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The economic geography of the impacts of climate change

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Abstract

Our ability to understand the geographical dispersion of the impacts of climate change has not yet progressed to the point of being able to quantify costs and benefits distributed across globe along one or more climate scenarios in any meaningful way. We respond to this chaotic state of affairs by offering a brief introduction to the potential impacts of a changing climate along five geographically dispersed portraits of how the future climate might evolve and by presenting a modern approach to contemplating vulnerability to climate impacts that has been designed explicitly to reflect geographic diversity and uncertainty. Three case studies are offered to provide direct evidence of the potential value of adaptation in reducing the cost of climate impacts, the versatility of thinking about the determinants of adaptive capacity for specific regions or sectors, and the feasibility of exploring both across a wide range of 'not-implausible' climate and socio-economic scenarios. Three overarching themes emerge: adaptation matters, geographic diversity is critical, and enormous uncertainty must be recognized and accommodated.

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1. Introduction

The contribution of Working Group II to Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001b) devoted nearly 1000 pages of text to a thorough assessment of the current literature on the potential impacts of climate change and climate variability.[1] Organized across seven different sectors and eight different regions, their work provides immediate access to the 'state of the art' in evaluating the vulnerabilities of communities, nations, and regions to possible climate futures—at least as of the year 2000. The present paper will not try to duplicate the

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[1] The first IPCC assessment (IPCC, 1990) began the process of reviewing the scientific literature in support of what became the United Nations Framework Convention on Climate Change. It was augmented by a supplementary report (IPCC, 1992) and subsequently followed in three parts by the Second Assessment Report, the SAR, in the middle of the decade (IPCC (1996a), (1996b), and (1996c)). The Third Assessment Report also appeared in three parts. Working Group I focused on the natural science of climate change (IPCC, 2001a). Working Group II concentrated on impacts and adaptation (IPCC, 2001b); and Working Group III reported on the state of our understanding about mitigation (IPCC, 2001c).

IPCC coverage. It will, instead, focus attention on a few of the strengths and weaknesses in our current understanding that are most germane to the economic paradigm in an effort to highlight how economists might be able to exploit those strengths and overcome those weaknesses.

Few impact analyses have, for example, looked at transient change, so few have accounted for how different rates of change might influence costs and damages. Few impact studies have recognized fully the wide range of uncertainty that colors our vision of future climate, so few have investigated robust responses that might accommodate wide ranges of possible change. Few studies have provided insight into the implications of location-specific and path dependent social, political, and economic environments in determining the capacity of these systems to adapt to change, so few have accommodated the implications of global diversity. These and other topics surely lie within the purview and interest of the economic community.

This list of shortcomings, drawn from an economist's perspective, could easily be extended, but we must recognize from the start that researchers from other disciplines would construct different lists. It follows that all contributing disciplines must recognize the limitations imposed on their approaches to the problem by deficiencies in understanding or methodological coverage that are beyond their control. An economist might think that it would be productive at this point to express the Third Assessment Report in terms of costs and benefits distributed across globe along one or two specific climate change scenarios. To do so, however, would be both imprudent and impossible. It would be impossible to pick one climate scenario and still reflect the enormous uncertainties that cloud our understanding of how future climate might unfold even if we knew how the pattern of world development and associated changes in land-use over the next 50 years or so. It would also be impossible to translate any global climate change scenario into regional portraits that span the globe with sufficient resolution to inform impacts research at local levels. Finally, our ability to predict how communities and/or nations might adapt to those impacts over time is still in an embryonic stage, so translating exposure into vulnerability across the globe is currently beyond our reach, as well.

We respond to this chaotic state of affairs by offering a brief introduction to the potential impacts of a changing climate in the first section before turning to five geographically dispersed portraits of how the future climate might evolve in Section 2. Section 3 then presents a modern approach to contemplating vulnerability to climate impacts that has been designed explicitly to reflect geographic diversity and uncertainty. Three case studies are then offered in Section 4. They have been chosen to provide direct evidence of the potential value of adaptation in reducing the cost of climate impacts, the versatility of thinking about the determinants of adaptive capacity for specific regions or sectors, and the feasibility of exploring both across a wide range of 'not-implausible' climate and socio-economic scenarios. Concluding remarks simply reiterate three overarching themes: adaptation matters, geographic diversity is critical, and enormous uncertainty must and can be recognized and accommodated.

2. Introduction to the potential impacts of climate change

Schneider (1989) contains perhaps the most concise explanation of how the Earth's atmosphere works to maintain an inhabitable temperature and how it might be altered by human activity. Clouds and particles in the atmosphere, together with the Earth's surface, reflect roughly 30% of the incoming solar energy, but the remaining 70% of the energy is absorbed. This heats the surface of the Earth and the atmosphere, and it is then re-emitted in the infrared spectrum. An energy balance for the planet is achieved by this radiation, but only after energy trapped by clouds and greenhouse gases (GHGs) warms its surface. In fact, pre-industrial concentrations of GHGs made the Earth about 33 °C warmer than it would have been otherwise, and increased concentrations can further warm the planet. Since it is now understood that concentrations are increasing from human activity, the fundamental questions are clear. How much higher will temperatures climb, and how fast? How will this warming be distributed across the globe? Will some regions warm more quickly than others? Will other regions actually grow colder? How will higher temperatures affect sea levels? How might precipitation patterns change? Could warming change the frequencies and geographical distributions of extreme (weather) events? Might there be abrupt changes in climate?

Figure 1 displays a stylized overview of the most recent thinking on the impacts of climate change. It shows that the risks of adverse impacts from climate change measured along five dimensions increase with the magnitude of climate change indexed by increases in global-mean temperature. In all cases, white regions indicate no or neutral impacts and no risk, while increasingly shaded regions reflect increasingly negative impacts and significant risk. Two of the critical dimensions identified in Fig. 1 involve estimates of economic damage: 'Aggregate Impacts' and the 'Distribution of Impacts'. They are loose reflections of a literature that has, over the past decade or so, recorded estimates of the economic consequences of climate change with increasing geographical resolution but not necessarily with increasing accuracy. Published estimates show modest and, in some instances, positive impacts on market-based sectors with small temperature increases, but they also show that the impacts of even small climate change will not be evenly distributed across the globe. Developing countries will, in particular, be more vulnerable to the negative potential of climate change, and this raises the possibility that impacts could exacerbate income inequality between and even within countries. With larger increases in temperature, moreover, negative impacts would be exaggerated while net positive impacts in even developed countries would begin to decline and eventually turn negative (IPCC, 2001b, ch.19).

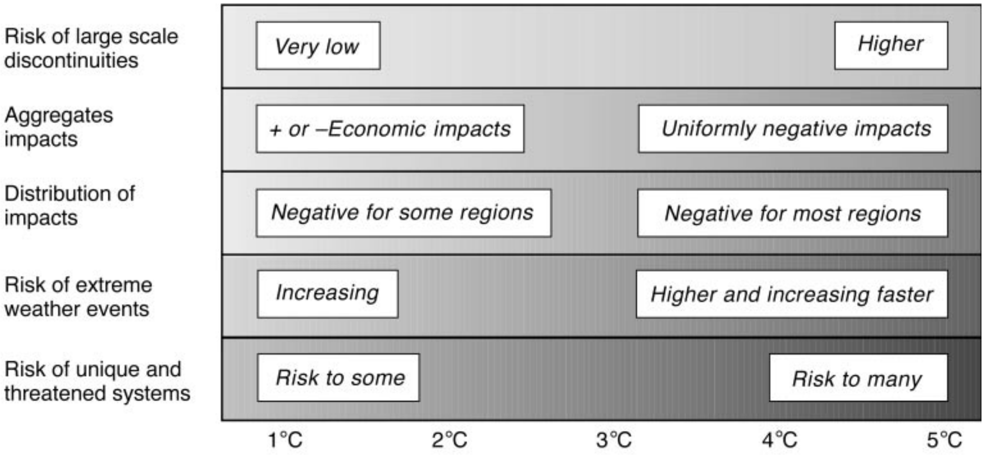

Figure 1. Overview of climate impacts as a function of increases in global mean temperature. Areas with darker shading indicate larger and more dangerous impacts and associated risks. *Source*: early versions of what became Fig. 19-7 in IPCC (2001b).

Table 1 records some of the estimates that support these conclusions; positive numbers denote benefits while negative numbers reflect costs. As a point of reference, notice that the estimates reported in 1995 by the IPCC in its Second Assessment Report (IPCC, 1996b) were dominated by declines in agricultural production for high and low climate sensitivities. Agriculture is, of course, a sector whose current practices would likely be threatened by higher temperatures and less precipitation. Most of the early estimates for agriculture (as well as for other sectors) were, however, drawn from vulnerability studies that paid little attention to the ability of humans and their institutions to reduce economic damage and expand economic opportunity by adapting. Moreover, most of the early studies relied on relatively primitive methods of tracking the different regional consequences of a 2.5 °C increase in global-mean temperature. It is well known that some regions would see temperatures increase by more than 2.5 degrees while others might actually get cooler, but there is no consensus about exactly how these differences will be distributed. It is also well understood that some areas would get wetter while others got drier. It is equally well understood that sea

Table 1. Indicative world impacts by region (in percent of current GDP)

	IPCC SAR	Mendelsohn et al.		Nordhaus & Boyer	Tol
	(2.5 °C)	(1.5 °C)	(2.5 °C)	(2.5 °C)	(1.0 °C)
North America					3.4 (1.2)
United States			0.3	−0.5	
OECD Europe					3.7 (2.2)
EU				−2.8	
OECD Pacific					1.0 (1.1)
Japan			−0.1	−0.5	
Eastern Europe/FSU					2.0 (3.8)
Eastern Europe				−0.7	
Russia			11.1	0.7	
Middle East				−2.0	1.1 (2.2)
Latin America					−0.1 (0.6)
Brazil		−1.4			
South/Southest Asia					−1.7 (1.1)
India			−2.0	−4.9	
China			1.8	−0.2	2.1 (5.0)
Africa				−3.9	−4.1 (2.2)
Developed countries	{−1.0, −1.5}	0.12	0.30		
Developing countries	{−2.0, −9.0}	0.05	−0.17		
World	{−1.5, −2.0}	0.09	0.10	−1.5	2.3 (1.0)

Source: Table 19-4, IPCC(2001b).

level would rise in some places and fall elsewhere (where the coastline is actually rising at present). Finally, few of the early studies were able to consider the effects of changes in humidity, frequency of extreme temperature events, or any of the other more subtle physical ramifications of global warming.

More recent cost estimates have begun to take a few small steps designed to overcome these shortcomings. The second column of Table 1 presents regional cost estimates of market impacts published recently by Mendelsohn et al. (2000) for a 2.5 °C global-mean warming and a 50 cm increase in sea level. Notice that the overall annual effect on world economic activity, a 0.1% increase, is opposite in sign to the decreases reported in the Second Assessment. Effects on agriculture still dominate the Mendelsohn regional estimates, but their regional distribution has made the largest impression on the research community. Table 1 shows, for example, that North America, Russia, and China could benefit from warming while India, Brazil, and Japan would suffer harm. It is important to understand, however, that Mendelsohn and his coauthors extrapolated statistical summaries of how various regions in developed countries have coped with their current climates to describe how other regions might respond if their climates changed and if they adapted perfectly and if relative prices were unchanged.

