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Projected Costs of Climate Change for Two Reference Scenarios and Fossil Fuel Cycles

Report to the European Commission

ExternE Project

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LIST OF ABBREVIATIONS

AEEI	Autonomous energy efficiency improvement
CMU	Carnegie Mellon University
CRED	Centre for Research on the Epidemiology of Disease
CVM	Contingent valuation methods
EV	Existence value
GCM	General Circulation Model
GDP	Gross Domestic Product
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse gas
GIS	Geographic information system
GISS	Goddard Institute for Space Studies
GNP	Gross National Product
GWP	Gross World Product (also often, but not in this report, global warming potential)
IEA	International Energy Agency
IFRCRCS	International Federation of Red Cross and Red Crescent Societies
IGCC	Integrated Gasification Combined Cycle (coal fuel cycle with abatement)
IPCC	Intergovernmental Panel on Climate Change
IS92	IPCC scenarios of GHG emissions developed in 1992
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
NGCC	Natural Gas Combined Cycle (fuel cycle with abatement)
NGCCx	Natural Gas Combined Cycle, without GHG abatement
NPV	Net present value
OECD	Organization for Economic Cooperation and Development
OF	Open Framework
OV	Option value
PF+FGD	Pulverised Fuel and Flue Gas Disulpherisation (coal fuel cycle without abatement)
TEV	Total Economic Value
TPV	Total Primary Value
UKMO	U.K. Meteorological Organisation
UN	United Nations
UV	Use value
VSL	Value of statistical life
WTP	Willingness to pay

PROJECTED COSTS OF CLIMATE CHANGE
FOR TWO REFERENCE SCENARIOS AND FOSSIL FUEL CYCLES

1. Overview: Temporal and Spatial Projections of Climate Impacts and Costs

The most visible assessment of the economic cost of climate change is the 1996 assessment by the Intergovernmental Panel on Climate Change (IPCC) (Pearce *et al.* 1996), supplemented by reviews such as Fankhauser and Tol (1996), Tol (1995) and Munasinghe (1995), and individual assessments, such as Fankhauser (1992, 1995), Nordhaus (1994b), and Intera (Little *et al.* 1993; Maul and Clement, 1994), among others. The IPCC expect damages[1] from climate change (for the $2xCO_2$ equilibrium) to be 1.5-2.0% of world GNP, with impacts in developed countries of 1.0-1.5% of national GNP compared to 2-9% in developing countries (Pearce *et al.* 1996). Such global figures belie the large range of uncertainty inherent in valuing climate change. Much of the total cost of climate change is attributed to changes in welfare, calculated by methods of contingent valuation that are subjective and sensitive to assumptions about future values. All of the available global estimates are partial, that is some potential impacts are not fully costed.

Fankhauser and Tol (1996: 668), in particular summarise recent trends:

- Increasing regional and sectoral differences—winners and losers are dispersed between countries, between sectors and between stakeholders within a sectors and countries. For example, wheat cultivation in northern Europe is likely to benefit from warming, smallholder maize production in semi-arid Africa is less likely to keep pace with demand.
- Lower market impacts in developed countries—adaptation is emerging as a cost-effective strategy to cope with expected impacts. However, estimates of the cost of climate change for individual sectors vary widely, based on assumptions of interlinkages between sectors, exposure to extreme events, and how costs are valued.
- Increasing importance of non-market impacts—accuracy of estimates is still low, but more non-market impacts have been quantified, especially for health effects and loss of life in extreme events.

The emphasis on adaptation in particular necessitates a time-dependent, dynamic analysis of climate change damages, rather than the first round of equilibrium assessments based on comparative statics. Integrated assessments that link sectoral impacts with non-climatic stresses are also cited as essential. Assumptions of multiple stresses in ecosystems, health and economies without climate change—the reference world of the future—provide the essential framework for gauging damages from climate climate and climatic hazards, and the scope for incremental adaptation.

This paper presents a pioneering effort to link realistic scenarios of climate change, first-order impact assessments and prevalent techniques in economic valuation. The methodology includes (i) explicit reference projections of the future with and without climate change; (ii) linkages between temporal and spatial climate change scenarios and impacts; and (iii) apportioning of the global cost

[1] Following convention in economics, we generally use the term damages and costs to denote net damages and costs. In such cases, benefits would be negative damages or negative costs. The issue of aggregating costs and benefits from disparate sectors and regions is discussed in section 14.

of climate change to individual fossil fuel cycles. This analytical framework enables comparisons to be made between two pathways of future climate change impacts, among carbon-based coal and gas fuel cycles, and between fuel cycle contributions to climate change and the average cost of climate change.

Marginal changes to explicit reference projections

Most assessments of climate change damages have assumed an instantaneous, equilibrium change. That is, climate change is assumed to happen to the present economy, or a future economy that is the same as the present one. The economy is not allowed to gradually change its resource use in conjunction with the threat of climate change. In contrast, this study has calculated the cost of climate change against a future world that is substantially different from the present world, including the pathway between the present and 2100. Figure 1 shows this approach, using the IS92a projection of Gross World Product (GWP) as an indicator of the reference scenario (IS92a). The effect of climate change is the cumulative departure between 1990 and 2100 between the reference projection (IS92A) and the reference projection as modified by climate change (IS92A*). The diagram shows the cost of climate change, using the high estimate for the IS92a scenario (CC: IS92a-High), which is below the IS92a, indicating that the aggregate impact of climate change is negative[2]. For some sectors, such as heating demand, the impact of climate change is positive and the climate change "impacts" would be above the reference GWP.

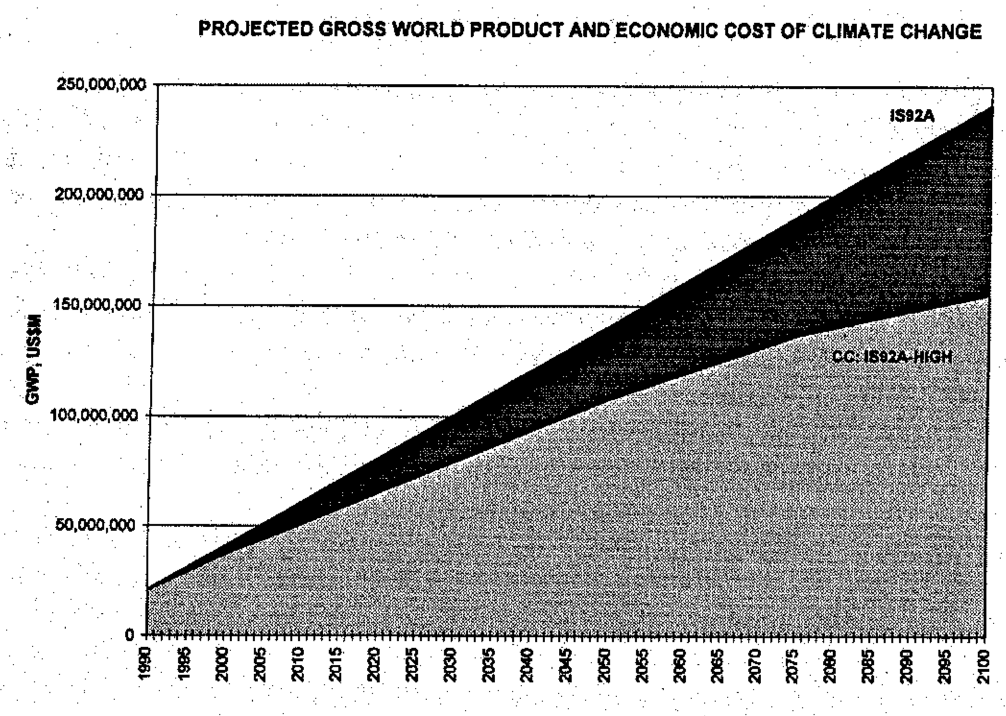


Figure 1. Cumulative Gross World Product with and without climate change damages. IS92A is GWP projected without climate change. CC: IS92A-HIGH shows the marginal effect of (adverse) climate change, based on the IS92a high estimate of impacts.

