Global temperature change (°C difference from the 1961-1990 period)	3.97	3.21 to 3.32	2.06	2.34 to 2.4
Millions of people at increased risk of hunger (Parry et al., 2004); no CO_2 effect	263	551	34	151
Millions of people at increased risk of hunger (Parry et al., 2004); with maximum direct CO_2 effect	28	-28 to -8	12	-12 to +5
Millions of people exposed to increased water resources stress (Arnell, 2004)	1256	2583 to 3210	1135	1196 to 1535
Additional numbers of people (millions) flooded in coastal floods each year, with lagged evolving protection (Nicholls, 2004)	7	29	2	16

Note: change in climate derived from the HadCM3 climate model. Impacts are compared to the situation in 2080 with no climate change. The range of impacts under the SRES A2 and B2 scenarios (Nakićenović and Swart, 2000) represents the range between different climate simulations. The figures for additional millions of people flooded in coastal floods assumes a low rate of subsidence and a low rate of population concentration in the coastal zone.

Table 1.6: Regional Scale Climate Impacts by 2080

Table 20.5. *Regional-scale impacts of climate change by 2080 (millions of people).*

	Population living in watersheds with an increase in water-resources stress (Arnell, 2004)				Increase in average annual number of coastal flood victims (Nicholls, 2004)				Additional population at risk of hunger (Parry et al., 2004)[1] Figures in brackets assume maximum direct CO_2-enrichment effect			
	Climate and socio-economic scenario:											
	A1	A2	B1	B2	A1	A2	B1	B2	A1	A2	B1	B2
Europe	270	382-493	233	172-183	1.6	0.3	0.2	0.3	0	0	0	0
Asia	289	812-1197	302	327-608	1.3	14.7	0.5	1.4	78 (6)	266 (-21)	7 (2)	47 (-3)
North America	127	110-145	107	9-63	0.1	0.1	0	0	0	0	0	0
South America	163	430-469	97	130-186	0.6	0.4	0	0.1	27 (1)	85 (-4)	5 (2)	15 (-1)
Africa	408	691-909	397	492-559	2.8	12.8	0.6	13.6	157 (21)	200 (-2)	23 (8)	89 (-8)
Australasia	0	0	0	0	0	0	0	0	0	0	0	0

Note: change in climate derived from the HadCM3 climate model. Impacts are compared to the situation in 2080 with no climate change. The range of impacts under the SRES A2 and B2 scenarios (Nakićenović and Swart, 2000) represents the range between different climate simulations. The figures for additional millions of people flooded in coastal floods assumes a low rate of subsidence and a low rate of population concentration in the coastal zone.
[1] Analysis of project results carried out for this table.

Figure 1.4: Geographical Distribution of Vulnerability in 2050 (A2 emissions; high climate sensitivity)

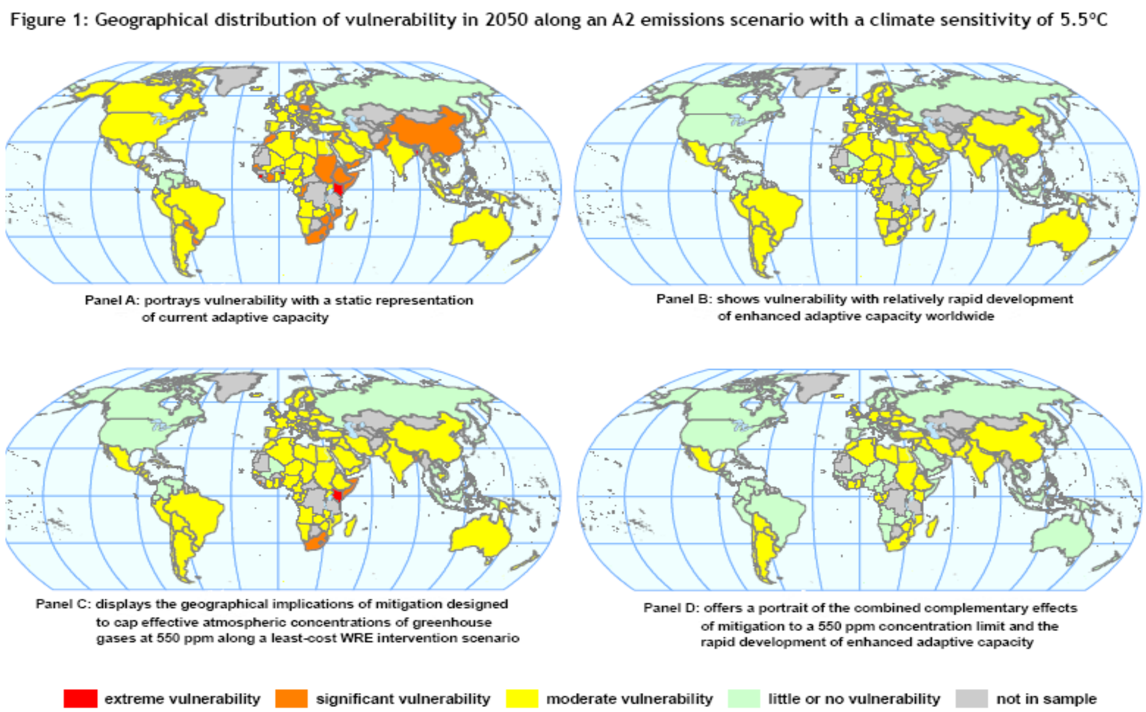
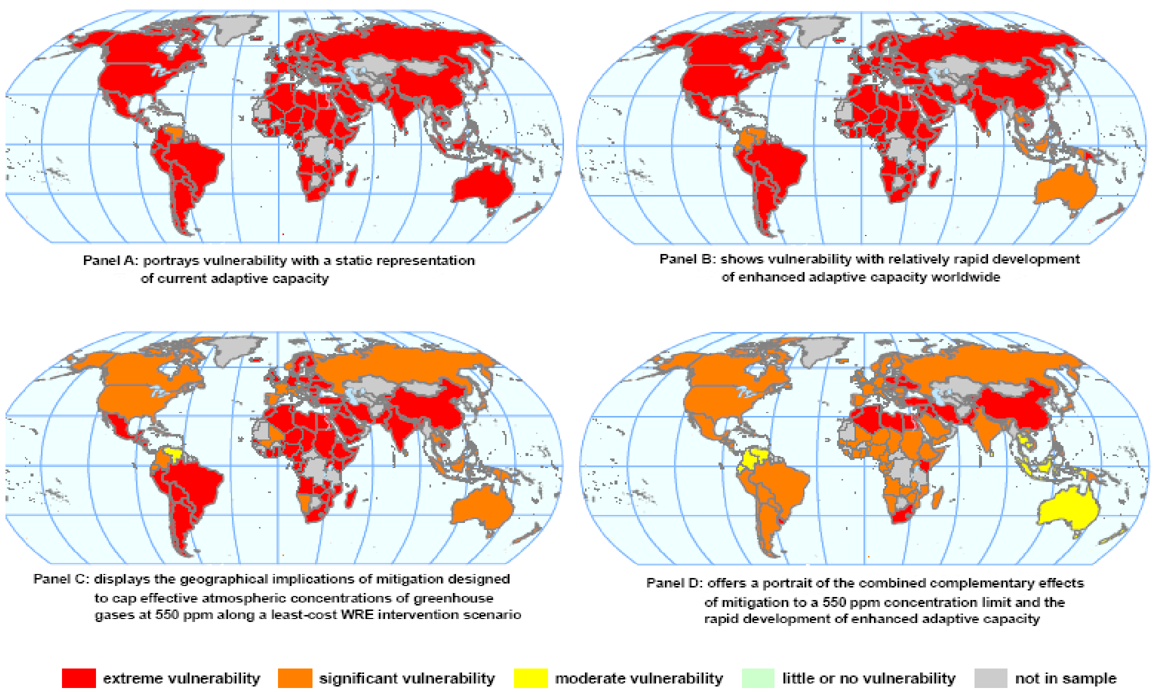


Figure 1.5: Geographical Distribution of Vulnerability in 2100 (A2 emissions; high climate sensitivity)

Figure 3: Geographical distribution of vulnerability in 2100 along an A2 emissions scenario with a climate sensitivity of 5.5°C



2. Modeling Emissions and Climate Impact Scenarios

Emissions Scenarios.

Six emissions scenarios were constructed using the MERGE model (see Appendix A for a description of the model). In three scenarios, a pessimistic set of assumptions about new energy technology was applied, termed "technology as usual" (TAU). In the other three scenarios, an accelerated technology path (ATP) was applied to represent the results of a targeted R&D investment program. For each technology scenario, the model was used to evaluate three alternative emissions control strategies. The first is a reference case in which there is no price on carbon dioxide emissions. The reference scenario is used as a baseline for measurement of the costs and benefits of the emissions mitigation effort entailed in the other two scenarios. However, note that there are two distinct reference cases, since the availability of new technology will affect deployment and emissions even in the absence of a carbon price.