The third column of Table 1 reports comparable results from Nordhaus and Boyer (2000) for the same 2.5 °C global-mean warming and 50 cm increase in sea level. They reported losses almost everywhere, but not because they were less sanguine about the ability of adaptive behavior to ameliorate damage and exploit benefits. Estimated damages are, instead, higher because Nordhaus and Boyer included rough representations of losses driven by extreme events (whose frequencies and distributions might change with the climate) as well as the reflections of the risk of sudden and severe change in the climate, itself.

The last column of Table 1 records cost estimates from Tol (1999) for a 1 degree warming in even greater geographical detail. Notice that Tol also reports standard deviations in parentheses; these values are best interpreted as the lower bounds of model-based uncertainty. Only Latin America, southern and Southeast Asia, and Africa suffer losses in his work, and many regions (including China again) benefit substantially. Modest warming might, it would seem, be a good thing; but we cannot leap to that conclusion too quickly. The reported standard deviations indicate a 66% likelihood based on model uncertainty that the true impact of a 1 degree warming would lie within a range that frequently includes zero.

The Nordhaus and Boyer (2000) estimates reveal the potential economic power of two other lines of evidence identified in Fig. 1. We know very little about one—the possibility that climate change might be sudden rather than smooth as the global mean temperature climbs. This possibility will be the focus of intensive research over the next few years.[2] We know a little more about the second—the likelihood that even smooth change might increase the frequencies and/or intensity of extreme (weather) events. We will see in a later section that the changes in those frequencies may be important triggers

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[2] Several possible events that could be related to warming and could also produce sudden changes in climate have been identified in the recent literature. They include a shutdown of the thermohaline circulation in the Atlantic Ocean, a disintegration of the West Antarctic Ice Sheet, a runaway carbon cycle, some transformation of the distribution of continental monsoons, qualitative modifications in cyclical weather patterns like ENSO, a destabilization of the international political order, an so on. See Chapter 19 of IPCC (2001b) for brief descriptions of each.

for economically motivated adaptation. For now, Table 2 summarizes a literature that is full of conjectures that many sectors could be highly sensitivity to a wide range of climate extremes. Few of the studies in that literature have made those claims with much confidence, though, particularly when it comes to attributing changes in the distribution of extreme events to anthropogenic climate change.

The fifth line of evidence highlighted in Fig. 1 reflects the expert judgement that 'we have high confidence that the overall patterns and processes of observations reveal a widespread and coherent impact of 20th century climate changes on many physical and biological systems' (IPCC, 2001b, pp. 914–915). The Third Assessment Report selected 56 of the 200 studies that related trends in impacts to trends in regional climate at various locations around the globe to support this claim on the basis of specific criteria related to time frame and natural variability.[3] These 56 studies investigated approximately 660 distinct natural processes and/or species. Many dealt with decadal to century-long trends in sea ice and glaciers. Others looked at change in terrestrial or marine ecosystems over at least 20 years. More than 59% reported changes in response to climate that were consistent with well-established expectations of a climate-driven impact. Roughly 5% showed responses in unexpected directions, and 36% showed no statistically significant correlation with a climate variable.

The general conclusion to be drawn from Fig. 1 is simple: climate will continue to change as the globe warms and it will produce demonstrable effects. The analyses that support this conclusion were, however, generally constructed from static snapshots of impacts for specific changes in global mean temperature. They therefore missed the time dependence of associated costs, and they subsumed enormous uncertainty about the geographical distributions of changes in critical climate variables other than mean temperature. As a result, these studies are particularly difficult to interpret from a global perspective because different regions of the world will warm, and sometime cool, at different rates. Researchers have, of course, honestly acknowledged that they have been looking through a lens clouded by uncertainty, geographical diversity, and site-specific path dependence. Theirs is not, therefore, the last word on future impacts. Indeed, we have just begun to confront the problem of exploring the full suite of geographically distributed economic implications.

3. Looking at future climate

The first step in this process continues to focus attention on future climate. Climate change over the long-term will be driven by complex dynamic systems about which our understanding is, at best, limited. Demographic patterns, socio-economic development, future land-use and forestry practices, political evolution, and technological change will all drive emissions of greenhouse gases and sulfur dioxide over the requisite century-long time horizon; each driver is a source of enormous uncertainty. The climate implications of these emissions will, in turn, be determined by the sensitivity of the climate system to corresponding changes in the associated atmospheric concentrations of greenhouse gases and by the radiative forcing associated with sulfate aerosols—two more sources of uncertainty. As the research community approaches the climate issue, therefore, it must work with scenarios that reflect these and other underlying uncertainties.

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[3] See Fig. SPM-1 in IPCC (2001b) and the text of Chapter 19 for details.

Table 2. Extreme climate-related phenomena—observed and projected[a]

Climate phenomena	Observed changes	Projected changes	Type of event	Time scale	Sensitive sectors
Higher maximum temperatures	likely	very likely	heat waves	daily/weekly	electric/settlements
			droughts	monthly/seasonal	forests/agriculture/water/electricity/tourism/health
Higher minimum temperatures	very likely	very likely	frost/frozen land	daily/monthly	agriculture/energy/health/transport
More intense precipitation events	likely in mid/high latitudes	very likely	flash floods	hourly/daily	settlements
		very likely	floods and mudslides	weekly/monthly	agriculture/forests/transport/water/settlements/tourism
	medium likelihood	uncertain	snow/ice	hourly/weekly	same
		uncertain	hailstorms	hourly	agriculture/property
Increased summer drying	likely in a few areas	likely in mid-latitude interiors	drought subsidence wildfires	monthly/seasonal	forests/agriculture/water hydro/settlements
El Nino events	inconclusive	likely	droughts or floods	various	forests/agriculture/water/hydro/settlements
Asian summer monsoons	not treated in IPCC (2001a)	likely	droughts or floods	seasonal	forests/agriculture/water/hydro/settlements

[a] Likelihood refers to confidence judgments used in IPCC (2001a): very likely (> 90% chance); likely (66%–90% chance) and medium (33%–66% chance).
Source: Table TS-4; IPCC (2001b).

3.1. Future emissions of GHGs and the SRES scenarios

The *Special Report on Emissions Scenarios* (IPCC, 2000) describes forty 'SRES scenarios' that were developed to replace the earlier IS92 scenarios in a way that more accurately represents our understanding of these uncertainties. The SRES scenarios exclude 'surprise' or 'disaster' scenarios, but each is firmly rooted in one of four different 'narrative storylines' that cover a wide range of demographic, economic, and technological futures. The A1 'Rich World' storyline describes a future with very rapid economic growth supporting a global population that peaks mid-century. New and more efficient technologies are produced and introduced easily while significant capacity building across the globe results in significant reductions in regional differences in per capita income. The A2 'Divided World' storyline meanwhile describes a world that continues to be extremely self-reliant and heterogeneous. Economic development is regionally oriented so that economic growth and technological change are more fragmented and slower. The B1 'Sustainable Development' storyline mirrors A1 somewhat, but adds rapid changes in economic structure toward information and service economies. Material intensity declines with the introduction of clean and efficient technology driven in part by global solutions to economic, social and environmental sustainability, and equity. Finally, the B2 'Dynamics as Usual' storyline brings the same orientation toward sustainability and social equity to a world that focuses its attention regionally much in the same way envisioned in A2. Each individual scenario reflects its parent storyline and describes consistently a particular variant in the relationship between socio-economic drivers and the emission of GHGs and sulfur dioxide. Moreover, the entire collection of scenarios spans much of the range of carbon emissions through 2100 reported in the published literature through 1999. It must be noted, however, that none of the SRES scenarios include mitigation initiatives like those that would be required if the United Nations Framework on Climate Change (UNFCCC) or the Kyoto Protocol were implemented.

Figure 2 presents portraits of representatives of the four SRES storylines reported by Schlesinger et al. (2000) in terms of population, per capita annual gross world product, primary energy intensity, carbon intensity, and carbon emissions.[4] Panel (a) also includes a trajectory for the noninterventionist 'Business As Usual' IS92a scenario from IPCC (1992). Population and per capita annual income are larger in 2100 than 1990 for each scenario, but energy intensity and carbon intensity always decline over this time frame. Carbon emissions display paths that grow monotonically for three scenarios (A1, A2, and IS92a). Emissions peak mid-century for the B1 and B2 scenarios, though, and actually fall below 1990 levels by 2100 for the B1 variant. Figure 3 displays associated concentration trajectories for critical GHGs in panels (a) through (c).[5] Carbon dioxide

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[4] The A1 representative was produced by the Asian-Pacific Integrated Model (AIM) (see Morita et al., 1998); the A2 scenario by the Atmospheric Stabilization Framework (ASF) (see Pepper et al., 1998); the B1 scenario by the IMAGE2 model (see Alcamo et al., 1998) and the B2 scenario by the MESSAGE model (see Gritsevskii and Gruebler, 1998).

[5] The carbon dioxide concentrations trajectories depicted in Panel A were produced from the carbon-cycle model of the Center for International Climate and Environment Research—Oslo (CICERO) (see Alfsen and Berntsen, 1999); the model, based on the work by Joos et al. (1996) was provided by T. K. Berntsen and J. S. Fuglestvedt. M. J. Prather calculated the methane and nitrous oxide concentrations depicted in Panels B and C. The equivalent carbon dioxide (ECD) values were computed from the equations in Table 1 of Myhre et al. (1998).

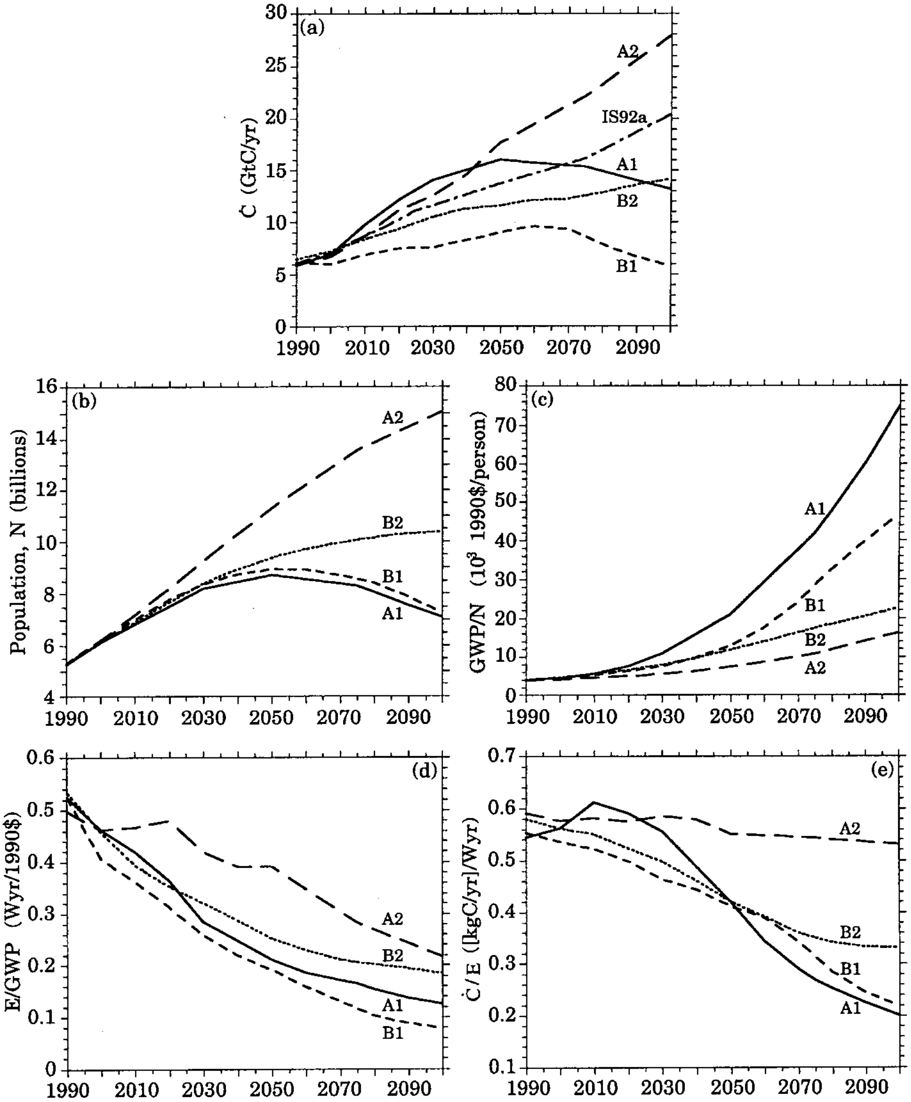

Figure 2. Portraits of the SRES scenarios.