[2] Note that the damages shown in this chart include values, such as the existence value of species and the value of statistical life, that are not included in GWP. This accentuates the difference between the reference and the impacts. Thus, converting total impacts to a percentage of GWP is not technically correct.

Since the economic valuation of climate change depends on the difference between a reference scenario and the reference with climate change, alternative reference scenarios of the future need to be evaluated. Two such scenarios are considered in this report, based on the IPCC's suite of scenarios developed in 1992 (labelled the IS92 scenarios):

- IS92a: Non-intervention projection or "business-as-usual" – medium population and economic growth leads to higher personal incomes. Standards of living improve, but large populations are still poor and resource use is still sensitive to climatic fluctuations, although less so than at present.
- IS92d: Sustainable or "resilient development" – low population growth, high personal incomes, and high energy efficiency reduce sensitivity to climatic fluctuations, even more so than in the IS92a world. More equitable standards of living enable countries to be resilience to resource limitations.

The contrast between the IS92a "non-intervention" and the IS92d "resilient development" scenarios highlights diverse views of the future. In both futures, conditions improve as gauged by economic growth and environmental concerns reflected in GHG abatement. Thus, the potential for regional collapse, as might be possible with water scarcity and famine in some semi-arid areas, is less likely than at present. To capture the extreme cases of resource scarcity and conflict, a different reference scenario would be required.

The reference projections are developed from the global projections of the IPCC (Pepper *et al.*, 1992), supplemented with data from the World Bank and World Resources Institute (1990, 1991).

Temporal and spatial linkages in impact assessment

The first generation of economic evaluations are marked by a high level of aggregation (often six to ten world regions) and weak connections between climate scenarios, impact assessments and economic valuation. In addition, insufficient attention was given to the range of uncertainty. The framework used here couples scenarios of global emissions, projections of global changes in temperature and sea level rise, spatial scenarios of climate change and first-order impacts, and country-level estimates of the economic impacts of climate change.

The 1995 version of MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) is used to calculate global-average temperature change and sea level rise for the two reference emission scenarios (IS92a and IS92d) (Osborn and Wigley, 1994; Raper, Wigley and Warrick, 1995; Wigley and Raper, 1992, 1993, 1995; Wigley, 1993, 1994). Spatial scenarios of climate change are created using results from the Goddard Institute for Space Studies (GISS) General Circulation Model (GCM) experiment (Hansen *et al.* 1988). The GISS equilibrium changes in mean monthly temperature and precipitation are scaled to the global projections from MAGICC for 2100 according to methods developed by the Climatic Research Unit (Viner and Hulme 1993; Carter *et al.* 1994). The baseline climatology is the 0.5 degree latitude by longitude data base compiled by Cramer and Leemans (1994).

First-order impact models are run for the current climate and for the scenarios of climate change. The relatively simple impact models rely on the agroclimatic indices, the balance of temperature and potential evaporation, and accumulated temperature departures (heating and cooling degree days). They provide spatial realism and are likely to indicate the direction and magnitude of impacts. National impacts of sea level rise rely on the vulnerability assessment compiled by the IPCC (1990) and Delft (1993).

The first-order impacts are summarised by country and linked to the economic valuation of the cost of climate change. For example change in average heating degree days between the present and 2100 (with climate change) for each country is related to estimates of the demand for and cost of space heating.

The country-level costs are summed to a global total. Sectors not included in the spatial model (biodiversity, natural hazards and health, welfare and other damages) are included as global estimates in order to present a relatively complete assessment of the cost of climate change. Net present values (NPVs) are calculated for a range of discount rates.

The assessment of uncertainty is built into the analytical framework. At each stage of analysis, low, medium and high estimates are compiled, corresponding to the low, best guess, and high estimate of global climate change from MAGICC. They are subjective estimates of the range of likely economic values of impacts, for example depending on the value of statistical life or the price of electricity. The assumptions and numbers presented here are still fairly conservative. This is, we have discounted the likelihood of large ecosystem collapses and assumed relatively modest differences between the two reference scenarios.

Fossil fuel cycle contributions to climate change

A few studies have calculated the proportion of the total cost of climate change that can be ascribed to individual fuel cycles (EC, 1995; Hohmeyer and Gärtner, 1992; Holland *et al.* 1995; IEA GHG, 1994, 1996; Tol, 1993, 1995). In this study, the marginal effect of each fuel cycle is calculated by adding fuel cycle GHG emissions to the global GHG emissions and running the fuel cycle emissions through MAGICC. To achieve a discernible result, the individual fuel cycles are scaled up by 100. The differences between projected global-average temperature for the reference scenario and the reference scenario with added fuel cycle emissions are used to apportion the global cost of climate change to the individual fuel cycles. For coastal impacts the global projections of sea level rise are used.

Five fuel cycles are compared, each against two reference scenarios (Table 1 and Table 2). The emissions, estimated by the ExternE project[3], cover the fuel complete cycle: fuel extraction, construction and decommissioning of the plan, power generation, disposal of wastes, intermediate transport stages and transmission of electricity (European Commission 1995). None of the fuel cycles include GHG capture.

The coal fuel cycle (UK Coal) is based on a station located in the British Midlands. It is a large plant, 1710MW in capacity, with correspondingly high emissions, particularly of CO_2 and sulphur. The smaller lignite power station (Lignite) is based on a hypothetical plant located near Cologne in Germany. Both coal plants use flue gas desulphurisation which reduces the emissions of sulphur.

The two oil-based fuel cycles both draw fuel from the North Sea. The hypothetical plants are situated north of Stuttgart. Both would be equipped with flue gas desulphurisation and low NOx burners. The combined cycle plant (Oil CC) has a electricity capacity of 527 MW, operating at full load for 6500 hours per year. The Oil CC plant is assumed to begin operation in 2005, in contrast to the other fuel cycles which begin in 1990. The gas turbine plant (Oil GT) operates during times of

[3] Greenhouse gas emissions were provided by the Energy Technology Support Unit, Harwell, UK.

peak load, rather than the base load carried by the other fuel cycles. It is assumed to operate 675 hours per year, with a capacity of 156 MW.

The natural gas fuel cycle (UK Gas) is based on North Sea gas fueling a combined cycle gas turbine plant in the Midlands, UK. It has the second largest capacity of the five fuel cycles, although relatively low emissions (negligible for SO_2).

Overview

It important to emphasise the overall structure of the analysis before presenting many of the details. The bulk of the paper and analysis focuses on sectoral impacts – on coastal resources, energy for space heating and cooling, agriculture, water resources, biodiversity and natural hazards. However, this analysis does not cover all of the potential impacts. To estimate the global cost of climate change, we use a set of multipliers to scale up from the above sectors to a global total. The chosen scalars are similar to published estimates of indirect costs. Nevertheless, the empirical basis for these scalars is weak. Realistic global totals, including all sectors, are required for the second major objective of the research: to assign a proportion of the cost of climate change to individual fuel cycles.

Table 1. Fuel Cycle Characteristics

Code IS92a	Code IS92d	Abb'n	Description	Start year	No. Years	Capacity MW	Avail. %	Annual Output kWh x10^9	Scalar
1	6	Lignite	Lignite coal, PF+FGD	1990	35	589	74	3.818	100
2	7	OilCC	Oil combined cycle	2005	35	527	74	3.416	100
3	8	OilGT	Oil gas turbine	1990	35	156	8	0.109	100
4	9	UKCoal	UK coal, PF+FGD	1990	40	1710	76	11.384	100
5	0	UKGas	UK gas combined cycle	1990	30	652	89	5.083	100

Note: Start year is for the beginning of construction.