Two mitigation scenarios were considered in which policy constraints place an implicit price on carbon emissions. Many mitigation studies assume full "where" and "when" flexibility to assure that a given stabilization target is achieved at least cost. That is, emissions are reduced where and when it is least costly to do so, subject to a long-term constraint on total greenhouse forcing in the atmosphere. Because this idealized framework would be very difficult to implement in reality given the current lack of strong institutions for international and intergenerational cooperation, we conduct most of our analysis along a second-best mitigation scenario with much more limited flexibility. In this case, for example, only nations in Annex B of the UNFCCC undertake emissions reductions (i.e., developing countries face a zero shadow price of carbon through 2100), and they do so according to annual emissions targets rather than toward a long-term stabilization goal.[2] Costs of mitigation are measured in terms of the deadweight loss in the economy as emissions reduction requirements force shifts to more expensive energy options. The discussion in this paper focuses primarily on the limited mitigation scenario, but an understanding of the potential cost reductions of a flexible policy implementation is important nonetheless; a brief discussion of the difference is offered in Section 5.

In light of the Copenhagen Consensus project goal of measuring the benefits of a fixed expenditure, the specific targets for the mitigation scenarios were chosen heuristically so that the total cost of mitigation effort reached the desired amount. While the focus of the current exercise is the allocation of $75 billion over the next 4 years, coping with climate change will involve a long term commitment to policy. Therefore the "budget" for this analysis assumes expenditure at an equivalent fraction of global GDP for the entire 21st century and beyond. Using the MERGE model's assumptions about economic growth and discounting, this amounts to a net present value of $800 billion, or roughly 0.05% of global GDP on an annual basis. It is our view that abandoning a four-year climate response program in 2012 is not an approach worth pursuing. That said, by focusing on the limited mitigation scenario, we do not assume an optimal allocation of these funds over time. We do not, therefore, commit future generations to underwriting decisions taken at the beginning of the 21st century. Instead, we assume that the funds will be expended as they become available and thereby approximate, at least roughly, the muddling through approach that would likely be forthcoming.

Because the emissions scenarios consider both mitigation effort and investment in R&D for new technology, the total budget is shared between these two activities. In the TAU scenarios, all $800 billion is allocated to the mitigation effort. Consistent with estimates from the Electric Power Research Institute (EPRI, 2007), we assume an additional funding requirement of $50 billion, largely in the next few decades, for the R&D component. Thus in the ATP scenarios, only $750 billion is allocated to mitigation effort. Note that in the optimal mitigation scenarios, most expenditure is delayed until

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[2] Additional experiments could be conducted in which non-Annex B countries begin to participate in mitigation efforts by mid-century. Their participation would have little effect on the cost of meeting prescribed global emissions targets because, under the assumption that annual expenditure on climate policy is constrained by the annual budget imposed by this Copenhagen Consensus exercise, only modest mitigation effort would be undertaken. For deeper cuts in emissions, participation of rapidly growing developing countries will be crucial.

future periods, whereas in the limited case, the annual emission targets necessitate an approximately constant annual rate of expenditure. Table 2.1 summarizes the six emissions scenarios.

Table 2.1: MERGE Emissions Scenarios

Scenario	Policy Description	Global Emissions (billion tons CO_2)		
		2000	2050	2100
TAU Reference	No Policy	24	44	67
TAU Cost Effective Mitigation	▪ Global participation ▪ Stabilization at 5.2 W/m^2	24	43	20
TAU Limited Mitigation	▪ Annex B only ▪ Emissions constant at 2010 levels	24	38	55
ATP Reference	No Policy	24	32	48
ATP Cost Effective Mitigation	▪ Global participation ▪ Stabilization at 4.5 W/m^2	24	29	14
ATP Limited Mitigation	▪ Annex B only ▪ Emissions reduced by 0.275% per year from 2010 levels	24	30	37

Impacts Scenarios.

Each emissions scenario was evaluated using the climate and impacts modules in the FUND model (see Appendix B for a description of this model). First using an central, "best guess" value for climate sensitivity (3.0^{o}C) and later considering a range of values, FUND calculates a temperature trajectory associated with the given emissions path.[3] Market and non-market damages from climate impacts are calculated as a regional function of temperature increase. These calculations include economically efficient reactive adaptations, so they represent net impacts inclusive of the costs of adaptation. In addition to R&D investment and mitigation effort, we examine a third response activity –

[3] Climate sensitivity is a measure of the increase in equilibrium global mean temperature that would be associated with a doubling of the atmospheric concentration of carbon dioxide from pre-industrial levels – roughly 550-560 ppmv versus 280 ppmv.

adaptation designed to confront specific health impacts more aggressively and proactively. This activity occurs *ex post* of climate changes and allows amelioration of their negative impact. Thus for selected emissions scenarios, damages are calculated with and without adaptation policies. The NPV cost of additional adaptation is $1 billion, much smaller than the cost of the other two activities. It is therefore not separated from the mitigation/R&D budget, but it is important to realize that it does not handle the wide range of impacts (particularly from extreme events and abrupt change) that are highlighted in Section 1.

3. Scoping the Proposed Responses

As suggested in Section 2, we explore four responses within a synthesis of two integrated assessment models: FUND and MERGE. A review of the details of the models, as provided in the two appendices, indicates that we thereby exploit the relative strengths of both (the technological detail of MERGE on the mitigation side and the geographic and sector diversity of FUND on the impacts and adaptation side). While the focus of the Copenhagen Consensus exercise is how to spend $75 billion over the next 4 years, it is also important to reiterate that coping with climate change will involve a long term commitment to policy. We therefore examine a collection of approaches that build toward a portfolio of adaptation and mitigation options that expend up to an equivalent proportion of global GDP over the next century. The present value of these expenditures, allocated either to specific initiatives or to cover the economic dead weight loss of mitigation, amounts to $800 billion (constant 2000 dollars); this sum will represent the cost side of our benefit-cost calculations.

The four responses that are the focus of our analysis are listed below; Figure 3.1 depicts their effects on emissions and temperature increases over time assuming a central climate sensitivity of 3 degrees centigrade.

(1) "Business as usual" – the TAU Reference case in Table 2.1.

Inaction on the climate front is certainly an option that must be taken seriously. Climate change has never been favored in the Copenhagen Consensus process; moreover, current policy seems to be long on rhetoric but short on action. Analyzing this case, both in terms of global aggregates and underlying regional and sectoral manifestations, also provides the baseline scenario against which potential benefits of the other policy options will be measured.

(2) "Mitigation only (annual)" – the TAU Limited Mitigation case in Table 2.1.

Allocate the full budget to covering the economic deadweight loss of mitigation with limited flexibility. Economic instruments (e.g., a carbon tax) are employed to reduce annual emissions of greenhouse gases up to the point where the economic cost matches the annual budget; there is no additional R&D investment in technology and no proactive adaptation.

(3) "R&D + mitigation (annual)" – the ATP Limited Mitigation case in Table 2.1.

Invest immediately in R&D to make new technologies for emission reduction and carbon sequestration available; these technologies complement near-term mitigation and eventually increase the efficiency of longer-term efforts to reduce emissions. There is no additional adaptation and mitigation is undertaken with limited flexibility (since annual expenditures for either R&D or dead weight loss coverage is limited annually to 0.05% of then current global GDP).

(4) Adaptation + R&D + mitigation (annual)" – a portfolio approach.

This approach will be a combination of approach (3) with an additional focus on adaptations designed to ameliorate specific health impacts related to some of the other Copenhagen Consensus topics. Additional expenditures covered within the specified budgetary limits will underwrite responses to the likelihood that climate change will exacerbate health hunger problems worldwide. These expenditures will cover only the increments attributed to climate change, and they will not be inclusive (in the sense of covering all of the potential impacts displayed in Section 1). Since these initiatives will not reduce the pace of climate change, their cost, taken in isolation, would reflect the degree to which the "Do nothing" alternative would make it more difficult to make progress in other contexts. Comparisons with earlier approaches will illustrate the value of responding to the climate problem with a variety of approaches that simultaneously "fight the disease" and "treat the symptoms". As reported in the IPCC AR4, mitigation and adaptation should both be more effective given the complementary effects of the other, and we confirm this expectation.

Figure 3.1 shows the trajectories of CO_2 emissions for four cases. Figure 3.2 does the same for increases in global mean temperature, as derived from MERGE. Notice that the "Business as usual" trajectory puts the increase in global mean temperature at approximately 3.5^{o}C in 2100 (relative to the 2007 level); we are, therefore, depicting a baseline that tracks roughly into the middle of the distribution of temperature increase reported in Figure 1.2 for the A2 "storyline". The first three correspond to options (1), (2) and (3) above. Adaptation is not depicted, since adaptation has no effect on emissions or temperature, so option (4) tracks along option "R&D + mitigation" trajectory. R&D

alone is also depicted to show that enhanced technology produces a lower trajectory in the near to medium term even without other policy intervention (this is the "ATP Reference" case in Table 2.1). It is included for reference, because enhanced technology will make any level of expenditure on mitigation more effective. It is not included as a climate policy option, however, because emissions and temperatures rise at an increasing rate over the long term to the point that both eventually exceed the "Mitigation only" alternative. For reference, as well, it is important to note that mitigation constrained to the annual Copenhagen Consensus budget requires imposing a persistent real shadow price of $20 per ton of CO_2 (by some means – a carbon tax or a carbon permit market, for example) with or without R&D investment in enhanced carbon saving or sequestering technology. Clearly, though, enhanced technology makes this intervention more effective in reducing emissions and slowing the rate of increase in global mean temperature.