Panels (a) through (e) display global carbon emissions (gigatons of carbon per year), world population (in billions of people), per capita gross world product (in thousands of 1990 $ per person), global energy consumption (in Watts per year) per dollar of gross world product, and global carbon emissions per unit of energy consumption (in kilograms of carbon per Watt per year) along representatives of the four SRES storylines, respectively. The A1 'Rich World' storyline describes a globally integrated future with very rapid economic growth supporting a global population that peaks mid-century. The A2 'Divided World' storyline describes a world with the same economic growth inhibited by extremely self-reliant and heterogeneous regions. The B1 'Sustainable Development' storyline incorporates rapid changes in economic structure toward information and service economies to an integrated future. The B2 'Dynamics as Usual' storyline brings the same orientation toward sustainability and social equity to a world that focuses its attention regionally much in the same way envisioned in A2. The original 'Business as Usual' IS92a is also depicted in panel (a) for reference. *Source*: Fig. 1 in Schlesinger et al. (2000).

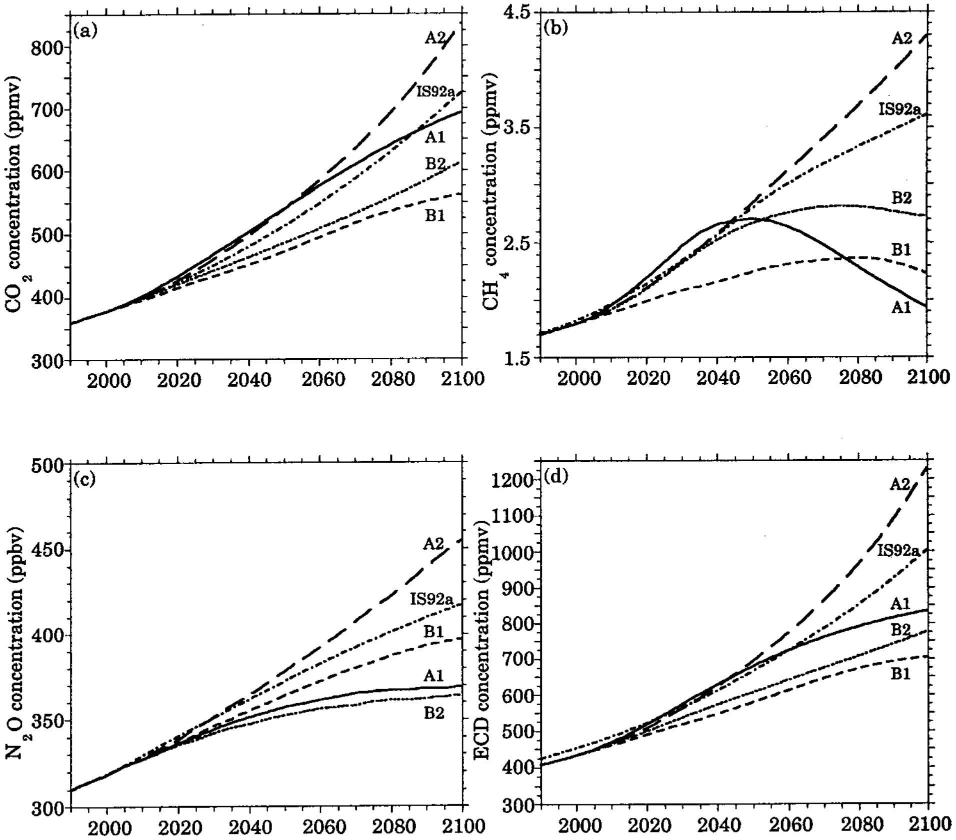

Figure 3. Greenhouse gas emissions and equivalent carbon dioxide equivalents for the SRES and IS92a scenarios.

Concentrations of critical GHGs are portrayed in panels (a) through (c). They are denominated in parts per million in volume (ppmv) or parts per billion for nitrous oxide (ppmb) along the SRES and IS92a scenarios that were depicted in Fig. 2. Panel (d) shows corresponding concentrations in terms of equivalent carbon dioxide units—concentrations of carbon dioxide that would be required to produce the same radiative forcing as the actual combinations of CO_2, methane, and nitrous oxide. *Source*: Fig. 9 in Schlesinger et al. (2000).

concentrations range from 552 ppmv for the B1 scenario to 836 ppmv for the A2 scenario—a range that misses about 30% of the trajectories published prior to the SRES initiative. Panel (d) shows the combined radiative forcing of these compounds along each scenario denominated in equivalent carbon dioxide units (ECD)—the amount of carbon dioxide required to give the same radiative forcing as the three compounds are taken together.

Figure 4 relates the ECD trajectories of Fig. 3 to changes in the global mean surface-air temperature for three different climate sensitivities. These sensitivities, defined in terms of warming associated with doubling pre-industrial atmospheric concentrations of carbon dioxide, are a fundamental source of uncertainty. Our understanding can do little more than bound its value between 1.4 °C on the low side and 5.2 °C on the high side (IPCC, 2001a). Notice that the temperature trajectories for any climate sensitivity are not really distinguishable through the middle of the 21st century. There are,

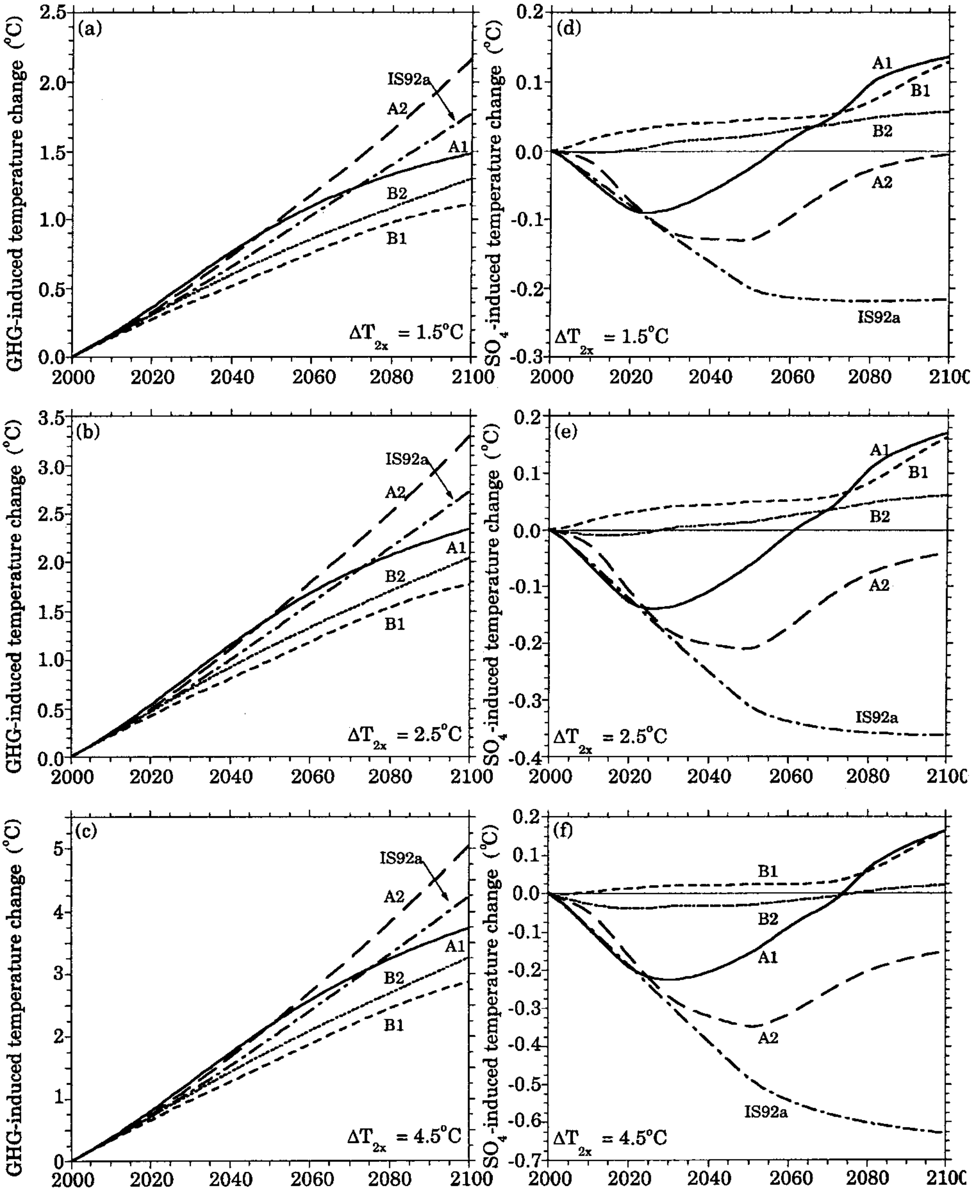

Figure 4. Changes in global mean temperature driven by GHG emissions with alternative climate sensitivities for the SRES and IS92a scenarios.

Transient temperature change scenarios are portrayed for the SRES and IS92a scenarios that were depicted in Fig. 2. Climate sensitivity is reflected in terms of change in global mean temperature that would be associated with a doubling of effective carbon dioxide concentrations. This parameter, denoted ΔT_{2x}, assumes values of 1.5 °C, 2.5 °C, and 4.5 °C, respectively, in panels (a) through (c). Panels (d) through (f) show the corresponding influence of sulfate aerosols along the same scenarios. *Source*: Fig. 10 in Schlesinger et al. (2000).