Table 2. Fuel Cycle Emissions, t/yr

Code IS92a	Code IS92d	Abb'n	Description	Emissions						
				CO2	CH4	N2O	CO	VOC	NOx	SOx
1	6	Lignite	Lignite coal, PF+FGD	4,383,633	299	38	0	0	2,695	2,557
2	7	OilCC	Oil combined cycle	2,124,006	127	51	0	0	2,992	2,913
3	8	OilGT	Oil gas turbine	92,078	7	2	0	0	99	146
4	9	UKCoal	UK coal, PF+FGD	10,025,218	33,038	684	1,253	182	25,063	12,532
5	0	UKGas	UK gas combined cycle	2,062,699	1,440	75	396	679	3,652	0

Note: Emissions are annual emissions (t) for an individual fuel cycle.

2. Impact Sectors and Reference Assumptions

Impact sectors

The relationships between climate change (changes in temperature, precipitation and sea level) and the direct and indirect sectors are shown in Figure 2. In this study we distinguish between sectors that are quantified by direct means of valuation, based on the cost of using specific resources, and sectors that can only be valued indirectly, for example by assigning a (subjective) value to the existence of species or to a person's life.

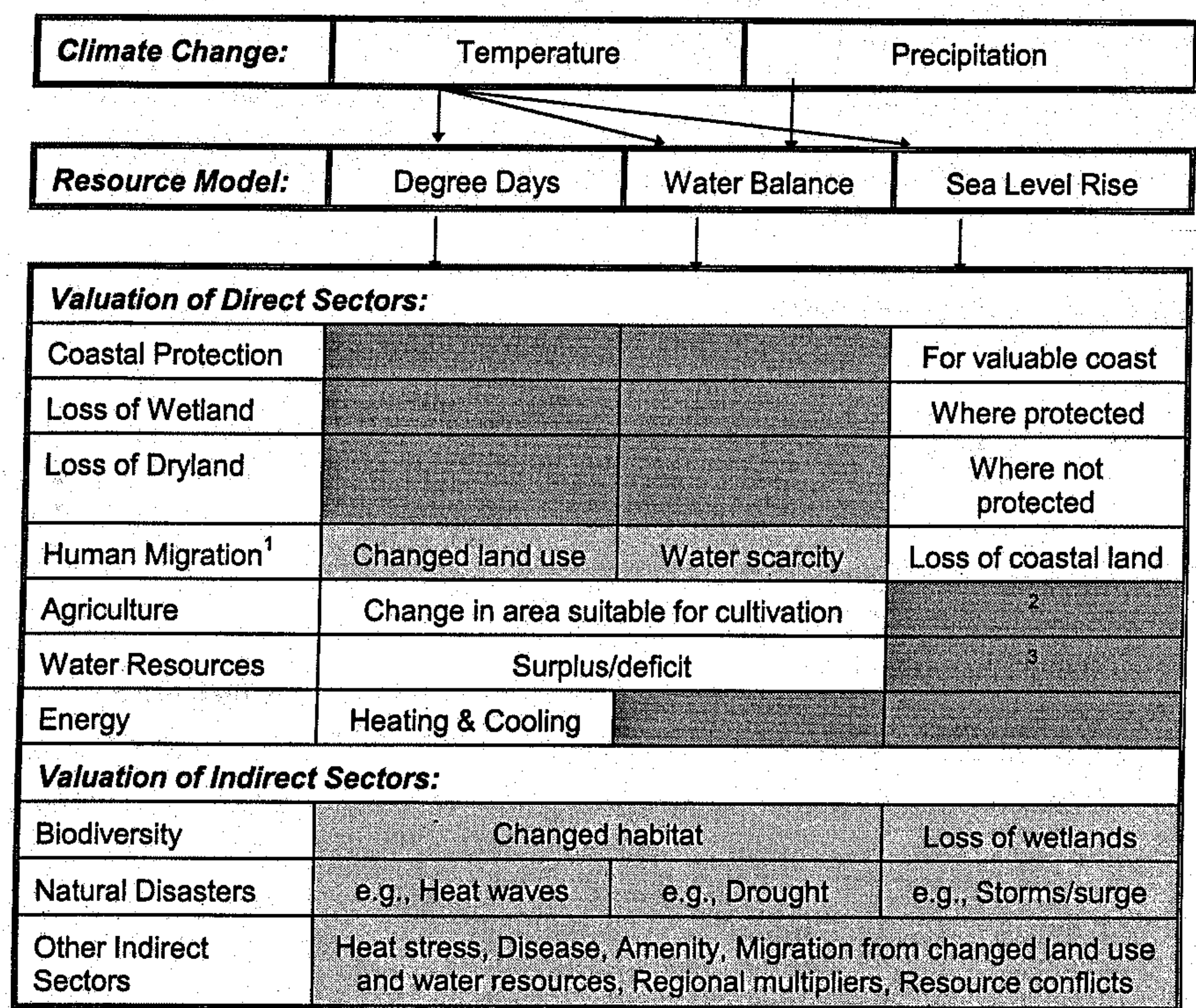


Figure 2. Impact Models and Sectors. Clear cells are direct impacts with quantitative estimates of damages based on "market" estimates of losses. Light shade indicates impacts that are evaluated by indirect means including the value of statistical life and contingent valuation. Other Indirect Sectors represents all other costs of climate change, derived from a scalar applied to sectors with net costs. Heavy shade indicates combinations of causes and impacts that are not estimated, are likely small or are not relevant. Notes: (1) Migration has both direct (refugees from sea level rise) and indirect (social disruption) aspects; (2) Loss of agricultural land due to sea level rise is included in loss of dryland; (3) Water resources might also be affected by sea level rise (although not estimated here).

The direct cost sectors are:

- Coastal changes due to sea level rise: coastal protection, loss of drylands, loss of wetlands and migration related to loss of drylands.
- Land resources: changes in agriculture and water resources, which can be either benefits or costs.
- Energy demand for space heating (a benefit) and cooling (a cost).

These costs are estimated based on direct methods of market prices, supply and demand.

The indirect costs sectors are:

- Biodiversity loss due to losses in wetlands and drylands and changes in resource use.
- Disasters related to climatic hazards.
- "Other" sectors related to health, welfare, ecosystem function and migration not included in the above.

These costs are valued by more subjective estimates of contingent valuation and the value of a statistical life. The other sectors (value of ecosystem function, for example) are valued simply as a scalar of other costs, resulting in comparable numbers as reported in the literature. For the present project, it was not deemed worthwhile to further develop these cost estimates. Existing approaches provide a wide range of values and are contentious when applied across countries.

Reference projections: Generic assumptions

Two reference scenarios are chosen from the IPCC suite of scenarios developed in 1992 (Table 3). Two major differences between the two scenarios are explicit: (1) population growth in the IS92a world reaches 11.3 billion by 2100, compared to 6.4 billion in the IS92d scenario, and (2) world GNP is larger, although per capita GNP is less ($21,500 rather than $28,200). In addition, it is possible to infer differences in the scenarios regarding: (3) technology and the rate of adaptation to resource scarcity and (4) effective demand – a more populous and wealthier world entails higher economic demand and costs. Thus, the two scenarios can be ascribed a range of values, possibly beyond the mechanistic projections undertaken by the IPCC, that set off the differences between the "non-intervention" scenario and a world of higher incomes and environmental values. Whilst the level of specification of the IPCC scenarios does not allow all these variables to be quantified with precision, it does identify the broad conditions (demographic, economic and social) which allow differences in energy end use projections to be developed.

Population Growth

In the IS92a reference scenario, world population grows from 5.3 billion in 1990 to 10.0 billion in 2050 and 11.3 billion in 2100. This is markedly different from the population projection in the IS92d scenario: reaching 7.8 billion in 2050 before falling back to 6.4 billion in 2100. The highest population growth is in developing countries, whereas the OECD countries have similar profiles in the two scenarios. As such, much of the difference between the two population patterns is in regions: with low space heating and cooling demand at present; greater pressures for water resources; larger share of agriculture in GDP; and higher human vulnerability to sea level rise and climatic extremes.