Figure 3.1 Emissions (gigatons per year of CO_2) for Alternative Policies

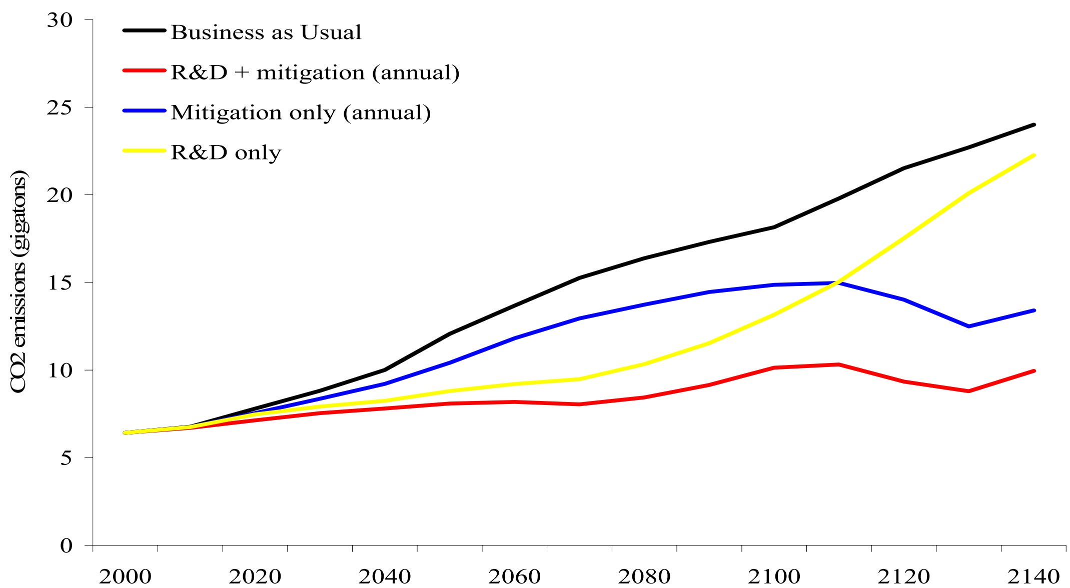
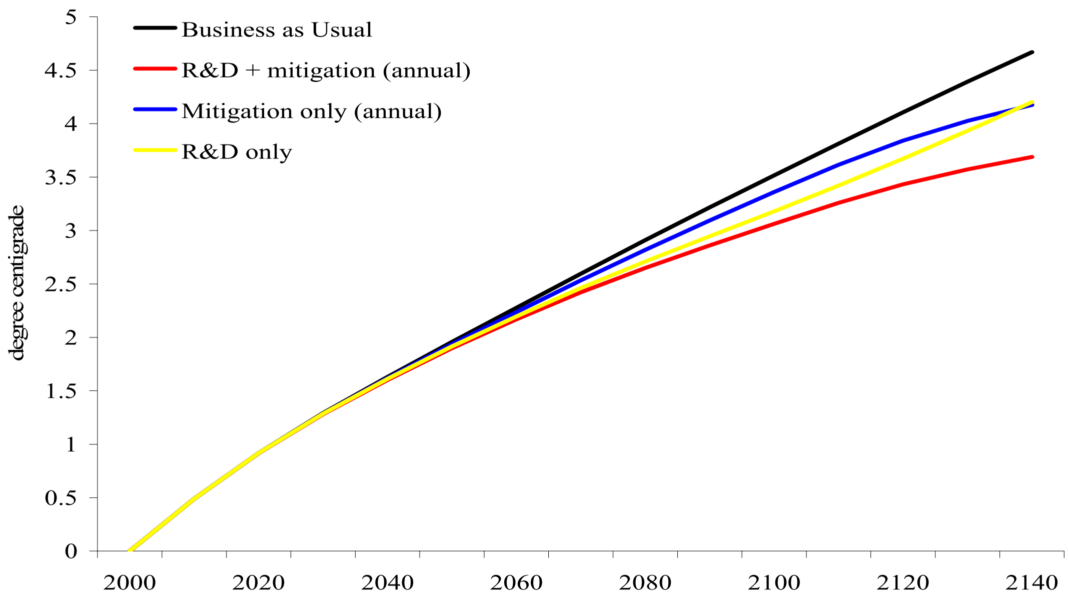


Figure 3.2 Increases in Global Mean Temperature (in degrees C above 2005 levels) for Alternative Policies



*Note: The adaptation only case is not depicted because it has no effect on emissions and therefore tracks the business as usual case.

4. Results

Table 4.1 displays the summary net present value statistics from our analysis of the four policy intervention alternatives described above. Because of the long time horizon over which impacts from climate change will emerge, the choice of discount rate is critical for the cost-benefit calculus. In these calculations, the rate used to translate the benefits of avoided damages in the distant future to a present value is the same as the rate describing the return on a risk-free investment in the economic model, that is, the marginal productivity of capital. This symmetry implies that we are indifferent between incurring $1 million worth of damages in 2100 and losing an amount today that if invested instead is guaranteed to be worth $1 million in 2100. However, arguments may be made in support of a variety of alternative perspectives on the appropriate discounting approach for climate change. For a review of these arguments, see Portney and Weyant (1999) or Stern, *et al.* (2007). The discount rate used here starts at 5% in 2007, falling to 4% by the end of the century. This choice is consistent with observed and anticipated market rates of return, where the decline reflects investors becoming more "patient" over longer time horizons. Note that this discount rate is used for reporting as well as for computing optimal investments (in energy technologies in MERGE, and in adaptation in FUND); therefore, changing the discount rate would change the reference scenario as well as the policy scenarios. It is important to note explicitly that our calculations do not depend on assuming the low pure rate of time preference employed both by Cline (2004) and Stern, *et al.* (2007).

Figure 4.1 displays the underlying trajectories of climate damages, including the "Business as Usual" option, in terms of percentage of global GDP. Figure 4.2 converts these estimates into benefits (damages foregone) for the three intervention alternatives. Notice that Figure 4.1 displays the potential for beneficial climate change, at least as measured by global aggregate economic activity, through the first half of this century. This observation is one explanation for why the benefit-cost ratio reported in Table 4.1 for "Mitigation only" can be less than unity (though the ratio climbs above unity for "ATP cost-effective" case from Table 2.1; this point will be discussed in Section 5). Conversely, the fact that our modeling allows for the possibility that modest climate change could be beneficial early in this century adds credibility to benefit-cost ratios of the three other interventions, especially the two which involve R&D enhanced mitigation.

Table 4.1: Policies, Costs, Benefits, and Benefit-Cost Ratios.

Scenario	Description	NPV costs	NPV benefits	BCR
(2) Mitigation only (annual with partial "where flexibility")	Spend $18 bln per year (rising with economic growth) on mitigation	$800 bln	$685 bln	0.9
(3) R&D + mitigation (annual with partial "where flexibility")	Accelerated phase-in of carbon-extensive energy technologies, followed by mitigation with a fixed annual budget	$800 bln	$1717 bln	2.1
(4) Adaptation + R&D + Mitigation (annual with partial "where flexibility")	As above plus purchase bednets and oral rehydration therapy for children in least developed countries affected by climate change	$800 bln	$2129	2.7

Figure 4.1: Trajectories of Global Damages for the Five Alternatives

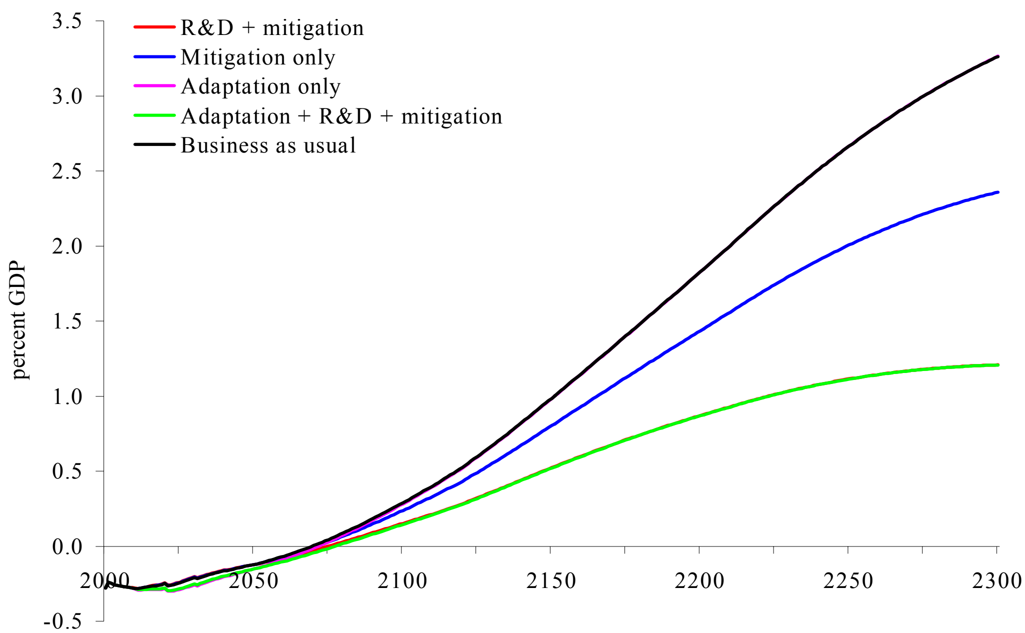
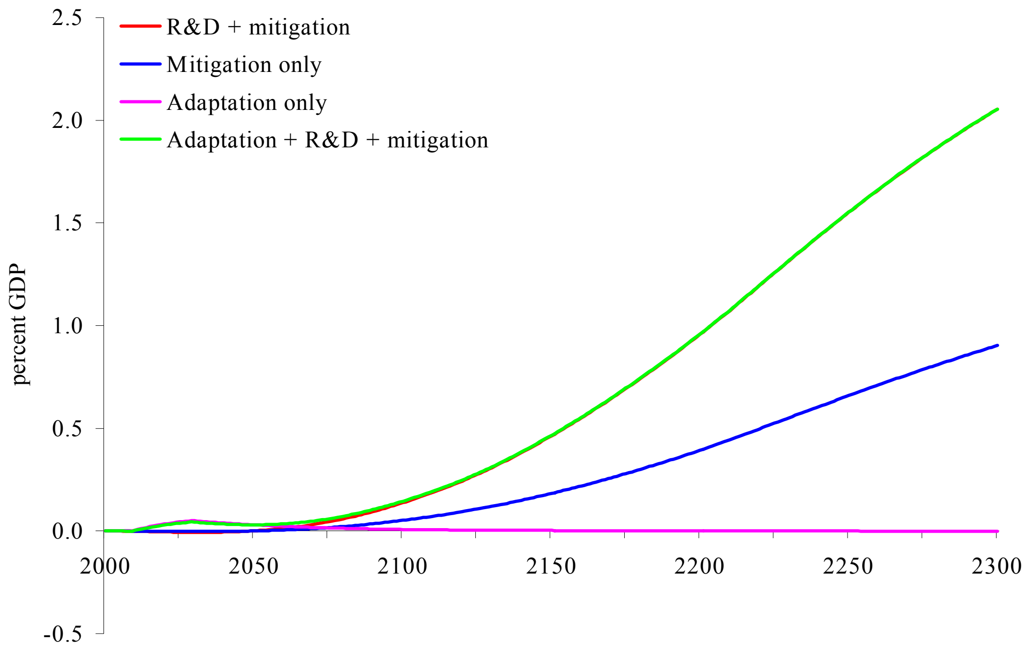