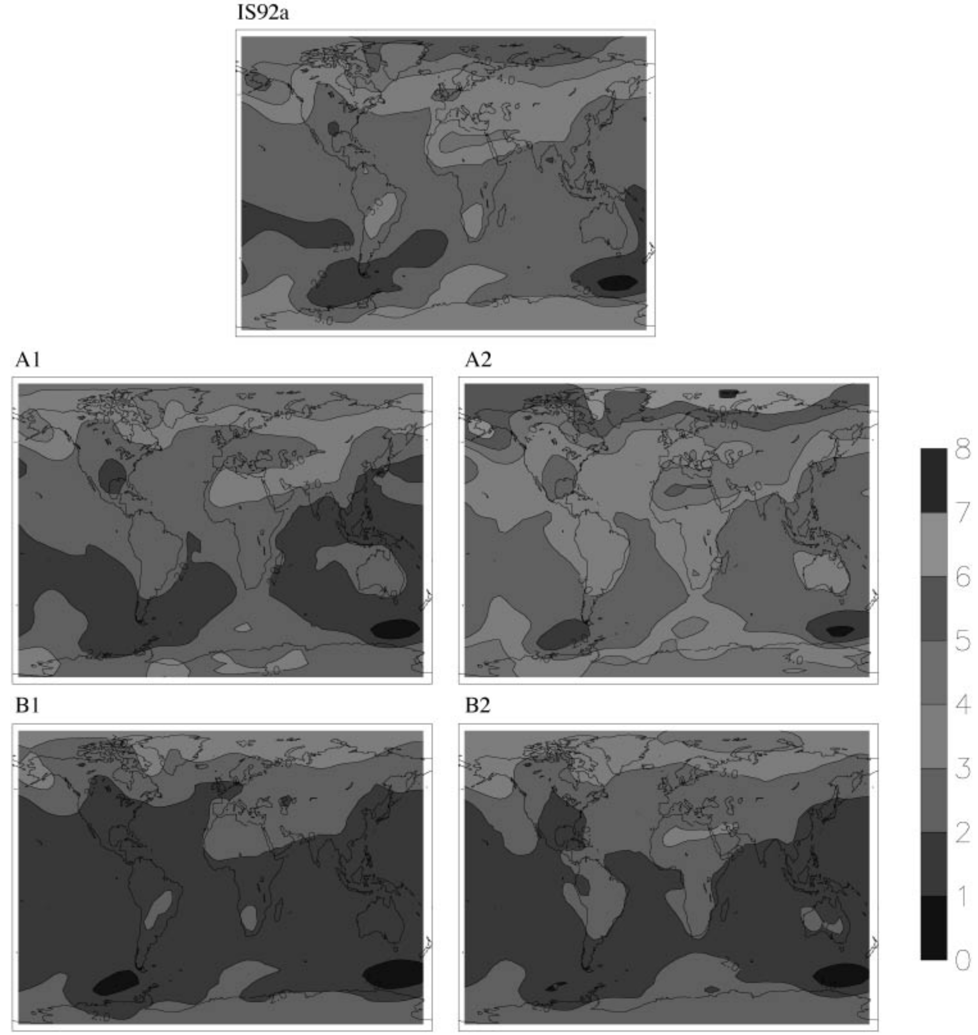

Figure 5. Geographical distribution of annual surface-air temperature change in 2100 relative to 2000 driven by GHG emissions with a climate sensitivity of 2.5 °C for the SRES and IS92a scenarios. Regional temperature changes through 2100 are depicted according to the scale on the right for the SRES and IS92a scenarios that were depicted in Fig. 2. The scale indicates temperature increase from a low of 0 °C to a high of 8 °C in colors that run from green through yellow, red, and dark purple. *Source*: Fig. 12 in Schlesinger et al. (2000).

however, differences across scenarios over the longer term. Estimates of total warming through 2100 range from 1.1 °C along the B1 scenario with climate sensitivity set equal to 1.5 °C to 5.0 °C along the A2 scenario with climate sensitivity set equal to 4.5 °C. Schlesinger et al. (2000) shows that about 41% of this 3.9 °C temperature range for 2100 can be attributed to scenario uncertainty derived from alternative views of social-political-economic development; but the source of the remaining 59% lies squarely in our fundamental uncertainty about climate sensitivity.

Figure 5 finally presents geographical distributions of surface temperature change in 2100 relative to 2000 for the four SRES representative scenarios and the IS92a scenario due to GHGs alone with a climate sensitivity of 2.5 °C.[6] GHG-induced warming is smallest in the tropical latitudes and increases toward both poles. Warming also increases across the scenarios from B1 through B2, A1, IS92a and finally A2. Scenario uncertainty clearly translates into larger geographical uncertainty, particularly in the Arctic, even after ignoring uncertainty about climate sensitivity.

3.2. The future role of sulfate aerosols

The recent literature has emphasized a growing recognition that emissions of sulfur dioxide could play a large role in determining future climate change (IPCC, 2001a). The same set of representative SRES scenarios can be employed to explore this possibility and to demonstrate how quickly our perceptions of future climate can change. Figure 6 displays the corresponding trajectories for SO_2 emissions; notice that the four SRES paths differ significantly from the one associated with IS92a. Panels (d) through (f) in Fig. 4 show their effect on global mean temperature. Figure 7 combines the effects of GHGs and sulfates to display net changes in global-mean surface-air temperature and sea level, respectively, for three climate sensitivities. Combined estimates of total warming and sea level rise range from 1.2 °C and 27 cm along the B1 scenario with a climate sensitivity equal to 1.5 °C to 4.9 °C and 72 cm along the A2 scenario with a climate sensitivity equal to 4.5 °C. About 38% of the temperature range and 31% of the sea level range can be attributed to scenario uncertainty derived from alternative views of social-political-economic development; but the source of the remaining variation continues to lie squarely in our fundamental uncertainty about climate sensitivity.

Figure 8 brings the combined trajectories to bear on the issue of geographical distribution. The patterns are similar to the ones portrayed in Fig. 5 for GHGs, but it is important to note that the higher sulfate emissions of IS92a serve to reduce warming in the Arctic. If the new SRES scenarios are more representative of how the future might evolve, then lower sulfate trajectories can be expected to have a significant effect on climate projections, particularly when geographic dispersion is included in the analysis. Figure 8 also shows that all regions warm along all scenarios, but by differing amounts even for specific climate sensitivities. The increases for a 2.5 °C sensitivity, for example, range from 1.6 °C to 2.7 °C across scenarios B1 to A2 in the Southern Hemisphere and

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[6] These scenarios are the products of simulations performed separately for doubled CO_2 concentration and independent SO_2 emissions by the University of Illinois at Urbana-Champaign (UIUC) general circulation/mixed-layer-ocean model. Each case was normalized by its corresponding global-mean surface temperature change and time trajectories of global-mean surface temperature simulated by an energy-balance-climate/upwelling-diffusion-ocean (EBC/UDO) model. See Schlesinger et al. (2000) for descriptions of the content of these models.

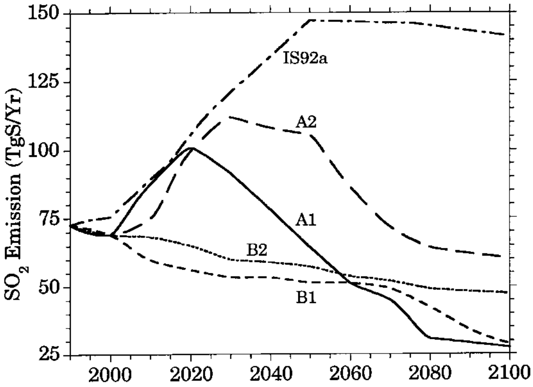

Figure 6. Sulfur dioxide emissions for the SRES and IS92a scenarios.
Emissions of sulfur dioxide denominated in terragrams of sulfur (TgS) per year for the SRES and IS92a scenarios that were depicted in Fig. 2. *Source*: Fig. 1 in Schlesinger et al. (2000).

from 3.1 °C to 5.3 °C in Siberia. These large differences for specific regions appear in spite of little differentiation in global mean temperature.

3.3. Summarizing future climate for impacts analysis

IPCC (2001b) recorded ranges of exposure in terms of possible rates of change in precipitation and temperature, respectively, for 32 major geographical regions across the SRES storylines with climate sensitivities ranging from 1.5 °C to 4.5 °C.[7] Wide ranges of uncertainty in both of these critical indicators of climate change were obvious for all regions. It is still not obvious, however, if these uncertainties matter in terms of socio-economic impacts. Large reductions in precipitation, measured in percentage terms, would have little effect in the Sahara, for example, but reductions in precipitation across eastern Africa could have significant implications for flow in the Nile and, as a result, for political stability and economic sustainability in the Nile Basin. Indeed, Strzepek et al. (2001) produced the range of 'not-implausible' scenarios for flow in the Nile depicted in Fig. 9. Drawn from climate scenarios that span the range of output from the SRES storylines, they include one trajectory with a 20% increase in the flow of the Nile into Lake Nasser by 2100; but they also include other trajectories with reductions as large as 80%. Could Egypt and the other countries of the Nile Basin adapt to these futures? That remains to be seen.

4. Adaptive capacity and improved geographical resolution

Many existing studies have been criticized for overstating the power of adaptation to reduce climate-related costs because their authors have applied statistical models drawn from the developed world to the economic environments of the developing world. These studies have assumed, at least implicitly, that the adaptive strategies that are available and practicable in the market sectors of the world's developed economies would

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[7] See Fig. TS-3 in IPCC (2001b) and associated text for a summary discussion.

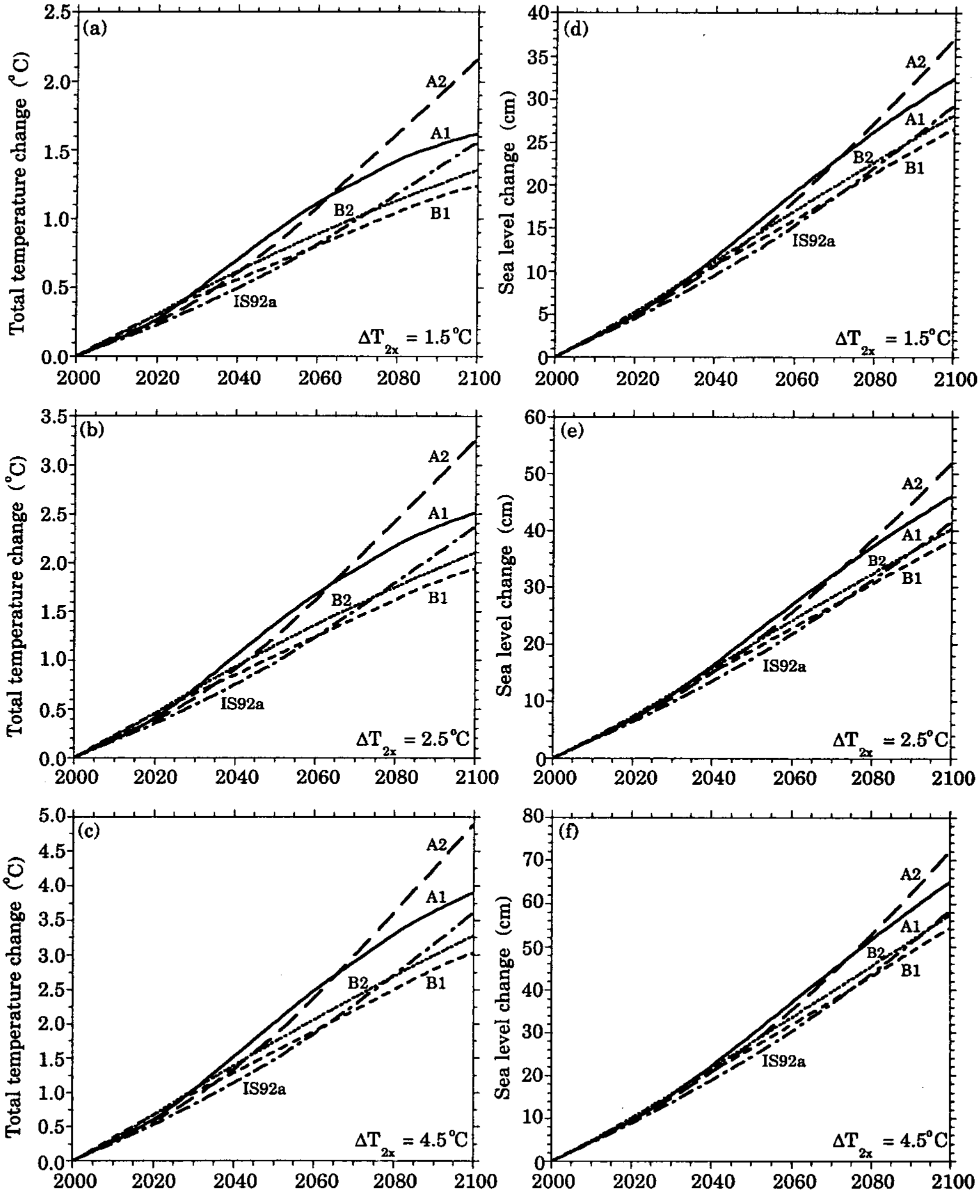

Figure 7. Changes in global mean temperature and sea level rise driven by GHG emissions and sulfate aerosol emissions with alternative climate sensitivities for the SRES and IS92a scenarios. Panels (a) through (c) portray changes in global mean temperature along the SRES and IS92a scenarios that were depicted in Fig. 2 for climate sensitivities (ΔT_{2x}) equal to 1.5 °C, 2.5 °C, and 4.5 °C, respectively. Panels (d) through (f) display the corresponding trajectories for sea level rise in centimeters. *Source*: Fig. 11 in Schlesinger et al. (2000).