Population growth is incorporated into the evaluation in several ways. Coupled with economic growth, per capita GDP is used to project future economic demand for goods and services. Higher populations imply higher usage and demand for resources, as noted below, resulting in higher prices. Density of populations in coastal areas increases proportionate to the population growth.

Economic Growth

Economic growth in the IS92a scenario – 2.9% to 2025 and about 2.0% thereafter – is significantly higher than in the IS92d scenario – 2.7% to 2025 then falling to about 1.6% in 2100. Country level estimates of GNP and economic growth rates are based on data such as WRI (1990, 1991). Combined with population growth, per capita incomes differ in the two scenarios. Average world per capita output rises to $21,500 in the IS92a scenario compared to $28,200 in the IS92d scenario, and compared to $3,800 at present. The higher wealth in both scenarios implies greater resources are available to mitigate the impacts of climate change, to reduce absolute poverty, and to mitigate disasters. Much of this capacity to cope is generated through technological change. We assume in both scenarios a reduction in absolute poverty, at least in percentage terms. However, this reduction is more marked in the IS92d scenario. (As such, the IS92a is not a "business-as-usual" scenario, rather it reflects continuation of the current trends toward increased nutrition and food security.)

Technological Change

The variation in rates of economic development between the two scenarios implies that rates of technological advance will be different. For both scenarios, a reasonable rate of improvement is anticipated, with greater technology being stimulated and affordable in the IS92d than in the IS92a scenarios. The specific rates of technological improvements implied in each scenario are described below for each sector.

Demand, Economic Exposure and Values

The two scenarios reflect differences in resource pressures, effective demand (and prices), settlement patterns and densities, and exposure to extreme events. For example, lower per capita wealth implies lower investment available for protection and mitigation of the impact of climatic changes. The notion of the IS92d being a scenario of sustainability and environmental concern is based on the higher rates of GHG abatement. In such a world, general environmental concerns would be given considerable weight and climate change would be taken as a serious threat, implying a higher willingness to pay to prevent its adverse impacts. For example, social and environmental values will affect cultural attitudes and legislative control over energy using equipment.

Table 3. Assumptions for Two Reference Scenarios

Sector	Assumptions	Unit	1990	Projection: 2100	
				IS92a	IS92d
Population	No.	B	5.3	11.3	6.4
Economy	World GNP	$B	19,958	242,950	180,480
	GNP per capita	$	3,800	21,500	28,200
	GNP Growth rate	%/yr	1.3	2.0	1.6
	Agricultural GNP	%	6.2	2.9	2.6
Energy prices	Fuel	$/GJ	6	24	18
	Electricity	$/GJ	21	39	34
Energy demand	Heating	EJ/yr	67	198	64
	Cooling	TWh/yr	692	11,492	1,658

3. Assessment of Climate Change

Global climate change

The two reference scenarios of emissions, the IS92a and IS92d, result in different but overlapping projections of global temperature change (Figure 3). These results, from the 1995 version of MAGICC, are slightly warmer than the projections used in the earlier IEA GHG study. The medium estimates for the two scenarios are global average increases in temperature by 2100 of 2.33°C for the IS92a and 1.75°C for the IS92d. This range between the two scenarios is fairly consistent for the low, medium and high estimates. Precipitation will also increase in a warmer world. However, global-mean projections are less useful, given the large variability in precipitation between and within regions.

Comparable projections of sea level rise are shown in Figure 4. The medium estimates are 43 cm for the IS92a and 36 cm for the IS92d. As for temperature, there is considerable overlap between the two scenarios, with the low estimates almost an order of magnitude lower than the high estimates. The difference between the two scenarios is less than for temperature, due to the slower responses of oceans to changes in the Earth's radiation budget. The global sea level rise is taken as representative of actual changes for each country in the economic valuation. In fact, many local situations will be strongly influenced by local land movements, either rebound following deglaciation or subsidence due to groundwater withdrawal or compaction of sediments. These local changes are incorporated to some extent in the national data base of risk used in this study. Changes in sea level rise are used to drive the coastal resources impacts (protection, loss of wetlands and drylands, and migration).

Emissions and full fuel cycles

The projected global warming results from specific scenarios of greenhouse gas emissions. These emissions can be expressed in terms of the contribution to global warming for selected years (Table 4). Carbon dioxide is the predominate contributor, although its forcing varies by over 10% between the two scenarios. The concentrations of greenhouse gases differ between the two scenarios and this can influence the relative contribution of individual fuel cycles to global warming. That is, the effect of each fuel cycle will be somewhat different depending on its relative contribution to GHG concentrations taken as the reference case.

The contribution of each fuel cycle to global warming is shown in Figure 5 through Figure 10. The graphs represent the ratio of the reference scenario + fuel cycle to the reference scenario. The fuel cycles that begin operating in 1990 all start with relatively high ratios of fuel cycle warming to the reference. (MAGICC assumes climate change in 1990 is 0, with 1995 as the first reported year, resulting in an artificial spike). The warming contribution steadily declines, more notably after operation has ceased.

As expected, the largest effects are from the UK Coal and Lignite fuel cycles, which have the largest CO_2 emissions. The UK Gas fuel cycle has a lower effect than the coal plants. The two oil fuel cycles show quite different profiles. The Oil GT fuel cycle follows the same pattern as the coal and gas plants, although the smaller emissions lead to a more rapid decrease in the effect on global warming. The Oil CC fuel cycle, starting fifteen years later, has more gradual effects. The effect of the (substantial) CO_2 emissions are offset by the relatively high SOx emissions.

Each fuel cycle makes a larger contribution to the global emissions in the IS92d world. Hence, the effects compared to the IS92d reference are slightly higher than for the IS92a reference. The pattern of effects are much the same for the low, medium and high estimates. The relative contributions to global warming are larger for the low climate sensitivity. The differences between the fuel cycles are similar in their contributions to sea level rise. (Note that the jumps in the ratios are due to the effect of rounding on very small ratios.)

Table 4. Contribution to Global Warming from Greenhouse Gases for IS92a and IS92d

			Contribution to Global Warming					
		dT, °C	CO2	CH4	N2O	CFCtot	SO2	Total
IS92a								
	1990	0	0%	0%	0%	0%	0%	0%
	2025	0.5860	93%	18%	4%	10%	-24%	100%
	2050	1.1025	92%	17%	4%	10%	-23%	100%
	2075	1.7040	87%	15%	4%	9%	-15%	100%
	2100	2.3304	86%	13%	4%	7%	-11%	100%
IS92d								
	1990	0	0%	0%	0%	0%	0%	0%
	2025	0.5689	77%	11%	3%	12%	-4%	100%
	2050	1.0088	75%	9%	4%	13%	-1%	100%
	2075	1.4099	74%	7%	4%	14%	2%	100%
	2100	1.7523	77%	5%	4%	12%	3%	100%