Figure 4.2: Trajectories of Global Benefits for the Four Intervention Policies through 2300



Turning now to options (3), and (4) ["R&D + mitigation (annual)" and "Adaptation + R&D + mitigation (annual)", respectively], it is important to note that coupling mitigation constrained by an annual expenditure with early investment in R&D for enhanced carbon saving and carbon sequestering technology brings the benefit-cost ratio for mitigation up to 2.1 even with a discount rate set to mimic the return to private capital. The policy portfolio described in option (4) brings the power of enhanced R&D and expanded investment in adaptation together to raise the benefit-cost ratio of annual mitigation to 2.7. Both adaptation and R&D complement constrained mitigation efforts to such a degree that the associated benefit-cost ratio increases by a factor of 3 without spending an additional dime.[4]

[4] Notice that we do not consider adaptation alone as a response option, essentially because doing only adaptation addresses only the "symptoms" and not the "disease". We do, though, concentrate on the separable value of adaptation in the next section on caveats. We also do not address R&D as a stand-alone response, because mitigation policy and R&D go hand in hand. The smaller the cost differential between the carbon-free technology and the carbon-venting technology, the smaller the tax (either implicit or explicit) needed to bring climate-friendly into the marketplace. Put another way, R&D is most effective as a tool that complements mitigation efforts. It follows that the value of R&D cannot be calculated by manipulating the values recorded in Table 4.1 for the policy portfolios recorded there.

5. Discussion and Caveats

We offer, in this section, brief discussions of three extensions to our analysis. In the first, we examine the implications of allowing mitigation policy designed in 2008 to be allocated over time so that it maximizes the efficacy of covering the deadweight loss of climate policy with a fund whose discounted value amounts to $800 billion. This compensation over time is assumed to be financed by an annuity that derives its backing from annual contributions that are consistent with the Copenhagen Consensus budget constraint. Adding this "when flexibility" raises the benefit-cost ratio of "Mitigation only" to 3.3. A second subsection depicts some regional implications of all of the options; and the third subsection adds uncertainty about climate sensitivity to the mix. In this case, the ratio of the expected net benefits of "Mitigation only" with "when flexibility" more than doubles to an extremely respectable 6.9.

Improved Cost Effectiveness with "When Flexibility".

All of the alternatives discussed above recognize, at least implicitly, the difficulty in imposing policies that would allocate mitigation efforts efficiently over time – "when flexibility" in the vernacular of the climate literature that is designed to minimize the discounted cost of achieving a given stabilization target. Achieving a concentration target imposes, at least to a first approximation, a limit on cumulative emissions over the very long term. Intuition born of the economics of exhaustible resources can, therefore, be applied to envision emissions trajectories that would minimize the discounted cost of achieving the target and thereby set an efficiency benchmark against which other, second best approaches, can be judged. Again to a first approximation, the shadow price of carbon in this intertemporally optimal framework would be determined by an initial "scarcity rent" that increases roughly at the rate of interest over time.

Figure 5.1 offers insight into the significance of the optimal time path by adding the trajectory of global benefits for a "Mitigation only" option that allows for "when flexibility". As shown in the first row of Table 5.1, cost-minimizing "when flexibility" financed over time by an $800 billion annuity, funded by the same expenditure pattern as in the budget-constrained case, would increase the benefit-cost ratio of "Mitigation only" from 0.9 to 3.3. Table 2.1 suggests how this dramatic effect is possible. Adding "when flexibility" to the policy design means reducing emissions from 67 gigatons of CO_2 to 20 gigatons per year in 2100 (as compared with 55 gigatons for "Mitigation only" without inter-temporal flexibility). This more stringent control late in the century is "financed" by savings generated from curtailed emissions reductions through the middle of the century (43 gigatons per year in 2050 is only a 2% reduction from 44 gigatons along the "Business as Usual" alternative, while the 38 gigaton target for "Mitigation only (annual)" represents an almost 20% reduction).

While an optimal allocation of mitigation effort over time may be unrealistic, we emphasize that a mitigation scenario in which essentially no incremental effort is taken on over time is also unlikely. In order to achieve the stated UN goal of stabilizing GHG concentrations, at any meaningful level, emissions reductions far beyond those depicted in our annual expenditure budget scenarios must be realized. Moreover, as further mitigation becomes necessary, costs over time will inevitably rise, and it will become increasingly important to include the participation of developing countries.

Figure 5.1: Trajectories of Global Benefits of Alternative Approaches

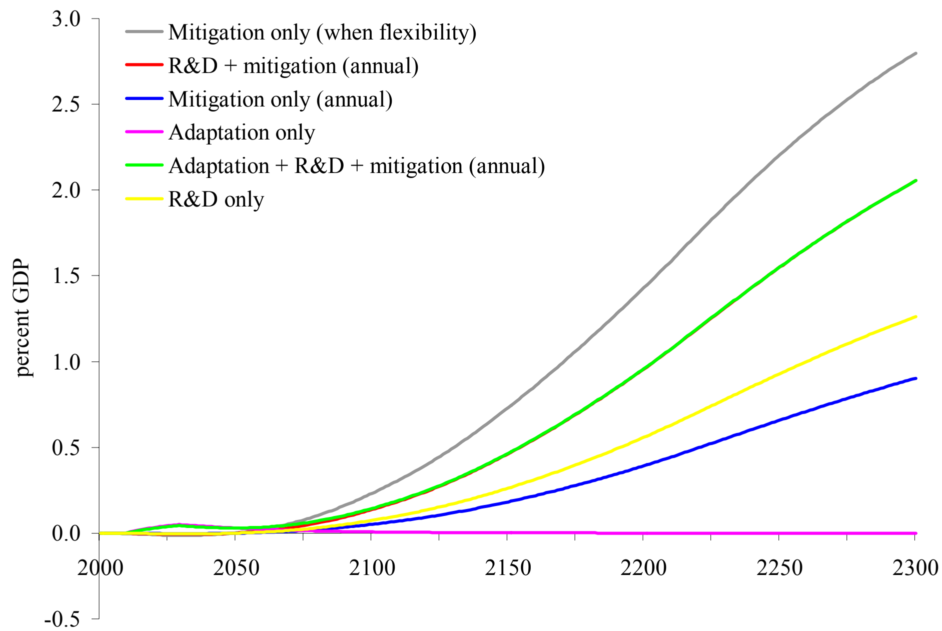


Table 5.1: Costs, Benefits, and Benefit-Cost Ratios for Dynamically Flexible Mitigation.

Mitigation only (when flexibility added)	Spend an annuity of $18 bln (rising with economic growth) on mitigation	$800 bln	$2676 bln	3.3
Mitigation only (when flexibility added with uncertainty)	As above, but with uncertainty about the climate sensitivity	$800 bln	$5483 bln	6.9

Regional diversity.

It is important to note that the impacts of climate change, and thus the benefits of any policy approach, are not evenly distributed across the globe. Figure 5.2 shows that market damages for four regional aggregates: the OECD, Eastern Europe and the Former Soviet Union, China, and the world's Least Developed Countries. Notice that market damages are actually negative (i.e., modest climate change is beneficial) across much of the world early in this century for this level of regional disaggregation, at least. This does not mean that the market impacts of small increases in temperature are positive everywhere, of course. Moreover, if the country by country impacts within each region were aggregated using population-based equity weights, then the positive aggregates would shrink quickly and turn negative earlier. Finally, it is also important to note that the trajectories of market impacts for our five policy options do not deviate significantly from one another until late in this century.