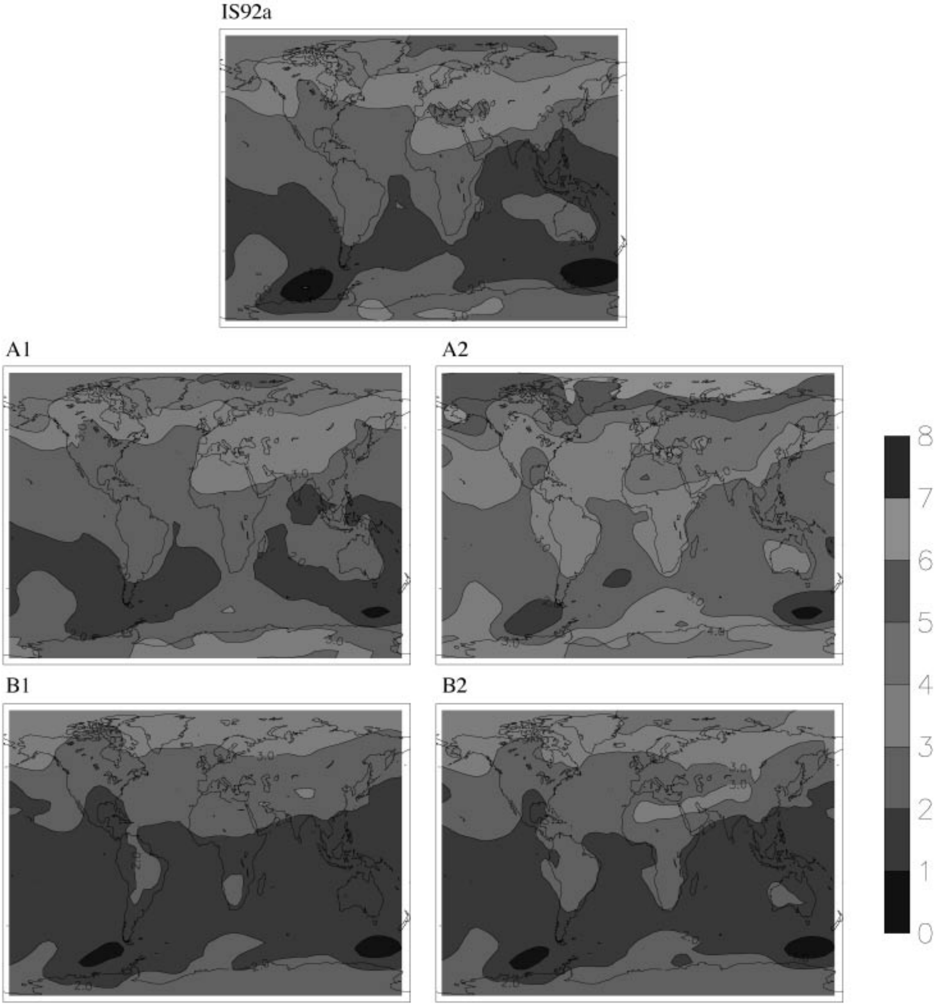

Figure 8. Geographical distribution of annual surface-air temperature change in 2100 relative to 2000 driven by GHG emissions and sulfate aerosols with a climate sensitivity of 2.5 °C for the SRES and IS92a scenarios. Regional temperature changes through 2100 are depicted according to the scale on the right for the SRES and IS92a scenarios that were depicted in Fig. 2. The scale indicates temperature increase from a low of 0 °C to a high of 8 °C in colors that run from green through yellow, red, and dark purple. *Source*: Fig. 18 in Schlesinger et al. (2000).

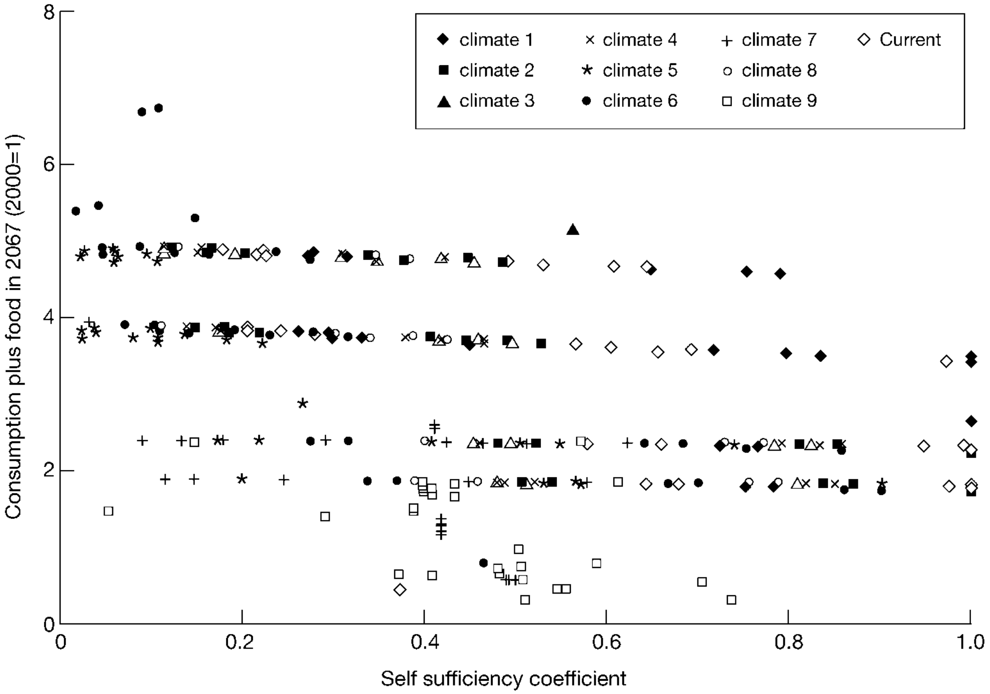

Figure 9. Annual flow into Lake Nasser along 'not implausible' climate futures (2000 flow=1). Projections of annual flow from the upper Nile into Lake Nasser along nine climate scenarios that were chosen to span a range of 'not implausible' futures. The futures were drawn to represent the variability displayed in a collection of over 600 runs of a hydrologic model calibrated by Yates and Strzepek (1998) to accept precipitation and temperature output from 14 regional global circulation models along five different emissions scenarios with three alternative climate sensitivities and sulfate forcing coefficients. *Source*: Fig. 4 in Strzepek et al. (2001).

routinely be available to people who inhabit the world's developing countries. These are people who may face similar climate related stresses in the future, but they will face them in the context of extraordinarily dissimilar socio-economic circumstances.

In addition to the obvious diversity in economic context, any system's environment varies from day to day, month to month, year to year, decade to decade, and so on (see Mearns, et al., 1997; or Karl and Knight, 1998). It follows that changes in the mean conditions that define those environments can actually be experienced most noticeably through changes in the nature and/or frequency of variable conditions that materialize across short time scales and that adaptation necessarily involves reaction to this sort of variability. This is the fundamental point in Hewitt and Burton (1971), Kane et al. (1992), Yohe et al. (1996), Downing (1996), and Yohe and Schlesinger (1998). Some researchers, like Smithers and Smit (1997), Downing et al. (1997), and Smit et al. (1999), use the concept of 'hazard' to capture these sorts of stimuli, and claim that adaptation is warranted whenever either changes in mean conditions or changes in variability have significant consequences. For most systems, though, changes in mean conditions over short periods of time fall within a 'coping range'—a range of circumstances within which, by virtue of the underlying resilience of the system, significant consequences are not observed (see Downing et al. (1997) or Pittock and Jones (2000)). There are limits to resilience for even the most robust of systems, of course. It is therefore critically important to understand the boundaries of systems' resilience; how, exactly, are the thresholds beyond which the consequences of experienced conditions become significant actually determined?

A unifying vulnerability model with which to explore this question across a wide range of contexts has begun to emerge.[8] Any system's vulnerability to climate change and climate variability will be determined by *its exposure to the impacts of climate, its baseline sensitivity to those impacts, and its adaptive capacity*. All three of these factors are clearly dependent on specific circumstances that can be path dependent and geographically idiosyncratic, and therein lies the rub. The determinants of adaptive capacity, for example, include:

1. The range of available technological options for adaptation.
2. The availability of resources and their distribution across the population.
3. The structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria that would be employed.
4. The stock of human capital including education and personal security.
5. The stock of social capital including the definition of property rights.
6. The system's access to risk spreading processes.
7. The ability of decision-makers to manage information, the processes by which these decision-makers determine which information is credible, and the credibility of the decision-makers, themselves, and
8. The public's perceived attribution of the source of stress and the significance of exposure to its local manifestations.

Table 3 summarizes the state of our knowledge about the distribution of adaptive capacity across many of the major regions of the globe. The numbers recorded in each box are designed to refer the reader back to the relevant determinant listed above, but those links hardly convey the major insight to be drawn from the table. The paucity of entries in the adaptive capacity column accomplishes this task. The open space there is visual evidence that the research community has a long way to go before it can claim to understand how each region might be able to cope with exposure to uncertain climate change as well as current and uncertain future climate variability.

5. Estimating of the economic cost of climate change with adaptation

Three themes have emerged from careful consideration of the content of Table 3 in the context of the vulnerability model just described; and each can be viewed as a challenge for the research community. First of all, adaptation can reduce the economic cost of exposure to climate change and climate variability, but adaptation cannot be expected to eliminate all of those costs. Secondly, the potential role of adaptation in reducing costs depends on the adaptive capacity of the exposed community, region, or sector and the certainty with which that community, region or sector can predict future climate and separate its signal from the noise of climate variability. Finally, a third theme follows from the second. The uncertainty that confounds climate researchers confounds

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[8] See Chapter 18 in IPCC (2001b) for a thorough discussion of these points.