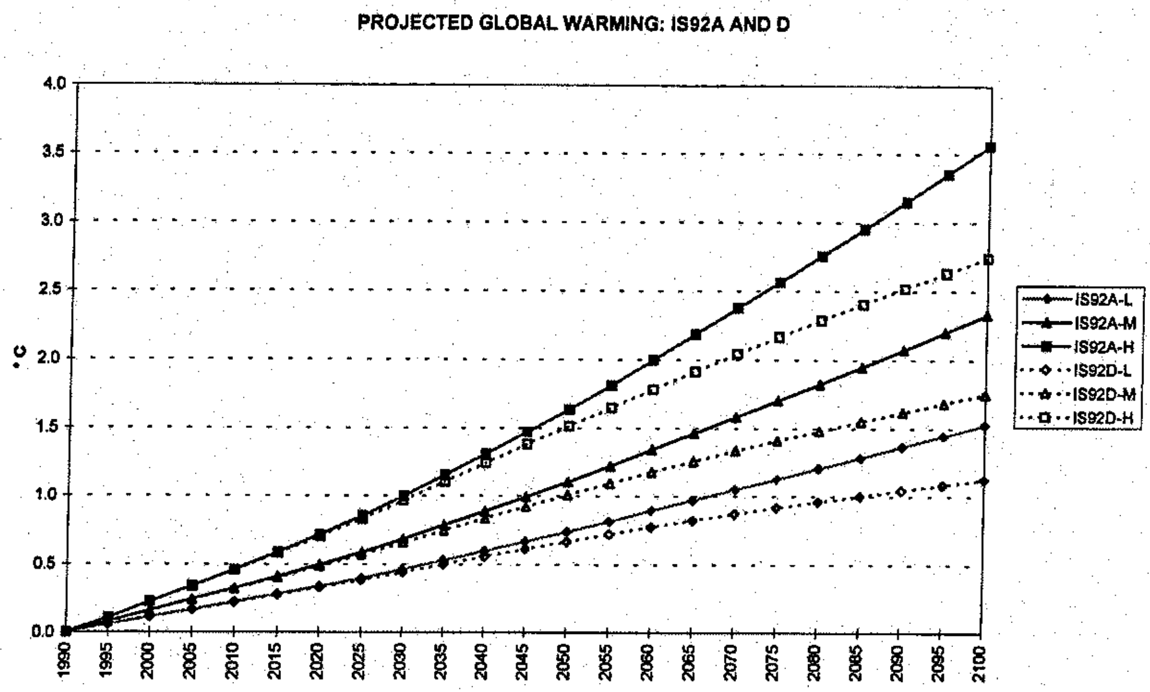


Figure 3. Projected Global Warming for the IS92a and IS92d Scenarios. Source: 1995 version of MAGICC.

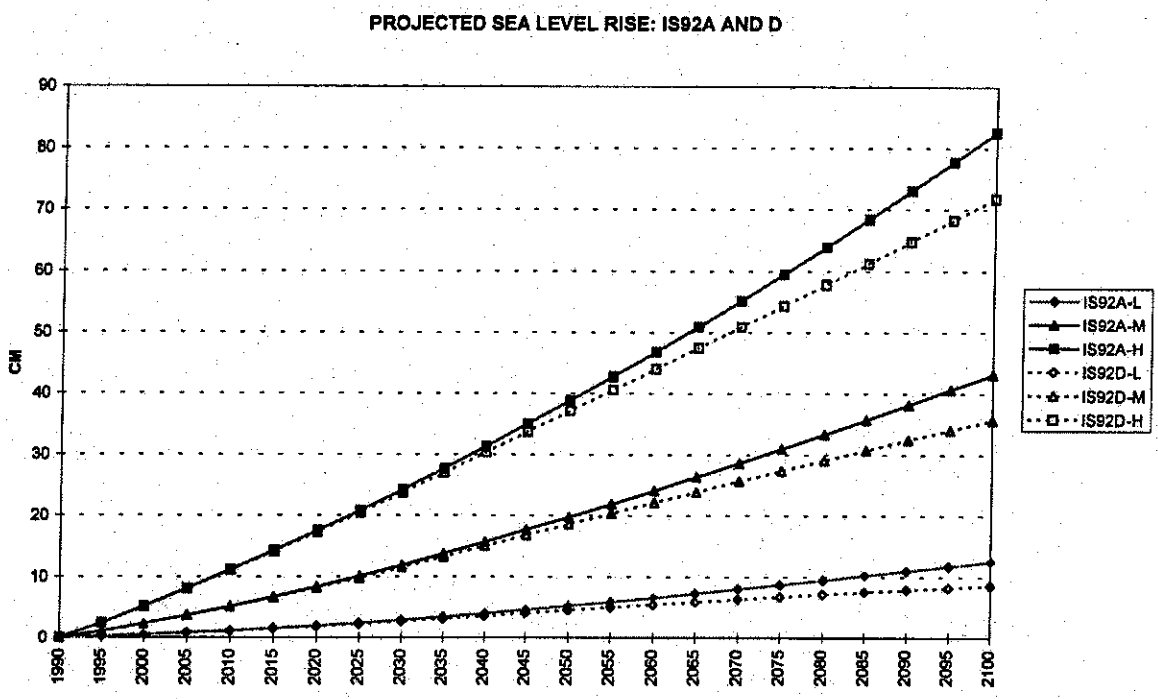


Figure 4. Projected Sea Level Rise for the IS92a and IS92d Scenarios. Source: 1995 version of MAGICC.

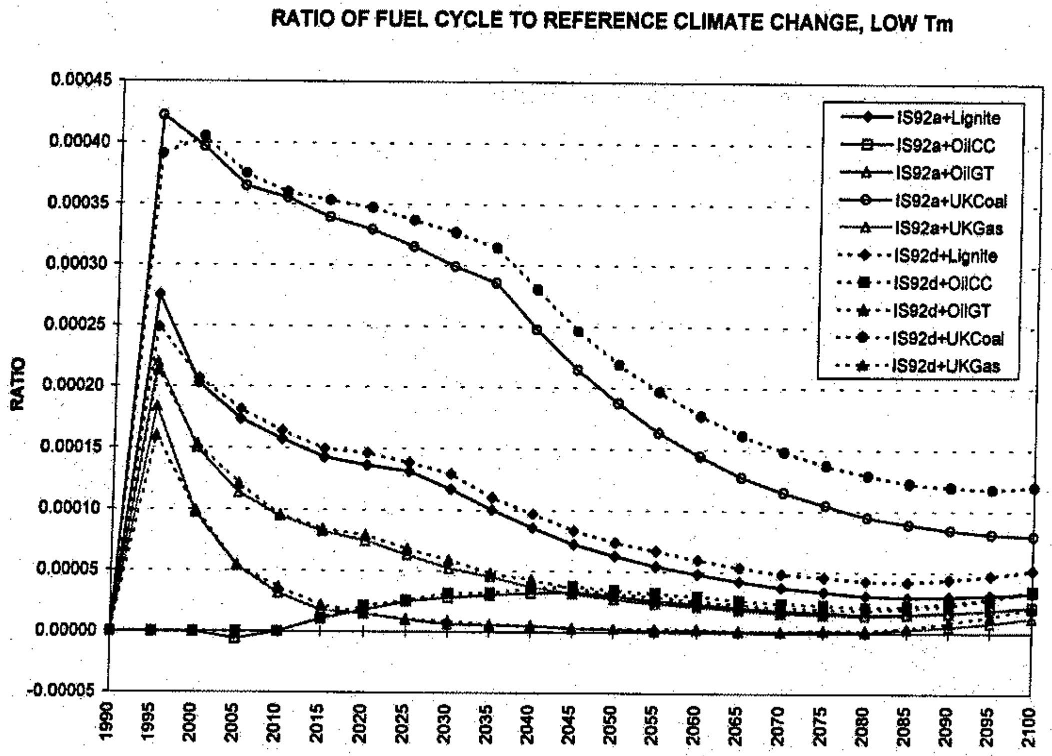


Figure 5. Ratio of Fuel Cycle to IS92a and IS92d Climate Change Scenarios: Low Estimate for Global Temperature. Source: 1995 version of MAGICC.