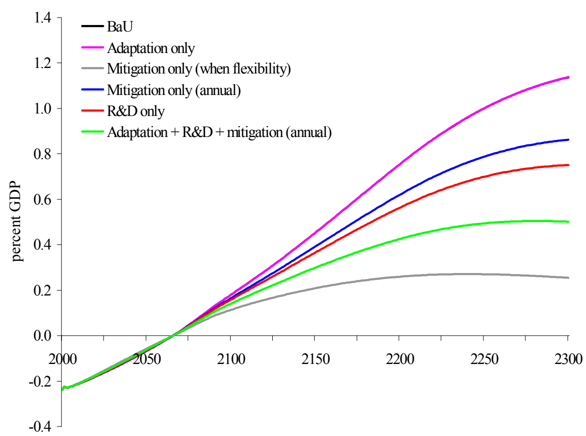
Non-market damages displayed in Figure 5.3 for the same four regions show a decidedly different pattern. All begin with positive values (i.e., negative impacts). They continue higher almost immediately for China and the OECD, but they fall precipitously for Eastern Europe and the former Soviet Union and LDC's. This is again because development can diminish many non-market impacts (e.g., health impacts) by improving adaptive capacity. Notice, as well, that the implications for non-market impacts of our five alternative policies deviate from one other much earlier than for market impacts.

Adaptation.

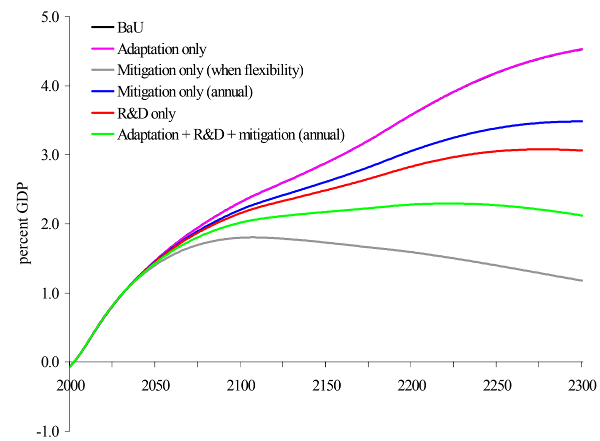
Our fourth option includes limited but proactive investment in adaptation designed to confront the marginal increase in vulnerability to infectious disease that could result from climate change. We do not, however, include adaptation as a stand-alone policy, however, because its scope is too limited. It does nothing to slow the pace of climate change, and so it does nothing to address the myriad of non-health impacts noted in Section 1. Indeed, we included it in the final portfolio primarily to illustrate the cost (in terms of another topic of the Copenhagen Consensus exercise) of ignoring climate change.

Recall that Figure 4.2 displayed the underlying trajectories of benefits (damages foregone) for the three intervention alternatives plus adaptation alone. Because adaptation has no effect on climate change, however, the trajectories for the options that include adaptation are difficult to distinguish from their baselines. Figure 5.4 shows that this observation is an artifact of the scale that defines the vertical axes of the earlier figures. Since the benefits for adaptation appear almost immediately (though they depreciate quickly over time as development overtakes the need for these specific adaptations in the health sector), focusing on a shorter time frame allows some differentiation of the cases with and without mitigation to emerge.

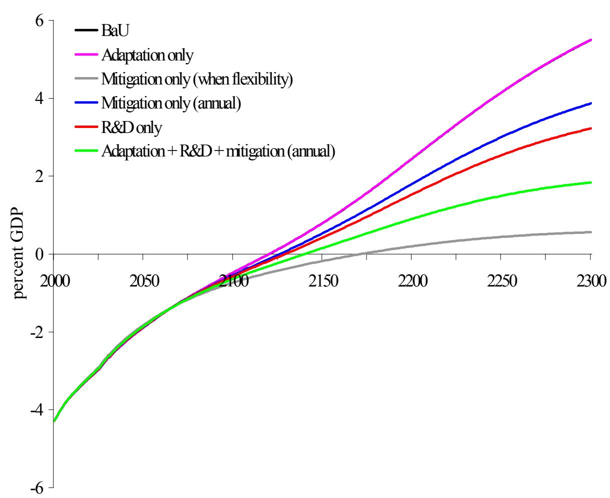
We calculated that efforts to promote global health would, if that course of inaction were chosen, see something on the order of $409 billion in additional disease-related cost and the alternative of spending additional $1 billion expenditure on bednets and oral rehydration therapy. We did, however, calculate the benefits of adaptation alone intervention. Finding that spending $1 billion on bednets and oral rehydration therapy Figure 5.2: Trajectories of Estimated Market Damages



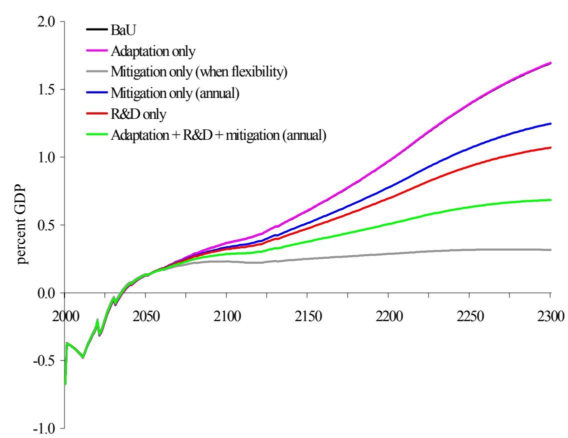
Panel A: OECD



Panel B: EEFSU

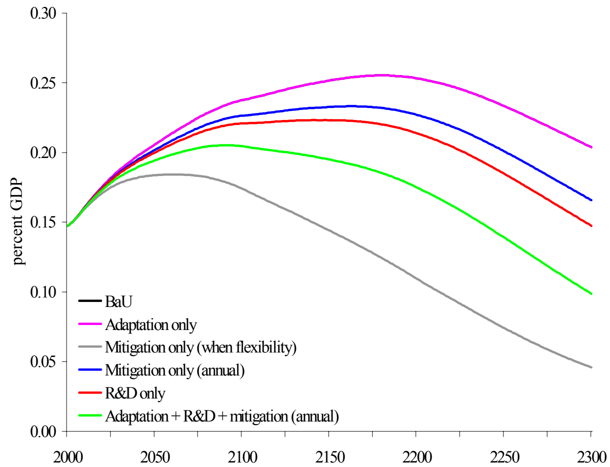


Panel C: China

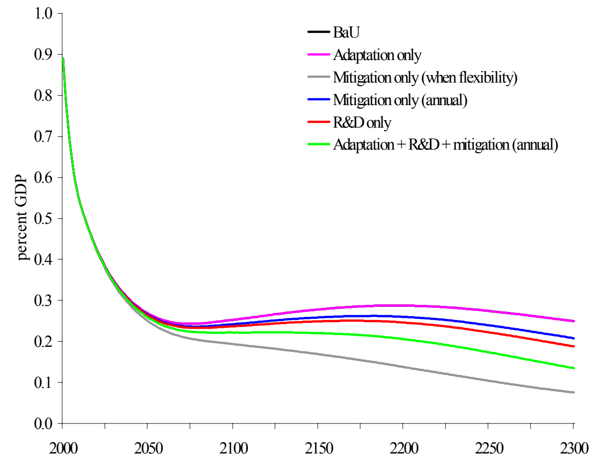


Panel D: LDC's

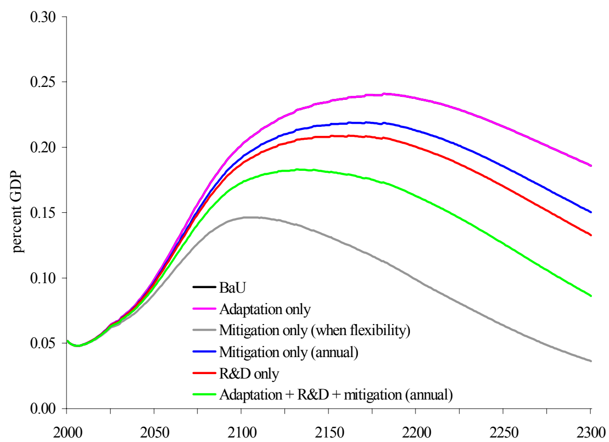
Figure 5.3: Trajectories of Estimated Non-Market Damages