Table 3. TAR (WGII-IPCC, 2001) Summary of adaptation and adaptive capacity*

Sector/region	Adaptation	Adaptive capacity
Africa (Ch. 10)	Regional assessments of vulnerability, impacts and adaptation are required to fill gaps in information. 7&8 Adaptation options include: increase irrigation efficiency through canal linings and better management, more reuse of drainage water, better use of the Nile valley aquifer, changes in crop types, development of western desert groundwater resources, and desalination. 1 Specific measures in water resources, coastal resources, forests, ecosystems, and agriculture would enhance the flexibility of resources to adapt and have net benefits greater than costs. 3 The use of improved technologies in agriculture, e.g. irrigation and crop husbandry, would result in better adaptation. 4, 6 & 7 The most promising adaptation strategies to declining tree resources include: natural regeneration of local species, energy-efficient cook-stoves, sustainable forest management, and community based natural resource management. 1, 3, 4, & 7 A risk sharing approach between countries will strengthen adaptation strategies. 4, 6, & 7	Adaptive capacity was largely influenced by the ability to communicate potential risks to vulnerable communities and the ability to react as a result of perceived risks. 5 & 8 A critical factor is the ability to mobilize emergency evacuation. 2 & 3
Asia (Ch. 11)	Priority issues, that could lead to catastrophic impacts for temperate and tropical Asian counties include: sea level rise, potentially more intense cyclones, and threats to ecosystems and biodiversity. A macro strategy involves rapid development to increase income levels, education, and technical skills, and improve public food distribution, disaster preparedness, and management and health care systems. 4 & 6 A micro strategy involves modifying the management of sensitive sectors by developing new institutions or modifying existing institutions that promote adaptation and modifying climate sensitive infrastructures. 3 & 7 Crucial for countries with large populations are food security, disaster preparedness and management, soil conservation, and human health sectors. 2, 3, 4, 6, & 7	Poor resource and infrastructure bases (disparities in income level, weak financial mechanism, technological gaps, cultural diversity) exist in most developing countries in Asia and hinder adaptive capacity. 2 & 6 Adaptive approaches include: strengthening legal and institutional frameworks, removing pre-existing market distortions, correcting market failures (such as inadequate economic valuation of biodiversity), and promoting public participation and education. 3 & 8 Adaptive capacity varies between countries depending upon social structure, culture and economic capacity, and level of environmental disruptions. 3 Limiting factors include: institutional inertia, a scarcity of technological adaptation options and additional economic burden. 1, 2, & 3

Continued

Table 3. (*continued*)

Sector/region	Adaptation	Adaptive capacity
	Adaptations proposed for human health, which involves improving the health care system, are already required to address the current human health situation in several Asian countries. 3 Implementation of adaptation measures is hindered by the economic policies and conditions, e.g. taxes, subsidies, and regulations, that shape decision making, development strategies, and resource-use patterns. 4 Adaptation depends upon the affordability of adaptive measures, the existence of appropriate institutions, access to technology, and biophysical constraints, such as land and water resource availability, soil characteristics, genetic diversity for crop breeding (e.g. development of heat-resistant cultivars) and topography. Adaptation measures for present day variability include: sea defences, institutional adaptations, plant breeding and the adoption of new technologies in agriculture. 1 Adaptation will require increased access to appropriate technologies, information, and adequate financing. 7 Anticipation and planning is required to prevent capital-intensive development of infrastructures or technologies that are ill-suited to future conditions, and missed opportunities to lower the cost of adaptation. 3 & 6	
Latin America (Ch. 14)	Several strategies for adaptation are shared between countries. 1 Adaptation measures in the fishery sector include: changing the species capture (e.g. switching from anchovy to tuna fish to reduce losses due to sea water warming), and price increases (to reduce losses to 40%). 1 Adaptation to flooding in water shortage areas includes the creation of artificial lakes through the damming of excess water. 2 & 3	

Small island states (Ch. 17)	Coastal assets will be further stressed with the projected increase in sea level. The three categories of strategies for adaptation to sea level rise are: retreat, accommodate, and protect. Progress will require the integration of appropriate risk reduction strategies with other sectoral policy initiatives in areas such as sustainable development planning, disaster prevention and management, integral coastal management, and health care planning. 7 Adaptation measures such as retreat to higher ground, raising of the land, and the use of building set backs appear to have little practical utility, especially when hindered by limited physical size. 1 Measures for reducing the severity of health threats include: the implementation of effective health education programs, preventative maintenance and improvement of health care facilities, cost-effective sewerage and solid waste management practices, and disaster preparedness plans. 3 & 6 Support from policy-makers and the general public is essential for implementing adaptive measures. 7 Raising public awareness and understanding about climate change and sea level rise, and the need for appropriate adaptation is necessary. 8	Given their size and limited individual capacities, external technical, financial, and other assistance is necessary. 2, 5, & 7 Regional cooperation has been proposed as an effective means of designing and implementing adaptation measures and building adaptive capacities (e.g. Caribbean Planning for Adaptation to Global Climate Change). 3 Legitimate concerns have been raised due to the limited resources and low adaptive capacity in SIS. 2 The main concern about capacity is the challenge of meeting the social and economic needs of their populations in a manner that is sustainable. 4, 5, & 6 Low adaptive capacity is the result of a combination of physical size, limited access to capital and technology, and a shortage of human resource skills. 1, 2, & 5 Other factors affecting capacity include: lack of tenure security, limited access to traditional resources for construction, overcrowding, preparedness, and level of traditional knowledge. 4 & 5

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*The numbers recorded with each entry in the table identify the most relevant determinants of adaptive capacity. The determinants are described in the text; in short, though, the associations are as follows: (1) technological options; (2) resource availability and distribution; (3) institutional structure; (4) human capital; (5) social capital; (6) access to risk spreading mechanisms; (7) ability to manage information; (8) public perception.

Source: drawn from Table 18-7, IPCC (2001b).

policy makers, as well. Methods must be devised that accommodate a wide range of uncertainty and ambiguity even as researchers struggle to understand the relative efficacy of adaptation across the globe from the perspective of those policy makers. This section will review three case studies chosen from the authors' experience to illustrate these themes and to offer at least one method with which their inherent challenges might be overcome.

5.1. The economic cost of sea level rise along the developed coastline of the United States

A series of studies that estimated the economic cost of sea level rise on developed property in the United States can provide evidence of the importance of adaptation and the implications of recognizing extreme events in that context. The series began when Yohe (1989) produced estimates of the cost for the United States under the assumption that none of its coastline would be protected. This earliest work reported only the current value of all of the property that would, without any intervention, be inundated by rising seas through the year 2100. Yohe et al. (1996) subsequently reported estimates for the same representative sample of coastal locations that were derived from a model that allowed property values to appreciate over time and included decisions to protect or to abandon property at a very micro-level. Even with no foresight and therefore no autonomous adaptation, planned adaptation based on cost-benefit analyses of protection options reduced economic costs by 90% along sea level rise scenarios that spanned the IPCC-SAR range of possibilities through the year 2100 (10 cm to 90 cm).[9] Adding perfect foresight allowed market-based autonomous adaptation to reduce estimated costs by another seven percentage points across the same wide range of sea level futures.[10] In both cases, though, some residual damage remained because not all property was protected and because protection was not free. The difference between the first two estimates reflects the significant role that planned adaptation can play in affecting the costs associated with climate change. The difference between the second two estimates reflects the significant role that autonomous adaptation can play in augmenting those plans.

Subsequent work by West and Dowlatabadi (1999) inserted a stochastic time series of coastal storms into the same methodology and applied the resulting model to a representative community; their results offer preliminary insight into how climate variability and extreme events might influence estimates of the economic cost of climate change. In their model, storms could destroy or damage property directly by rain and wind or indirectly from erosion; but damaged structures could be rebuilt if the expected value of reconstruction exceeded the cost. This decision rule allowed the same structure to exist multiple times in multiple storms (and it could be a structure that would ultimately be abandoned in the face of rising seas). It also allowed a property destroyed by a storm not to be rebuilt so that damage could be correctly attributed to storms and

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[9] Planned adaptation worked to protect property when the cost of that protection was less than the cost of abandonment, but residual losses in property that was nonetheless abandoned (between 10% and 33% of the developed coastline depending upon the sea level trajectory) were observed.

[10] Autonomous adaptation worked to depreciate the value of threatened structures to zero if they were to be abandoned. These structures may or may not have been protected without this depreciation and with property value appreciation and so autonomous adaptation produced a measurable efficiency gain.

not to rising seas. Running multiple manifestations of the same stochastic storm profile over 50 years with and without sea level rise showed that the cost that could be attributed to rising seas could increase costs by as much as 50% (relative to the perfect foresight base). But the cost could also fall by as much as 10% if large storms claimed significant property before the rising seas took their toll.

5.2. Applying the concept of adaptive capacity

Informed by a Workshop on Adaptation in Coastal Zones held in Charleston, South Carolina in Februrary of 1999, Dowlatabadi and Yohe (2000) argue that adaptation to sea level rise and coastal storms along the North American coastline can be expected to be so effective in reducing the economic cost of sea level rise because adaptive capacity is so high. Indeed, a coastal community located on the Atlantic shore would score high marks for each determinant. Protection options are plentiful. Resources are available. Local planning and emergency management agencies are well supported by a federal infrastructure and can process information well. Property rights are well defined. Property owners have direct access to private and public insurance; and the public at large recognizes the risk of living near the ocean. The relative efficacy of protective measures may be questionable, particularly along the open coastline, but long-term retreat from the sea is also a viable option in most states. It remains to be seen, however, if organizing research around the determinants of adaptive capacity would be an effective diagnostic tool in cases where the evidence is not as clear as it is in the United States.

Tol et al. (2001) report on an extensive assessment of adaptation against the increased risk of climate-induced flooding in the Rhine Delta; and their work can support an instructive application of the vulnerability model to examine this issue. Six feasible options for the Netherlands were identified by major consultancies: (1) store excess water in Germany; (2) accept more frequent floods; (3) build higher dikes; (4) deepen and widen the river bed; (5) dig a fourth river mouth; and (6) dig a bypass and create a northerly diversion.

Just as in the United States, macro-scale forces tend to dominate in this Dutch setting. Resources would be available for any option. The Netherlands is the eleventh largest economy in the world (by PPP), and the distribution of resources across the population is irrelevant because flood protection is administered by the national government. The structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria could be more problematic, however. Water management and land use planning are administered by separate agencies; as a result, pressure to expand into the flood plain can limit the options for water management because of conflicts among many stakeholders. Indeed, public works are increasingly decided through direct participation of the population; long postponements result, and radical solutions are disadvantaged. The stock of human capital, including education and personal security, is very high in the Netherlands, though; and Dutch water engineers are among the best in the world. The stock of social capital is also high. The Netherlands is a consensus-oriented society in which the collective need is an effective counterweight to individual interests. Property rights are clearly defined, and the judiciary is independent. The system's access to formal risk spreading processes is limited because flood insurance cannot be purchased. Decision-makers are quite capable of managing information and determining which is credible; as a result, their decisions are generally taken to be credible. Dutch bureaucrats are typically well educated and supported by able consultancies; but an ‘old-boy’ network of professors, civil servants, and consultants controls water management practices. The public, as well as the water managers, are well aware of climate change and its implications for flood risk.