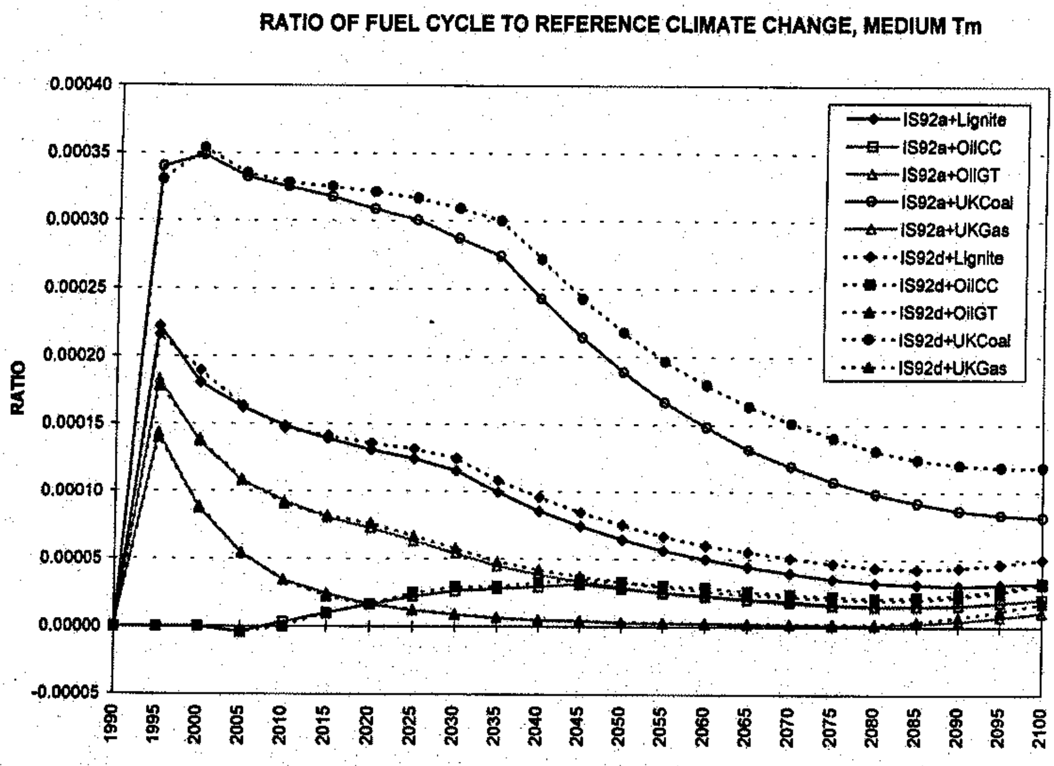


Figure 6. Ratio of Fuel Cycle to IS92a and IS92d Climate Change Scenarios: Medium Estimate for Global Temperature. Source: 1995 version of MAGICC.

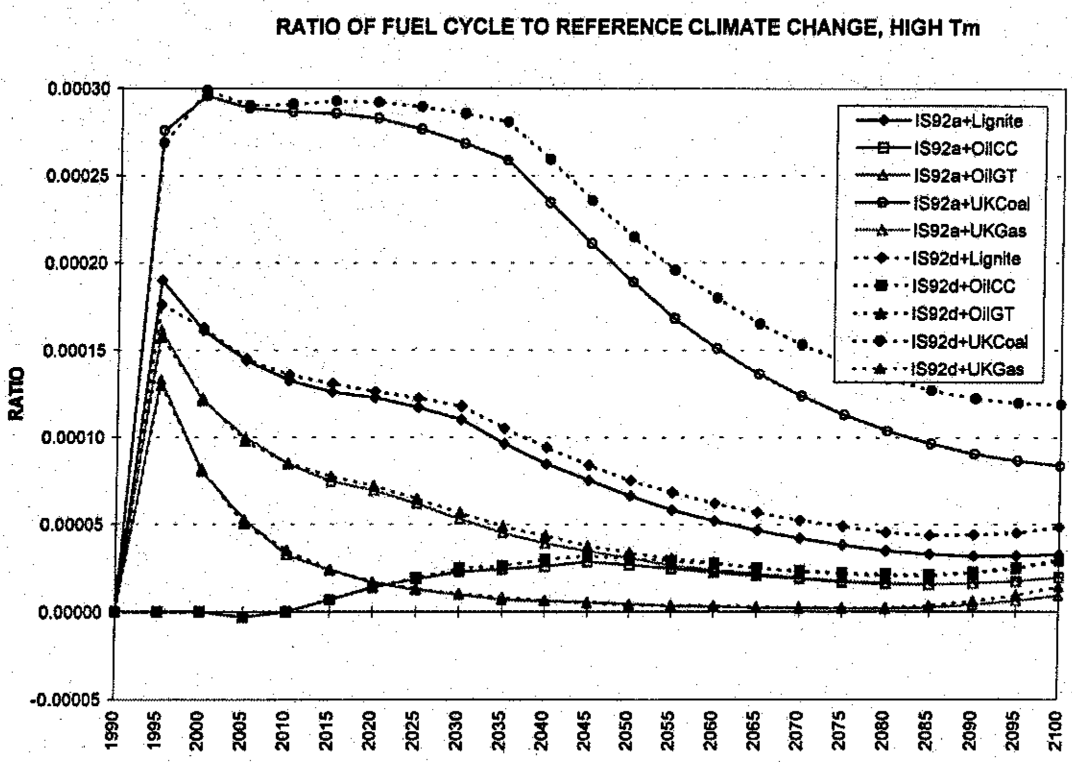


Figure 7. Ratio of Fuel Cycle to IS92a and IS92d Climate Change Scenarios: High Estimate for Global Temperature. Source: 1995 version of MAGICC.

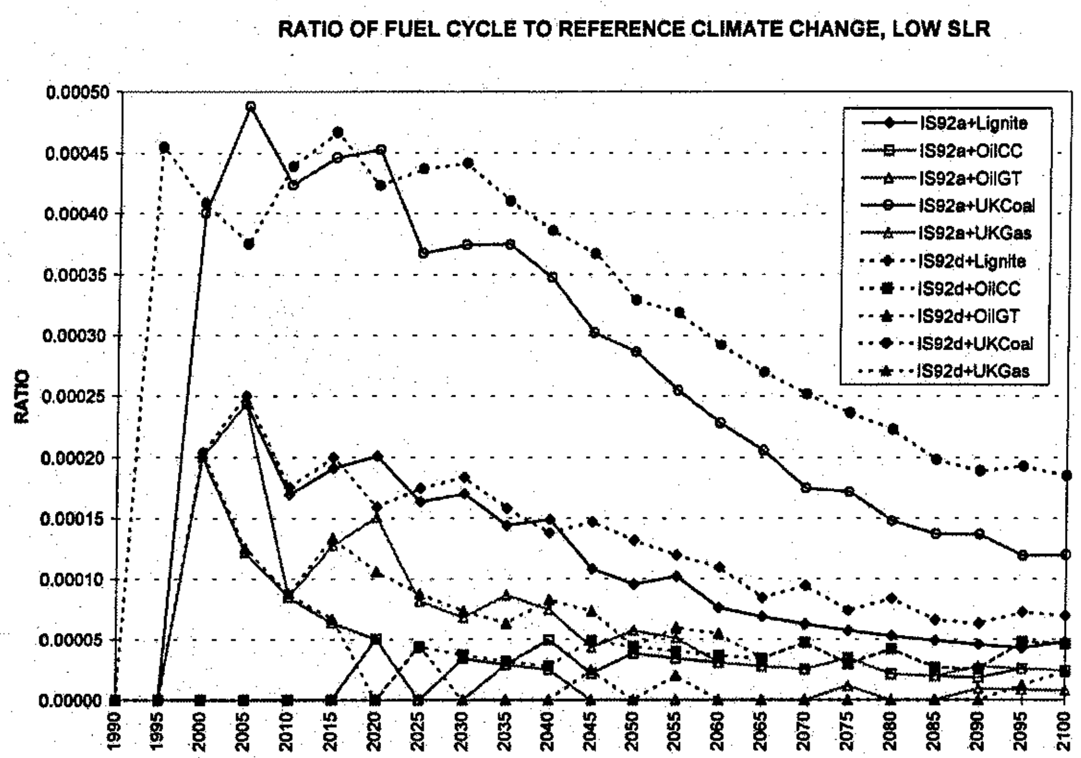


Figure 8. Ratio of Fuel Cycle to IS92a and IS92d Climate Change Scenarios: Low Estimate for Sea Level Rise. Source: 1995 version of MAGICC.