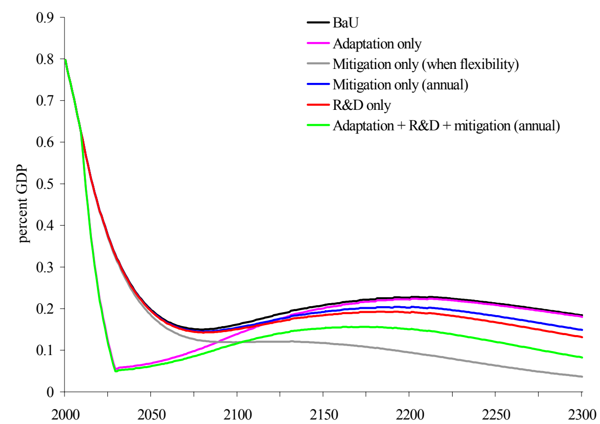
Panel A: OECD



Panel B: EEFSU



Panel C: China

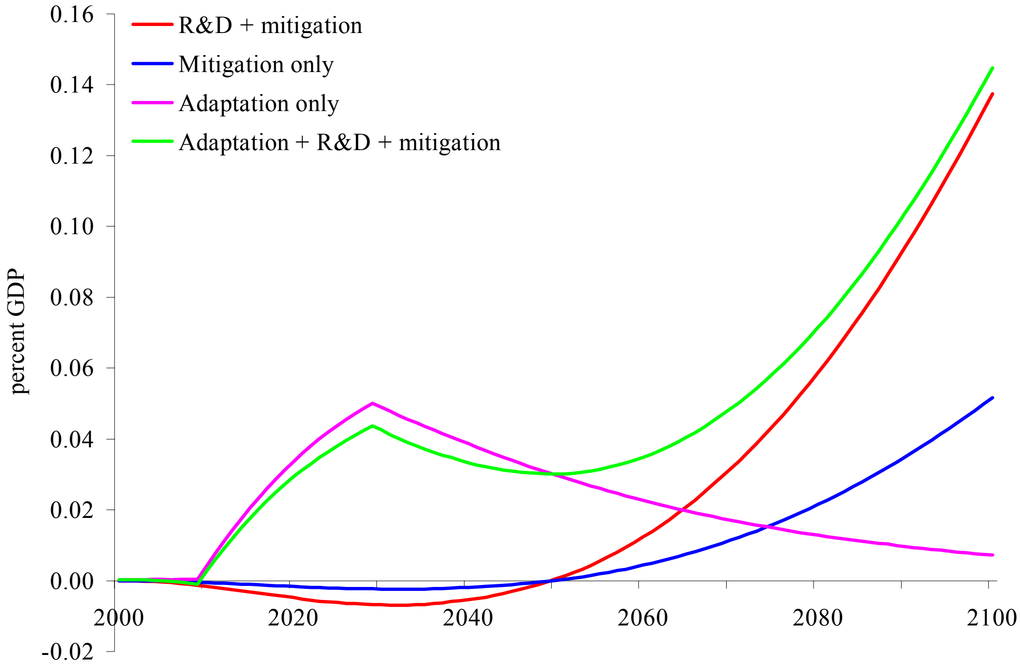


Panel D: LDC's

would produce $409 billion, we produced a benefit-cost ratio that was an order of magnitude higher than that of Jamison *et al*. (this volume).[5] This in itself is evidence that

[5] In their Table 7, an investment of $500 mln per annum in malaria control would save 7.5 mln DALYs. This amounts to $67/DALY, even though their Table A1 has a $2-24/DALY ratio. We used $17/DALY, so we are in the latter range. We assume that a $10 bednet protects a family of four (two adults and two children) for four years (http://www.nothingbutnets.net), and that there are 15 DALYs per malaria death. If we had used $67/DALY, our benefit-cost ratio would fall from 300 to 200, because diarrhea dominates malaria in our analysis. Diarrhea kills more children (http://www.who.int/healthinfo/bod/en/index.html), and its worst consequences can be prevented with cheap, low-tech interventions (Laxminirayan *et al*., 2006). Note that Jamison *et al*. (this volume) do not consider diarrhea. The difference between the high

Figure 5.4: Trajectories of Global Benefits for the Four Intervention Policies through 2100



efforts to improve health worldwide in the absence of climate policy would, essentially, be swimming upstream against a current that was accelerating as the pace climate change accelerated.

More to the point of the portfolio approach described in Option (4), however, it is important to note from Table 4.1 that total net present benefits of mitigation, R&D investment *and* this limited adaptation is \$2129 billion while the comparable discounted sum for mitigation and R&D is only \$1717 billion. Even this limited adaptation adopted in the context of a complete portfolio adds more than it would taken alone. Put another way, the sum of the present values of mitigation, R&D, and limited adaptation taken

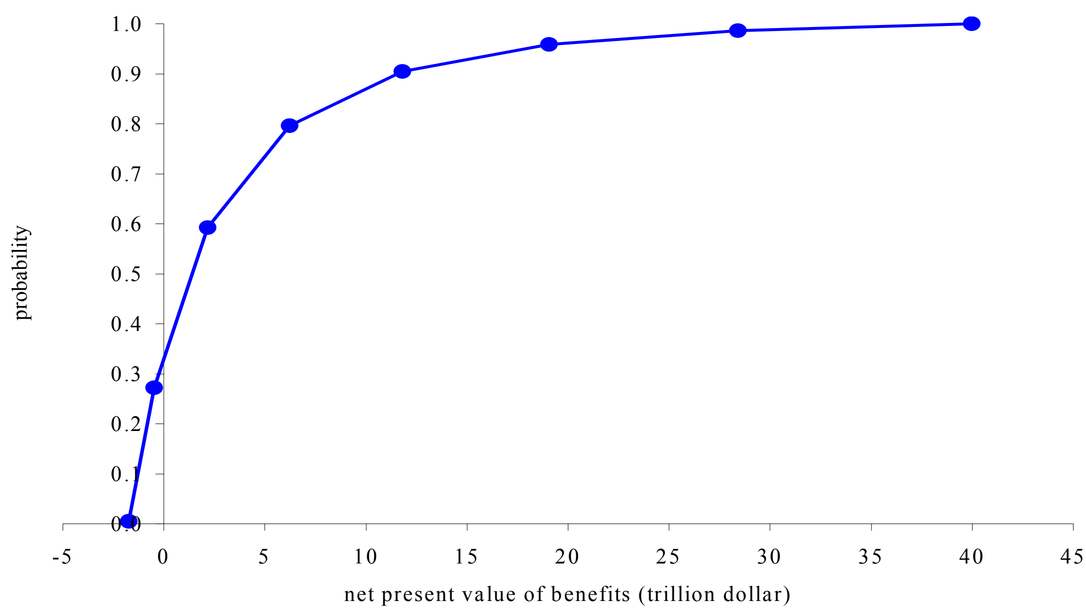
benefit-cost ratio of Jamison *et al.* (this volume) and our very high benefit-cost ratio is therefore explained by the valuation of the benefits rather than the estimate of the costs. Jamison *et al.* (this volume) assume a benefit of \$1,000/DALY, or \$15,000 per malaria death. In FUND, mortality is valued by the value of a statistical life rather than by the value of a year of life lost. The assumed value is 200 times per capita income, which in Sub-Saharan Africa implies \$100,000 per malaria death. The survey of Viscusi and Aldy (2003) suggests that our US value of a statistical life is on the low side, while our income elasticity is too high; together, this argues for a value of statistical life in Africa that is decidedly higher than \$100,000. Viscusi and Aldy (2003) also show that the value of a statistical life is not at all proportional to age (even when controlling for wealth differences) as implicitly assumed by putting a value on a DALY.

individually is smaller than the present value of all three taken together even when subjected to the constraints of the Copenhagen Consensus spending rules.

Uncertainty

All of our analysis was built upon the foundation of a deterministic baseline, and so it misses the uncertainties that cloud our ability to foresee precisely the consequences of climate change and climate policy. While we did not conduct a full investigation of the implications of all of the profound sources of uncertainty, we did examine the implications of one of the most important – the value assumed for climate sensitivity. Figure 5.5 provides an indication of the significance of this uncertainty by displaying a cumulative distribution of net present value for the "Mitigation only" alternative with "when flexibility" (the TAU Cost Effective Mitigation case in Table 2.1) for climate

Figure 5.5: Cumulative Distribution of Net Present Value of Mitigation Only for the "When Flexibility" Benchmark.

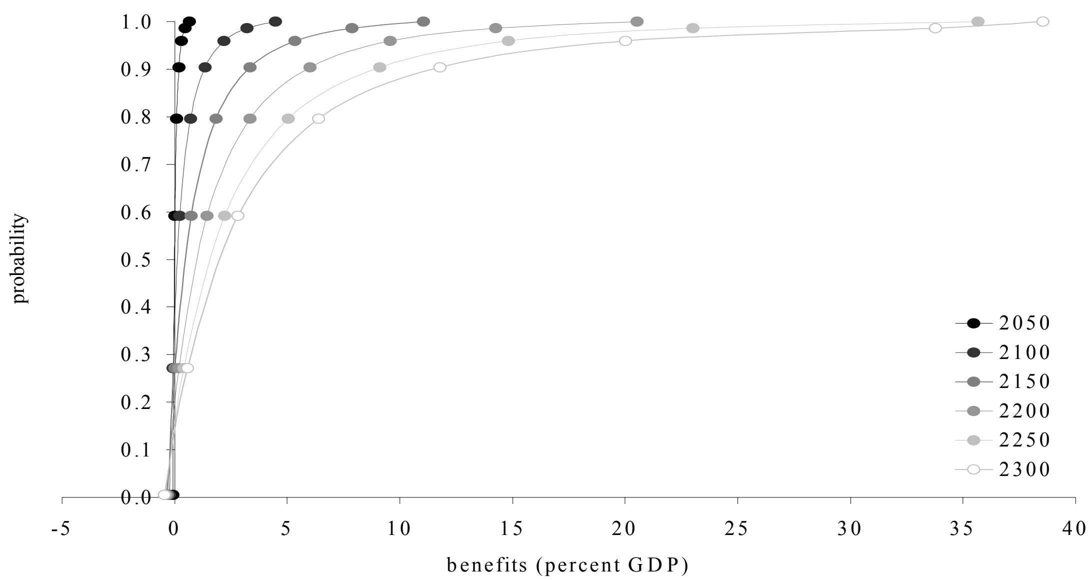


sensitivities ranging from 0.5°C to 7.5°C. The probabilities assigned across this range are consistent with published estimates.[6]

[6] The probabilities assigned to climate sensitivities 0.5°C, 1.5°C, 2.5°C, 3.5°C, 4.5°C, 5.5°C, 6.5°C, and 7.5°C were 0.5%, 26.7%, 32%, 20.4%, 10.8%, 5.5%, 2.7% and 1.4%, respectively. They are consistent with estimates drawn from IPCC (2007a) by Weitzman (2007) and characterized by a lognormal distribution with $\mu = 1.0$ and $\sigma = 0.5$.