Table 4 offers expert judgment into how these macro-scale observations might be translated into the micro-scale determinants of each of the options. The strength of each determinant was scored on a subjective scale from 0 on the low side to 5 on the high side. The low score for storing water is a reflection of the international cooperation that would be required to implement and to manage such a scheme. Accepting floods, creating a fourth mouth for the river, and constructing a bypass also scored low marks, but their deficiencies were far less ubiquitous; instead, specific determinants like distributional ramifications and/or risk spreading were sources of weakness. Higher dikes and manipulating the river bed were awarded higher scores, but neither is perfect. Indeed, manipulating the river bed would appear to be most feasible, but it is hampered by a relatively low efficacy factor; i.e., such a plan could not eliminate the risk of flooding. On the other hand, higher dikes face participation difficulties on the feasibility side, but could offer extremely effective flood protection. The results of organizing an examination of adaptive capacity around its underlying determinants are thus surprisingly pessimistic. Each alternative, for one reason or another, has a weakness that can be discovered by a process that looks at each determinant in turn.

5.3. Coping with enormous uncertainty

The third and final application looks at adaptation under enormous uncertainty in a different context—a less well developed economy contemplating macro-scale adaptations to climate change. Strzepek et al. (2001) described a process by which ‘not implausible’ climate scenarios were selected for Egypt as the first step of a project designed ultimately to conduct detailed integrated assessments of their impacts across a range of similarly ‘not implausible’ socio-economic scenarios.[11] Recall that Fig. 10 displays nine representative climate scenarios in terms of flow into Lake Nasser. Each was driven by specific assumptions about GHG and sulfate emissions, climate and sulfate aerosol sensitivities, and the results of some specific global circulation model; but each was selected for its value in representing a wide range of futures that cannot, as yet, be discarded as completely impossible. Taken together, they span a range of outputs produced by running COSMIC for rainfall and temperature for nine upstream countries through a hydrological model authored by David Yates and Kenneth Strzepek; and they provide an arena in which the robustness of alternative adaptations and the value of climate information can be evaluated.[12]

A careful review of Fig. 9 sets the stage for thinking about the ramifications of alternative socioeconomic scenarios, especially with a view towards framing experiments designed to investigate the role of three possible macro-scale adaptations: municipal recycling, drip irrigation, and groundwater pumping. Scenario 1 could produce favorable outcomes from climate change as long as potential floodwaters could

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[11] The method employed to select the representative scenarios is fully developed in Yohe et al. (1999).

[12] See Yates and Strzepek (1998) for a description of the hydrologic model and Strzepek et al. (2001) for its accommodation of COSMIC inputs; see Schlesinger and Williams (1998) for a description of COSMIC.

Table 4. Evaluating the determinants of adaptive capacity for flood control options along lower Rhine delta[a]

Determinant	Store water	Accept floods	Higher dikes	River bed	4th Mouth	Bypass
2. Resources	1	3	4	4	1	1
3. Institutions	1	1	3	4	1	2
4. Human capital	1	2	5	4	4	3
5. Social capital	1	3	4	5	2	2
6. Risk spreading	2	1	5	4	4	3
7. Information	1	2	4	4	2	2
8 Awareness	3	3	5	5	3	3
Feasibility factor[b]	1	1	3	4	1	1
Efficacy factor[c]	0.8	1.0	1.0	0.6	0.8	0.6

Notes:
[a] The numbers recorded in the table indicate subjective ratings of the strength of each determinant of adaptive capacity for each adaptation option on a scale from 1 (very weak) to 5 (very strong). The numbers preceding each determinant refer back to the list in the text.
[b] The feasibility factor is an overall ranking index; it is the minimum of the subjective ratings across all determinants.
[c] The efficacy factor is a subjective judgment of likelihood that the indicated option will effectively eliminate the threat of flooding.
Source: Yohe and Tol (2002).

be diverted into vacant and domestic regions of the Sahara Desert. Flow into Lake Nasser would be stable along this scenario through 2030 and then climb over the next 70 years. Scenarios 2 and 3 would be relatively benign. Flow would fall by roughly 8% by 2030, but that level would be maintained across the rest of the 22nd century. Scenarios 4 and 8 would also portend modest climate change with a gradual decline by 2100 of approximately 12%. Scenario 6 offers the first portrait of serious shortfall in Nile flow. Flow would fall by 25% by 2025, thereby tracking even the worst climate outcomes over the near-term; but it would decline only gradually thereafter for a total reduction of 40% by 2100. Scenario 5 tracks scenario 6 through 2025, but subsequent reductions would be more severe. Indeed, flow into Lake Nasser would be 55% and 65% lower then the present value by 2067 and 2100, respectively. Finally, scenarios 7 and 9 would produce the worst outcomes in terms of climate change. Near-term reductions of 30% by 2025 are not much worse than 5 and 6; but flow falls by 75% by 2067 and by 80% around the turn of the next century.

Motivated by an understanding of the critical role played by the determinants of adaptive capacity, Strzepek et al. (2001) highlighted the potential significance of high-capital and low-capital futures in evaluating the potential for effective adaptation. Variation across socio-economic futures captured this distinction in a Ramsey-style growth model with three different population trajectories and high or low settings for three critical parameters: nonagricultural productivity growth, growth in agricultural yields, and investment efficiency. Since domestic food security is a critical policy objective of the Egyptian government, favorable and unfavorable terms of trade were also considered. Fig. 10 displays the results of running the growth model without

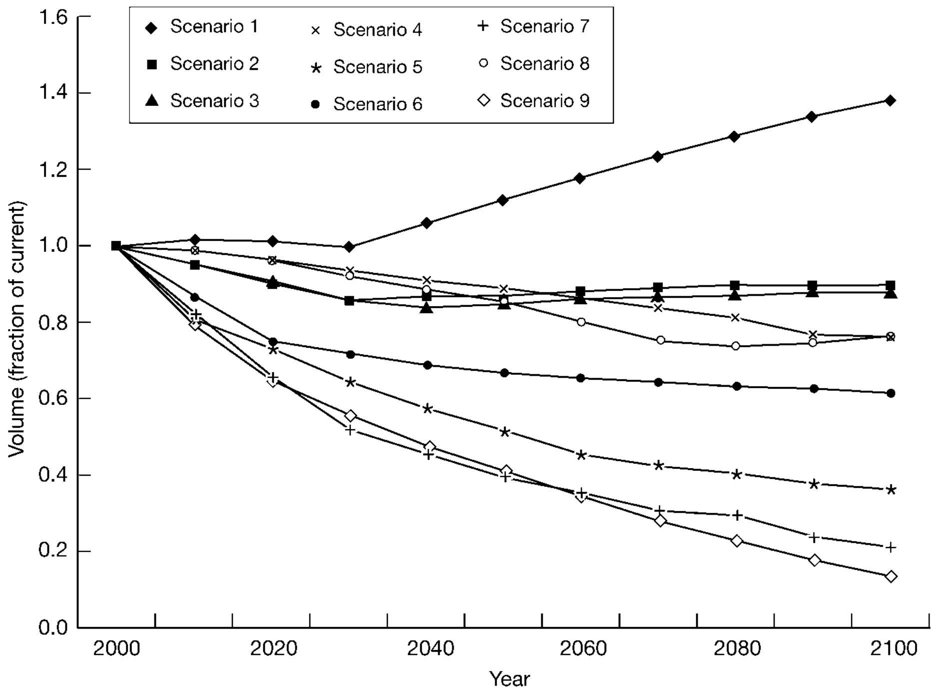

Figure 10. Economic output for Egypt along 'Not Implausible' Climate and Socio-Economic Futures.
The vertical axis reflects an index of the sum of consumption goods and food available to the Egyptian population in the year 2067 as a fraction of 2000 totals for over 900 climate/socio-economic scenarios. The horizontal axis indicates the proportion of total food consumption actually grown domestically.
Source: Fig. 3 in Yohe et al. (2002).

adaptation for 600 combinations of climate and socio-economic futures in terms of an index of Egyptian food self-sufficiency and total food plus consumable good consumption in the year 2067.[13]

Allowing adaptation to climate along 36 of the 600+ scenarios, themselves selected to represent of the diversity displayed in Fig. 10, showed that adaptation could make a significant difference in Egypt, especially for pessimistic climate scenarios. Panel A of Fig. 11, for example, links outcomes in 2067 with and without adaptation for four socio-economic scenarios for the middle population trajectory along climate scenario 3. Notice that the value of adaptation is seen most clearly in terms of increased food self-sufficiency, sometimes at the expense of some economic activity. Panel B meanwhile links outcomes for the same scenarios for the same population trajectory along the most pessimistic climate future—scenario 9. Here, adaptation was devoted to increasing economic activity. Moreover, food security suffers in three cases, and quite substantially

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[13] The year 2067 was chosen for display because it reflects a point in the relatively distant future by which time the nine climate scenarios had, for the most part, diverged. The implications of climate and socioeconomic circumstances were therefore fully represented. The self sufficiency coefficient reflects the proportion of total food consumption supported by domestic food production.

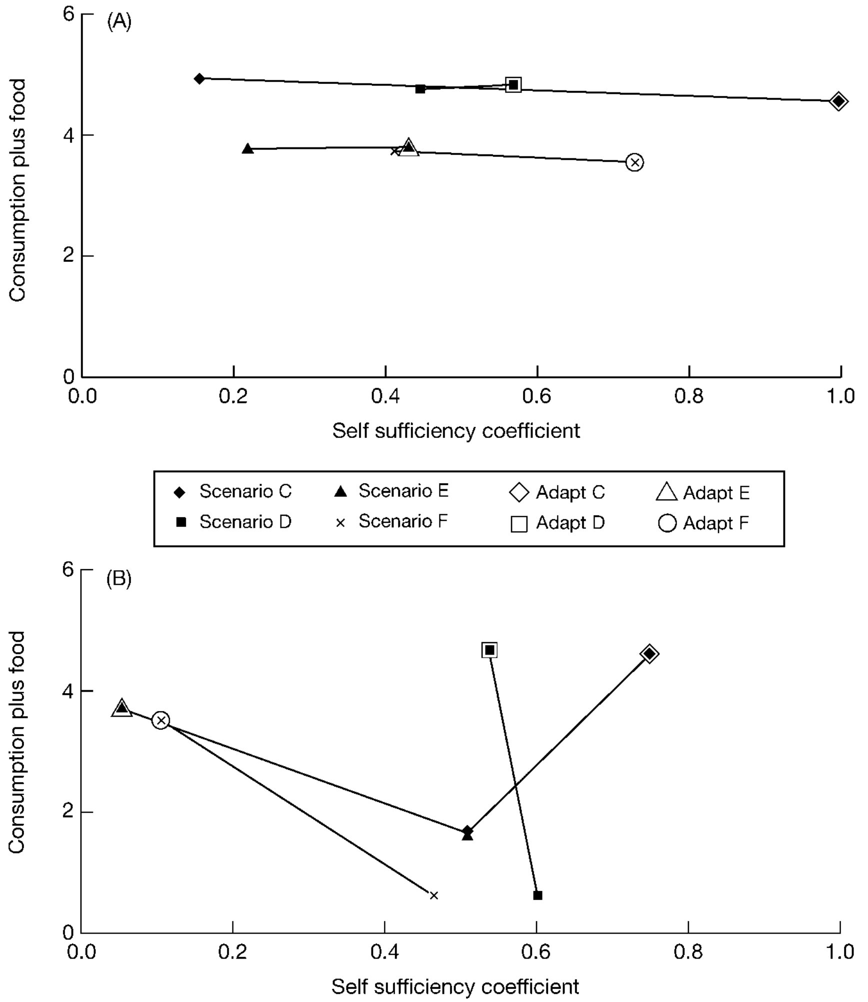

Figure 11. Panel A displays outcomes in 2067 along four representative socio-economic scenarios and climate scenario 3 depicted in Fig. 9 with median expected population growth. Smaller points indicate outcomes without adaptation; larger points connected by dotted lines indicate outcomes with efficient adaptation (drip irrigation and municipal recycling). Panel B displays comparable results along climate scenario 9; adaptation now includes groundwater pumping beginning around 2025 and significant reallocation of domestic investment in anticipation of the enormous investment required to deliver this water to major population centers.

in two where economic robustness is hampered by inefficient investment (scenarios E and F). In fact, only along scenario C, marked by high efficiency in investment and the agricultural sector, could both policy objectives improve with adaptation. The results therefore show that socio-economic context of the sort suggested by the determinants of adaptive capacity mattered. Indeed, scenarios hampered by inefficient investment displayed diminished capacities to adapt along either the food security or the economic activity scale, or both. It is, finally, significant that food security was the major beneficiary of adaptation to all climates but the most severe.