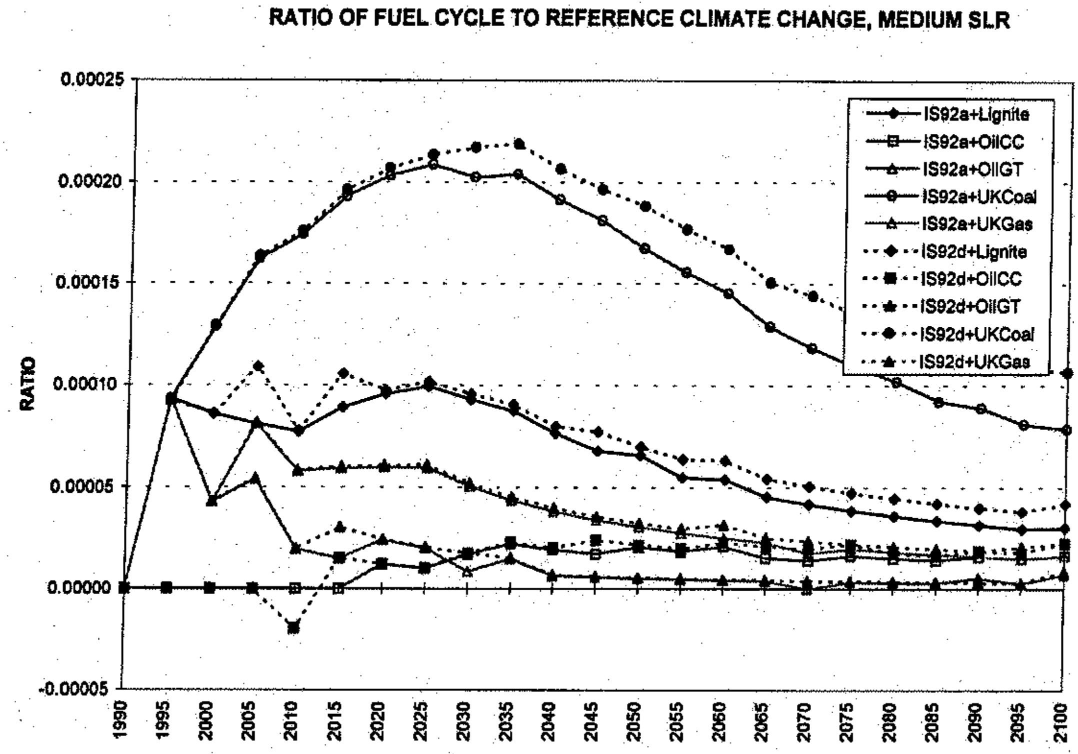


Figure 9. Ratio of Fuel Cycle to IS92a and IS92d Climate Change Scenarios: Medium Estimate for Sea Level Rise. Source: 1995 version of MAGICC.

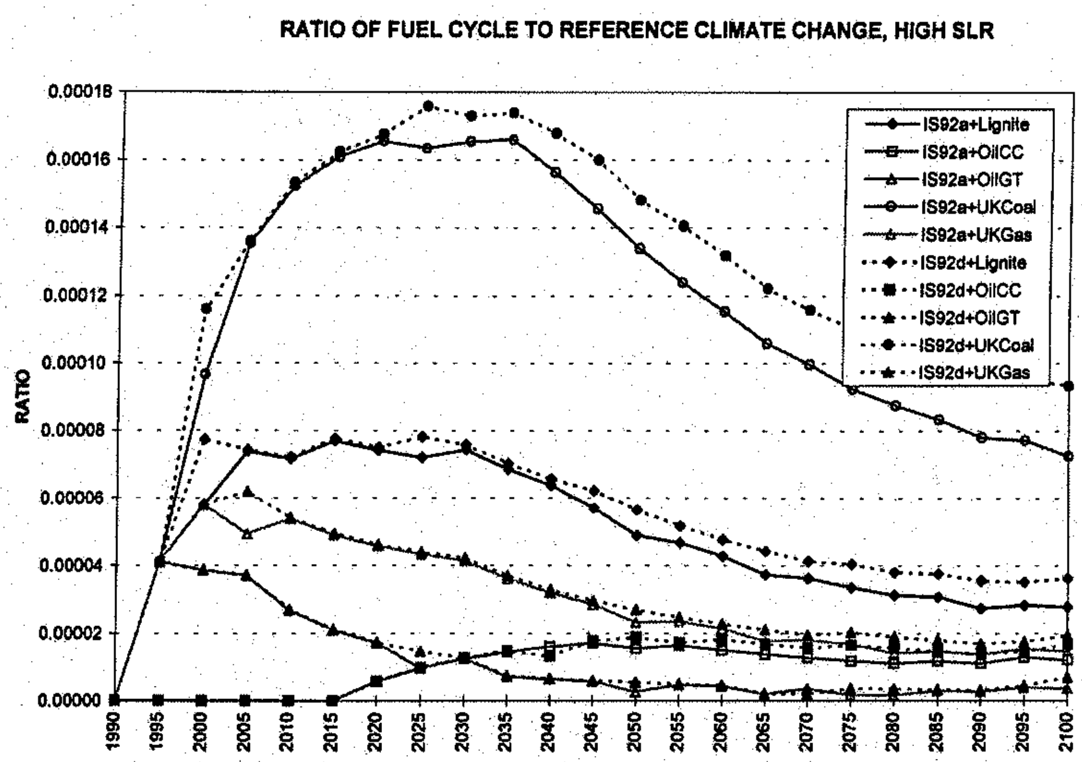


Figure 10. Ratio of Fuel Cycle to IS92a and IS92d Climate Change Scenarios: High Estimate for Sea Level Rise. Source: 1995 version of MAGICC.

4. Impact on Coastal Resources: Protection, Wetlands, Drylands and Migration

Methodology

The impact of climate change on coastal resources is based upon assumptions of protection and partial retreat. The protection scenario specifies which of the possible responses to sea level rise is most likely to be adopted. The most common approach (as used by Fankhauser) is to assume that valuable coastline (i.e. densely populated) will be protected with some loss of wetlands, while sparsely populated coastline will not, leading to loss of drylands and migration. A time-dependent analysis requires a different appraisal to the economic value of land loss than had been applied by Fankhauser (1992, 1995) and others.

Protection costs represent the capital costs of building coastal defences, such as dikes and sea walls for densely populated coastline. These costs have been estimated in a study carried out for the IPCC in 1990 by Delft Hydraulics and subsequently updated (Delft, 1993; see also Hoozemans and Hulsbergen, 1995). The results are calculated for a 1 metre rise in sea level, and are quoted at a country level in 1990 US dollars. The global total of the costs quoted was \$986,716 million. Fankhauser (1992) scaled these results to a 50cm rise by assuming that the costs will be related to sea level rise by a polynomial function. Titus *et al.* (1991) estimated a power factor of 1.28, which is the value used by Fankhauser. A factor greater than 1 implies a diseconomy of scale in coastal protection costs, reflecting a greater need to protect against extreme events. This study has used the same value in order to scale the Delft results to the low, medium and high levels of sea level rise in the IS92a and IS92d scenarios.

Sea level rise tends to cause coastal wetlands (including salt marshes and mangroves) to migrate inland. New wetland forms further inland to replace the wetland which has been inundated. In coastlines with constant slope, it may be that there is no net loss of wetland. However, coastal protection usually blocks this process by placing a physical barrier either in front of or behind the wetlands so that they are unable to retreat. Wetlands are therefore lost when coasts are protected.