It is clear that low sensitivities can produce negative net present values for mitigation (i.e., the $800 billion discounted cost is higher than the discounted value of damages avoided) even assuming a cost minimizing allocation over time in the implementation of climate policy. It is equally clear, though, that high climate sensitivities produce high damages (catastrophic damages for some regions at 7.5^{o}C) and thus high benefits for the $800 billion investment in mitigation alone. The second row of Table 5.1 shows that the expected present value of this option climbs to more than $5 trillion to support a benefit-cost ratio of nearly 7. Figure 5.6 displays the inter-temporal distribution of benefits by depicting cumulative distributions of benefit estimates for selected periods across the range of climate sensitivities; the positive ranges essentially disappear as the future unfolds.

Figure 5.6: Cumulative Distributions of the Benefits of Mitigation Only for the "When Flexibility" Benchmark over Time.



Geo-engineering

As noted earlier, scientists and policymakers are beginning to appreciate that responding to climate change will require a portfolio of actions. The portfolio typically includes mitigation to slow the rate of climate change, adaptation, to limit the damages that do occur, research and development on new and improved low carbon energy technologies to manage the costs of the transition to a low carbon world, and reducing scientific uncertainty so we can make better informed decisions in the future. This paper has focused on the first three. An oft ignored albeit controversial alternative is geo-engineering, for example changing the albedo of the atmosphere to reflect incoming light back into space to offset potential warming. This occurs naturally through volcanic eruptions or anthropogenically through the release of sulfur dioxide into the atmosphere when burning coal to generate electricity. Before policy-makers can decide if geo-engineering should play a role along with other alternatives (for instance, if global warming occurs even more rapidly than the high-end of the IPCC scenarios), a major research effort is needed to understand the efficacy, costs, and potential consequences and risks of the various geo-engineering strategies that have been proposed, and to identify other potential alternative strategies.

While there is a danger that some may interpret geo-engineering research as a "quick fix" to the climate problem that obviates critical adaptation and mitigation efforts, a failure to conduct careful research into different alternatives would be an even bigger risk. At present, it appears that geo-engineering could be simple, cheap and effective, and that it could be unilaterally deployed by a medium-sized country. There is, however, the chance of unintended consequences which, if the geo-engineering project were designed to "make a dent" in the climate problem, could occur on very large scales. For instance, geo-engineering could reverse global or regional warming, but leave ocean acidification unaffected and accelerate changes in precipitation patterns. Articles on geo-engineering by well-respected researchers are beginning to appear in the literature, but a more extensive research program in this area is needed.

6. Concluding Remarks

Table 4.1 reports our summary results, and all but the "Mitigation only (annual)" option show benefit-cost ratios in excess of one. In our assessment of the options, we conclude that the portfolio approach – option (5) that combines annual mitigation, investment in carbon-saving and carbon sequestering technology, and additional adaptation measures to combat potential increases in the incidence of some infectious disease – is the best choice. It has the highest benefit-cost ratio (a respectable 2.7), and it takes advantage of the complementarity noted in IPCC (2007b). To be more specific, calculations of the benefits derived from investing in R&D alone suggest that the total benefits of the portfolio approach that expends $50 billion on R&D (in present value) and "investment" in mitigation to $750 billion (also in present value) exceeds the sum of "Mitigation only" and "R&D only" by a discounted value of $50 billion. In other words, the complementarity works to allow R&D essentially to pay for itself when it is embedded (as it would be) in a more extensive mitigation program. Moreover, adding adaptation to the portfolio increases its discounted value (relative to adaptation alone) by another $3 billion. Clearly, each option makes the other options more effective; i.e., the benefits of implementing the portfolio approach exceed the sum of their individual benefits.

Table 5.1 meanwhile shows that exploiting "when flexibility" and recognizing the uncertainty in our understanding of the climate system both significantly increase the value of climate policy. As noted above, implementing "when flexibility" is difficult. It implies committing future generations to intertemporal allocations in ways that could be very difficult to enforce. On the other hand, though, uncertainty about the climate system is profound, and the risk-reducing value of climate policy should not be ignored. Since Table 5.1 suggests that the expected benefit of policy would double even if only current uncertainty about the climate sensitivity were included, we conclude that the true benefit cost ratio of the portfolio approach described in option (5) is easily above 5

While we certainly acknowledge that climate policy is a very long term enterprise for which a four year time horizon is virtually meaningless, it is important to recognize that our results are different from those reported to the 2004 Copenhagen Consensus exercise by Cline (2004) in many ways. We do not, for example, conduct an optimization exercise; i.e., we do not rely on "when flexibility" and we model only partial "where flexibility" in allocating expenditures that are fixed annually by the prescribed budget. Our mitigation policies do not, therefore, imply increasingly stringent interventions with carbon taxes that begin in the hundreds of dollars per ton and climb from there; ours climb quickly to a level near $20 per ton of CO_2 and stay there (in real terms) almost indefinitely. This is, of course, a manifestation of our interpretation of the Copenhagen Consensus budget constraint and our characterization of anticipated annual decisions to mitigate – i.e., the specific second-best world within which we chose to operate.

It is also important to emphasize that we did not employ a very low discount rate in an effort to produce acceptable benefit-cost ratios. Much like Stern *et al*. (2006), Cline (2004) used a pure rate of time preference that approximates zero. Both analyses thereby adopted a prescriptive approach that elevates the discounted value of future benefits significantly. Yohe (2006) reports that, as a result, almost 50% of the climate damages reported by Stern *et al*. (2006) lie in the post 2200 residual; and Nordhaus (2006) confirms the concerns raised by Manne (2004) when he demonstrates that applying such a discount rate across the economy would lead to a 10 percentage point increase in the saving rate (almost 50% increase) and reduce present consumption by about 13 % (or $4 trillion). There are, of course, sound economic reasons for adopting a low discount rate for public investment when the private return to capital is taxed and public investment complements private investment (see Ogura and Yohe (1977), for example). Perhaps a case can be made that public investment in mitigation would complement private investment across a global economy, but that is beside the point here. By adopting a more conventional approach to discounting, we avoid all of this controversy.

We must admit, though, that none of our policies "solve the climate problem" in the sense of moving temperature increases significantly to the left in Tables 1.3 and 1.4. Indeed, Figure 3.2 shows that our portfolio option lowers the temperature increase from roughly 3.5^{o}C to something slightly below 3.0^{o}C in 2100. We do not, therefore, achieve the results reported for long-term stabilization at the top of Table 1.3. Nor do we reduce significantly the risk of some profound impacts across all sectors and in all regions that many might consider "dangerous" in the parlance of the United Nations Framework Convention on Climate Change. Cast in that light, especially given uneven distributions of impacts across regions and within specific populations, therefore, our portfolio proposal must be viewed more as a start that defines near-term policy in the context of a long-term discussion within which the expected benefits exceed tolerable costs by more than a factor of five. It is, therefore, reassuring that the shadow price for carbon in the mitigation component of our portfolio is in line with estimates of expected cost-minimizing hedging policies reported in, for example, Yohe, *et al.* (2004). There, an initial global carbon tax of roughly $10 per ton of CO_2 that would grow predictably and persistently at the rate of interest minimized the expected cost of achieving an as yet undetermined temperature target given a distribution over climate sensitivities of the sort described in Section 5. Our tax is twice that, but it remains constant over time; the hedging tax reaches $20 per ton within 15 years and continues to rise.

In closing, therefore, our results are born of a mainstream economic analysis. They support climate policy with benefit-cost ratios in excess of unity, and they are consistent with responses supported alternative risk-based approaches.

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Appendix A: The MERGE Model

The analysis is based in part on the MERGE model (a **m**odel for **e**valuating the **r**egional and **g**lobal **e**ffects of greenhouse gas reduction policies). MERGE is an intertemporal general equilibrium model. Like its predecessors, the current version is designed to be sufficiently transparent so that one can explore the implications of alternative viewpoints in the greenhouse debate. The current analysis utilizes those submodels that provide a reduced-form description of the economy, the energy sector, and related emissions of carbon dioxide; the "handoff" to FUND occurs here.

MERGE provides a bottom-up representation of the energy supply sector. For a particular scenario, a choice is made among specific activities for the generation of electricity and for the production of non-electric energy. Oil and gas are viewed as exhaustible resources. There are introduction constraints on new technologies and decline constraints on existing technologies. Mitigation effort can be simulated by applying constraints on annual emissions levels from participating countries, or by allowing optimal emissions reductions with respect to a long-term stabilization target.