How much would it be worth to the Egyptian economy to know that it should expect climate scenario 3 rather than 9, or the other way around? The value information like that is critically dependent upon the specific properties of the adaptative response under consideration. Improved ex ante information can hold negligible value for adaptations that are tied directly to direct observations of current circumstances as the future unfolds *as long as the appropriate signal of change can be effectively distinguished from the surrounding noise*. Improved information can, by way of contrast, be enormously valuable for adaptations that involve significant investment in infrastructure and/or significant reallocations of resources in anticipation of that investment. Drip irrigation and municipal recycling fell relatively well into the first category; either would involve modest investment in small projects that could efficiently come on line as climate change produced incremental need. Drilling for groundwater below the Sahara and pumping it to where it would be needed would, however, lie squarely in the second.

Reflecting current expectations of the Egyptian Ministry of Water and Irrigation, the growth model undertook direct investment in pumping groundwater only when five-year average flows into Lake Nasser fell 25% below current levels, but that turned out to be only half of the story. The perfect foresight assumed in its Ramsey formulation allowed the economy to reallocate capital between the agricultural and non-agricultural sectors well in advance of that date. As a result, information that could support early differentiation between two strikingly different climate futures could be expressed as measurable fractions of current GDP—roughly 0.5% of current GDP in present value. In addition, planning for bad news and adapting to good was shown to be a better choice than the other way around. Indeed, increased climate variability made it even better to 'plan for the worst' because it made the climate signal more difficult to detect and therefore delayed possible 'midcourse' corrections in adaptation and investment plans.

6. Concluding remarks

We began with a warning that it would be imprudent to reflect the content of the Third Assessment Report in terms of costs and benefits distributed across globe along one or two specific climate change scenarios. It is a warning that is entirely consistent with one of the fundamental conclusions of that report:

> Current knowledge of adaptation and adaptive capacity is insufficient for reliable prediction of adaptations; it also is insufficient for rigorous evaluation of planned adaptation options, measures and policies of governments . . . Given the scope and variety of specific adaptation options across sectors, individuals, communities and locations, as well as the variety of participants—public and private—involved in most adaptation initiatives, it is probably infeasible to systematically evaluate lists of adaptation measures; improving and applying knowledge on the constraints and opportunities for enhancing adaptive capacity is necessary to reduce vulnerabilities associated with climate change. (p. 880)

This is not to say that all is lost. The take-home message is simply that future research has a long way to go if it is to come to grips with the diversity of the socio-political-economic environments that produce wide ranges of sensitivities and imply enormous variances in adaptive capacity. Geographic diversity and enormous uncertainty are the sources of challenge for building and exercising methods so that the next assessment of the state of knowledge will not be so pessimistic. It goes without saying that geographically centered economic research has a significant role to play here.

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References

Alcamo, J., Leemans, R., Kreileman, E. (eds.) (1998) *Global Change Scenarios of the 21st Century: Results from the IMAGE 2.1 Model*. London: Elsevier Science.

Alfsen, K. H., Berntsen, T. K. (1999) Modeling atmospheric carbon concentrations, Working Paper No. 1, CICERO, Oslo, Norway.

Dowlatabadi, H., Yohe, G. (2000) The who-how of adaptation: towards more realistic impact assessments. *Global Environmental Change* 10: 214–227.

Downing, T. E. (ed.) (1996) *Climate Change and World Food Security*. Berlin: Springer.

Downing, T. E., Ringius, L, Hulme, M., Waughray, D. (1997) Adapting to climate change in Africa. *Mitigation and Adaptation Strategies for Global Change* 2: 19–44.

Gritsevskii, A., Gruebler, A. (1998) *The Scenario Generator: A Tool for Scenario Formulation and Model Linkages*. Laxenburg. Austria: International Institute for Applied Systems Analysis.

Hewitt, J., Burton, I. (1971) *The Hazardousness of a Place: A Regional Ecology of Damaging Events*. Toronto: University of Toronto.

Intergovernmental Panel on Climate Change (IPCC) (1990) *1990: Climate Change: The IPCC Scientific Assessment*. Cambridge: Cambridge University Press.

IPCC (1992) *1992: Climate Change: The Supplementary Report to the IPCC Scientific Assessment*. Cambridge: Cambridge University Press.

IPCC (1996a) *1995—The Science of Climate Change, Contribution of Working Group I to the Second Scientific Assessment of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

IPCC (1996b) *1995—Impacts, Adaptation and Mitigation of Climate Change: Scientific-Technical Analyses, Contribution of Working Group II to the Second Scientific Assessment of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

IPCC (1996c) *Climate Change 1995—Economic and Social Dimensions of Climate Change, Contribution of Working Group III to the Second Scientific Assessment of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

IPCC (2000) *2000: Special Report on Emissions Scenarios*. Cambridge: Cambridge University Press.

IPCC (2001a) *2000—The Science of Climate Change—The Contribution of Working Group I to the Third Scientific Assessment of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

IPCC (2001b) *2000—Impacts, Adaptation, and Vulnerability—The Contribution of Working Group II to the Third Scientific Assessment of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

IPCC (2001c) *2000—Mitigation—The Contribution of Working Group III to the Third Scientific Assessment of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Joos, F., Bruno, M., Fink, R., Siegenthaler, U., Stocker, T. F., Quere, C. L., Sarmiento, J. L. (1996) An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. *Tellus* 48: 397–417.

Kane, S. J., Reilly, J., Tobey, J. (1992) An empirical study of the economic effects of climate change on world agriculture. *Climatic Change* 21: 17–35.

Karl, T. R., Knight, R. W. (1998) Secular trends of precipitation amount, frequency and intensity in the United States. *Bulletin of the American Meteorological Society* 79: 231–241.

Mearns, L. O., Rosenzweig, C., Goldberg, R. (1997) Mean and variance change in climate scenarios: methods, agricultural applications and measures of uncertainty. *Climatic Change* 34: 367–396.

Mendelsohn, R., Morrison, W., Schlesinger, M. E., Andronova, N. G. (2000) Country-specific market impacts of climate change. *Climatic Change* 45: 553–569.

Morita, T., Matsuoka, Y., Jiang, K., Masui, T., Takahashi, K., Kainuma, M., Pandey, R. (1998) *Quantification of IPCC-SRES Storylines Using the AIM/Emission-Linkage Model*. Japan: National Institute for Environmental Studies.

Myhre, G., Highwood, E. J., Shine, K. P., Stordal, F. (1998) New estimates of radiative forcing due to well mixed greenhouse gases. *Geophysics Research Letter* 25: 2715–2718.

Nordhaus, W. D., Boyer, J. (2000) *Warming the World: Economics Models of Climate Change*. Cambridge MA: MIT Press.

Pepper, W., Barbour, W., Sankovski, A., Graatz, B. (1998) No-policy greenhouse gas scenarios: revisiting IPCC 1992. *Environmental Science and Policy* 1: 289–312.

Pittock, B., Jones, R. N. (2000) Adaptation to what and why? *Environmental Monitoring and Assessment* 61: 9–35.

Schlesinger, M. E., Williams, L. (1998) COSMIC—country specific model for intertemporal climate. Palo Alto, CA: Computer Software, Electric Power Research Institute.

Schlesinger, M. E., Malyshev, S., Rozanov, E., Yang, F., Andronova, N. G., deVries, B., Grubler, A., Jiang, K., Masui, T., Morita, T., Penner, J., Pepper, W., Sankovski, A., Shang, Y. (2000) Geographical distributions of temperature change for scenarios of greenhouse gas and sulfur dioxide emissions. *Technological Forecasting and Social Change* 65: 167–193.

Schneider, S. (1989) The changing climate. In *Managing the Planet—Readings from Scientific American*. New York: W.H. Freeman and Company, 25–39.

Smit, B., Burton, I., Klein, R., Street, R. (1999) The science of adaptation: a framework for assessment. *Mitigation and Adaptation Strategies for Global Change* 4: 119–213.

Smithers, J., Smit, B. (1997) Human adaptation to climatic variability and change. *Global Environmental Change* 7: 129–146.

Strzepek, K., Yates, D., Yohe, G., Tol, R. S. J., Mader, N. (2001) Constructing 'not implausible' climate and economic scenarios for Egypt. *Integrated Assessment* forthcoming.

Tol, R. S. J. (1999) New estimates of the damage costs of climate change, parts I and II. Working Papers D99-01 and D99-02, Institute for Environmental Studies, Vrije Universiteit, Amsterdam.

Tol, R. S. J., van der Grijp, N. M., Olsthoorn, A. A., van der Werff, P. E. (2001) Adapting to climate change: a case study on riverine flood risks in the Netherlands. In R. S. J. Tol and A. A. Olsthoorn (eds) *Floods, Flood Management and Climate Change in the Netherlands*. Amsterdam: Institute for Environmental Studies, Vrije Universiteit.

West, J., Dowlatabadi, H. (1999) On assessing the economic impacts of sea-level rise on developed coasts. In T. Downing, A. Osthoorn, and R. S. J. Tol (eds) *Climate Change and Risk*. London: Routledge, 205–220.

Yates, D., Strzepek, K. (1998) Modeling the Nile basin under climate change. *Journal of Hydrologic Engineering* 3: 98–108.

Yohe, G. (1989) The cost of not holding back the sea—economic vulnerability. *Ocean and Shoreline Management* 15: 233–255.

Yohe, G., Schlesinger, M. (1998) Sea level change: the expected economic cost of protection or abandonment in the Unites States. *Climatic Change* 38: 447–472.

Yohe, G., Tol, R. (2002) Indicators for social and economic coping capacity—moving toward a working definition of adaptive capacity. *Global Environmental Change* forthcoming.

Yohe, G., Neumann, J. E., Marshall, P., Amaden, H. (1996) The economic cost of greenhouse induced sea level rise for developed property in the United States. *Climatic Change* 32: 387–410.

Yohe, G., Jacobsen, M., Gapotchenko, T. (1999) Spanning 'not-implausible' futures to assess relative vulnerability to climate change and climate variability. *Global Environmental Change* 9: 233–249.

Yohe, G., Strzepek, K, Pau, T., Yohe, C. (2002) Bringing economic analysis to bear on adaptation: the Egyptian case study. In *Proceedings of the PIK Workshop on Enhancing the Capacity of Developing Countries to Adapt to Climate Change*. Potsdam: Potsdam Institute for Climate Impact Research.