Geographically, the world is divided into nine geopolitical regions: 1) the USA, 2) WEUR (Western Europe), 3) Japan, 4) CANZ (Canada, Australia and New Zealand), 5) EEFSU (Eastern Europe and the Former Soviet Union), 6) China, 7) India, 8) OILX (oil exporting will be captured countries, and 9) ROW (the rest of world). Note the OECD (regions 1-4) together with EEFSU constitute Annex B of the UN Framework Convention on Climate Change. The remaining four regions comprise non-Annex B. MERGE is calibrated to the year 2000. Future periods are modeled in 10-year intervals. Hence, the Kyoto Protocol's first commitment period (2008-2012) is represented as 2010.[7] All economic values, included technology costs, are reported in U.S. dollars of constant 2000 purchasing power.

Table A2 identifies the alternative technologies available for future electricity supply.[8] We assume two electric generation technology scenarios. The first is a "technology as usual" (TAU) development path where investment in new technologies continues to follow the reduced funding path observed over the past three decades. The second scenario involves an accelerated technology path (ATP) where an increased commitment to energy R&D leads to earlier breakthroughs, so that the introduction of advanced technologies occurs decades earlier than it would otherwise.

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[7] Conference of the Parties, "Kyoto Protocol to the United Nations Framework Convention on Climate Change", Report of the Conference of the Parties, Third Session Kyoto, 1-10 December, FCCC/CP/1997/L.7/Add1. http://www.unfccc.de.

[8] Technology assumptions refer specifically to the U.S. Assumptions for other regions are similar but vary in some cases.

We assume that existing coal and nuclear power plants are retired during the first half of the 21st century according to a schedule consistent with 60-year plant lifetimes. Existing natural gas assets are assumed to have 20-year lifetimes, and hydroelectric power is constrained to existing levels. With respect to new fossil-based generation, the model does not distinguish between technologies within a given category, such as between different coal feedstocks, pulverized vs. gasified processes, or the means by which CO_2 is captured in carbon capture and sequestration (CCS) technologies. We assume that the cost of new nuclear generation has both a market and non-market component (see Table A2). The latter, which is calibrated to current usage, rises proportionally to market share and is intended to represent public concerns about environmental risks in the technology and associated nuclear fuel cycle.

Table A2: Electric Generation Technology Assumptions

Technology	ATP Description	TAU Description
Coal (without CCS)	LCOE* = $57 - $41 / MWh Efficiency = 38% - 46%	*Same as ATP*
Coal with CCS	First available in 2020 LCOE* = $70 - $55 / MWh Efficiency = 36% - 42% Capture rate = 90%	Not available until 2060 *Cost and performance as in ATP*
Natural Gas (without CCS)	LCOE* = $50 - $70 / MWh** Efficiency = 49% - 60%	*Same as ATP*
Natural Gas with CCS	First available in 2020 LCOE* = $84 - $110 / MWh** Efficiency = 39% - 42% Capture rate = 90%	Not available until 2060 *Cost and performance as in ATP*
Nuclear (new ALWR***)	First available in 2020 LCOE* = $40 - $37 / MWh Non-market cost = $10 / MWh***	Limited to existing nuclear production levels until 2060 *Cost and availability as in ATP*
Hydroelectric	LCOE* = $40 / MWh	*Same as ATP*
Wind	LCOE* = $86 / MWh in 2010 LCOE* = $62 / MWh in 2050	LCOE* = $86 / MWh in 2010 LCOE* = $62 / MWh in 2100
Biomass	LCOE* = $86 / MWh in 2010 LCOE* = $69 / MWh in 2050	LCOE* = $86 / MWh in 2010 LCOE* = $69 / MWh in 2100
Solar (thermal)	LCOE* = $144 / MWh in 2010 LCOE* = $66 / MWh in 2050	LCOE* = $144 / MWh in 2010 LCOE* = $66 / MWh in 2100
Solar (photovoltaic)	LCOE* = $225 / MWh in 2010 LCOE* = $81 / MWh in 2050	LCOE* = $225 / MWh in 2010 LCOE* = $81 / MWh in 2100

* LCOE refers to full levelized cost of electricity.
** Assumes reference path for natural gas fuel price. Actual price varies by scenario within the model.
*** ALWR refers to advanced light water reactor. Non-market cost rises with generation share.

MERGE includes three categories of renewable technologies: wind, biomass, and solar (thermal and photovoltaic). The final category of renewables represents the electric backstop technology. The distinguishing characteristics of the backstop category are 1) a zero GHG emissions rate and 2) that once introduced, it is available at a constant marginal cost. It is intended to represent the fact that we will not run out of energy, but as conventional sources are exhausted there will be more expensive sources waiting in the wings.

Table A3 identifies alternative sources of *non*electric energy within the model. Oil and gas supplies for each region are divided into 10 cost categories, where the higher cost groups reflect the potential use of nonconventional sources. Coal may be used directly or converted into synthetic fuel liquids (at a large energy and emissions premium). In addition, plug-in hybrid electric vehicles (PHEVs) may be used to offset non-electric energy production for transportation with electric generation. With regard to carbon-free alternatives, the choices have been divided into two broad categories: biofuels refer to low-cost sources such as ethanol from biomass, while the backstop technology represents a high cost option, for example, hydrogen produced via electrolysis using solar photovoltaics or hydrogen from thermonuclear dissociation. The key distinction is that biofuels are in limited supply, but the backstop is available in unlimited quantities at a constant but considerably higher marginal cost.

Table A3: Non-Electric Energy Technology Assumptions

Technology	ATP Description	TAU Description
Coal (for direct use)	Cost = \$2.50 / GJ	*Same as ATP*
Petroleum (10 cost categories)	Cost = \$5 - \$7.25 / GJ	*Same as ATP*
Natural Gas (10 cost categories)	Cost = \$6 - \$8.25 / GJ	*Same as ATP*
Synthetic (coal-based) Liquids	Cost = \$8.33 / GJ	*Same as ATP*
Biofuels	Cost = \$10 / GJ	*Same as ATP*
Non-Electric Backstop	Cost = \$25 / GJ	*Same as ATP*
Plug-in Hybrid Electric Vehicles	First available in 2010 Cost = \$6 - \$0 / GJ (equivalent to \$4000 - \$0 per vehicle premium) Efficiency = 69 KWh/GJ (equivalent to 300 Wh / 0.03 gallons per mile)	First available in 2050 *Cost and performance as in ATP*

Typically, the energy producing and consuming capital stock is long lived. In MERGE, introduction and decline constraints are placed on *new* technologies. We assume that the production from new technologies in each region is constrained to 1% of total production in the year in which it is initially introduced and can increase by a factor of three for each decade thereafter. The decline rate is limited to 3.5% per year for new technologies, but there is no decline rate limit for existing technologies. This is to allow for the possibility that some emission ceilings may be sufficiently low to force premature retirement of the existing capital stock.

Turning from the supply to the demand side of the model, we use nested production functions to determine how aggregate economic output depends upon the inputs of capital, labor, electric and non-electric energy. In this way, the model allows for both price-induced and autonomous (non-price) energy conservation and for interfuel substitution. Since there is a "putty-clay" formulation, short-run elasticities are smaller than long-run elasticities. This increases the costs of rapid short-run adjustments. The model also allows for macroeconomic feedbacks. Higher energy and/or environmental costs will lead to fewer resources available for current consumption and for investment in the accumulation of capital stocks.

Where international trade in emission rights is permitted, regions with high marginal abatement costs can purchase emission rights from regions with low marginal abatement costs.[9] There is also trade in oil and natural gas. Each of the model's nine regions maximizes the discounted utility of its consumption subject to an intertemporal budget constraint. Each region's wealth includes not only capital, labor and exhaustible resources, but also its negotiated international share in global emission rights.

[9] In MERGE, emissions can be limited either directly in each region or by a carbon tax with "lump sum" recycling of revenue. When the carbon taxes resulting from a particular cap and trade scheme are used as inputs to control emissions, they produce identical regional emissions that were inputs under cap and trade.

Appendix B: The FUND Model

This paper uses version 2.9 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 2.9 of *FUND* corresponds to version 1.6, described and applied by Tol (1999, 2001, 2002a), except for the impact module, which is described by Tol (2002b,c) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. The model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (2006a). Finally, the model now has sulphur hexafluoride (SF_6) and a newly calibrated radiative forcing code. A full list of papers, the source code and the technical documentation for the model can be found on line at http://ww.uni-hamburg.de/Wiss/FB/15/Sustainability/fund.html.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to assess the long-term implications of climate change. Previous versions of the model stopped at 2200.

The period of 1950-2000 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes & Goldewijk, 1994). The scenario for the period 2010-2100 is based on MERGE scenario. The 2000-2010 period is interpolated from the immediate past (http://earthtrends.wri.org), and the period 2100-2300 extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide.

The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (http://earthtrends.wri.org). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible impacts are dead-weight losses to the economy (cf. Fankhauser and Tol, 2005). Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane, nitrous oxide and sulphur hexafluoride, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al*. (1992). The model also contains sulphur emissions (Tol, 2006a)

The radiative forcing of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride and sulphur aerosols is determined based on Ramaswamy *et al*. (2001). The global mean temperature *T* is governed by a geometric build-up to its equilibrium (determined by the radiative forcing *RF*), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al*., 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate impact module, based on Tol (2002b,c) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002c).

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol, 2002b). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002c).

The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002c).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002c).