There are many valuation studies concerning different types of wetland. Pearce and Moran (1994) summarise 15 separate studies, concentrating mainly on use values in a variety of regions. The focus of most studies are the productive and carrier functions – fish, forest products, water and recreation. Estimates of the values of these functions vary hugely from study to study. Of course, considerable variation between different locations is to be expected, but careful inspection indicates that most of the variation seems to arise from the different functions considered, as well as the economic methodology (notably the discount rate applied).

Productive use values range from \$150/ha to \$40,000/ha. The higher values tend to relate to mangrove systems. Recreational benefits are typically quite small, of the order of \$100/ha, but can rise to \$8,000/ha in some areas. A single study of the Charles River in New England gives a surprisingly high water supply value of \$200,000/ha. As this is not replicated elsewhere its transferability must be doubted. Use values in general seem to be in the range \$150-50,000/ha (\$0.015M/km^2-\$5M/km^2).

As expected, valuation studies tend to neglect regulation functions. Storm protection is considered in a single case, with a derived value of \$6,000/ha, but otherwise valuation is restricted to the resources within the ecosystem rather than its wider biophysical role. For this reason, the valuations derived must be considered to be underestimates of total use value.

There is less information on wetland existence value – none concerning wetland fauna. The only major CVM study of wetlands concerns Scottish blanket bog, which is of limited relevance to coastal systems. The value derived ($300/ha) implies that use values are likely to predominate.

Thus, the total economic value of wetland ecosystems cannot be measured satisfactorily because available studies do not value potentially important regulatory functions. On the basis of functions (largely productive) which have been valued, a range of $10,000/ha - $50,000/ha ($1M/km2 - $5M/km2) seems to be appropriate.

The IPCC study (1990) by Delft Hydraulics provides a country level estimate of the total area of coastal wetlands in the world (about 302,000 km^2). The study also quoted an estimate of the areas at risk of loss due to sea level rise, both with and without protective measures (between 169,000 and 179,000 km^2). For the purposes of this study, we have assumed that only a proportion of this wetland at risk will actually be lost as a result of sea level rise. The highest, most pessimistic assumption is that all of it will be lost; the lowest assumption that half will be lost, and the medium assumption that 75% will be lost. These assumptions are applied at a country level (Table 5).

Wetlands have a value in terms of the productivity of commercial fisheries, since they are an important source of nutrients supporting fish populations. Other direct uses of wetlands include recreational activities such as sport fishing and hunting. The presence of wetlands is also frequently important for flood protection in coastal areas.

Values for wetland areas are quoted by Titus *et al.* (1991) (1.5-7.5 $M/$km^2$), Turner (1991), Turner and Jones (1990), Rijsberman (1991) (3-13 $M/$km^2$) and Cline (1992) (2.5 $M/$km^2$). Fankhauser (1992) used a value of 5 $M/$km^2$ for OECD countries, 1.25 $M/$km^2$ for the USSR (also used as a global average), and 0.5 $M/$km^2$ for China.

Table 5. Sectoral Impact Assumptions for Coastal Resources

	Units	Low	Medium	High
Wetlands				
Capital value of wetlands, 1990				
IS92a or IS92d	$M/$km^2$	0.50	1.25	5.00
Loss of wetlands per 1m sea level rise				
IS92a or IS92d	%	50	75	100
Drylands				
Proportion of undeveloped coast, 1990				
IS92a or IS92d	%	50	80	100
Loss of land per km for 1m SLR				
IS92a or IS92d	km^2/km	0.60	0.90	1.2
Capital value of land, 1990				
IS92a or IS92d	$M/$km^2$	0.5	2.0	5.0
Migration				
Proportion of population density in low-lying areas, as a % of national average population density, 1990				
IS92a or IS92d	%	50	75	100
Annual cost of climate migrants, 1990				
IS92a or IS92d	$/year	75	1,000	4,500

Fankhauser used an assumed rate of rental return (10%) in order to annualise the total loss resulting from CO_2 doubling over an unspecified time period. We estimate costs over a specific period (to 2100). The annual loss is therefore assumed to be the lost capital value of the wetland in any particular year. The land values quoted can be interpreted as the net present values of an annual stream of income from the land. To define a range from low to medium to high which encompasses these estimates of capital values in the literature, the three estimates by Fankhauser are used.

These assumptions are applied at a country level. They are scaled in a linear way by the sea level rise estimates in the IS92a and IS92d scenarios, assuming that the Delft results apply to a rise of 1m. Values are projected to 2100 in line with the growth in agricultural GDP for each country and scenario. While both scenarios have the same starting values, this scaling according to growth in agricultural GDP results in different total world costs.

Dryland will be lost on unprotected coast which is low-lying – subject to inundation or vulnerable to coastal erosion. The area lost will depend upon a number of factors. For example, a higher degree of slope will result in a smaller loss of land. The IPCC study (1990) quotes country level estimates of the length of low-lying coast. The global total is about 347,000 km.

The partial retreat scenario assumes that "undeveloped" coastline will not be protected. A key assumption is the proportion of low-lying coast which can be regarded as undeveloped. Titus *et al.* (1991) predict a central estimate of a loss of 10,600 km^2 for the USA, given a 50cm sea level rise. The IPCC (1990) reports a low-lying coast length of 28,716 km for the USA. Fankhauser (1992) estimates a loss of 0.46 km^2 for each km of undeveloped coastline. This implies that approximately 80% of the coastline was regarded as undeveloped. This study adopts a range as shown in Table 5, applied globally in order to calculated the coastline at risk in each country This study assumes (in the absence of better information) the coastline of the USA is representative of the world. It therefore adopts a range as shown in Table 5 in order to calculate the coastline at risk in each country.

The actual loss of land in each country will depend upon the geometry of the coastline. This study has used Fankhauser's (1992) estimate of 0.46 km^2/km as a medium estimate, scaled to a 1m sea level rise (i.e. doubled) to be consistent with the IPCC (1990) (Table 5). These estimates have then been scaled to the IS92a and IS92d sea level rise projections.

A global average value of 2 \$M/km^2 was used for the value of land, with a range as shown in Table 5. As in the case of wetland, the annual loss is assumed to be the loss of capital value. The value is scaled into the future, using growth in agricultural GDP.

Climate change is likely to force migration of people away from inundated coastal areas, or from land no longer suitable for agriculture. At present we have estimated effects only for sea level rise. These results are related to the loss of drylands, itself a result of not protecting all coastlines from sea level rise. Further research could relate potential migration to loss of agricultural land or severe decreases in water resources.

The IPCC study (1990) quotes the population density of low-lying coastal areas by country. As a first estimate, these values could be multiplied by the loss of dryland to give a value for the numbers who would need to move as a result of sea level rise. Population density may however vary somewhat, and it seems reasonable to assume that it would be lower than the figures quoted in the immediate vicinity of low-lying coast at risk. It may also be that the IS92a scenario would anticipate a higher degree of population pressure and resource conflicts than the IS92d scenario.

However, as a starting point we have not distinguished between the two scenarios (Table 5). These assumptions are combined to produce an estimate of the number forced to migrate given the IS92a and IS92d sea level rise projections. These estimates are further scaled to the population growth projections in the two scenarios.

For other migration, the maximum rates would be related to the conjuncture of increased water scarcity, large reductions in the area suitable for agriculture, and possibly increases in hazards such as cyclones and heat waves. The combination of such changes could be mapped onto a spatial data base of population density.

The costs associated with migration have been assessed in various ways. Ayres and Walter (1991) estimate that the direct costs of resettlement in poor countries are about $72 per migrant per year. They advocate a cost of $1000 per migrant per year, based upon an estimate of the foregone productivity caused by migration - i.e. the production of the migrant had he or she not migrated. In China or India this would constitute about 3 years of production for the average citizen. Both Cline (1992) and Ayres and Walter (1991) calculate a cost of $4,500 per migrant per year for the United States. If this represents lost production, then it corresponds to about 2.5 months for the average citizen.

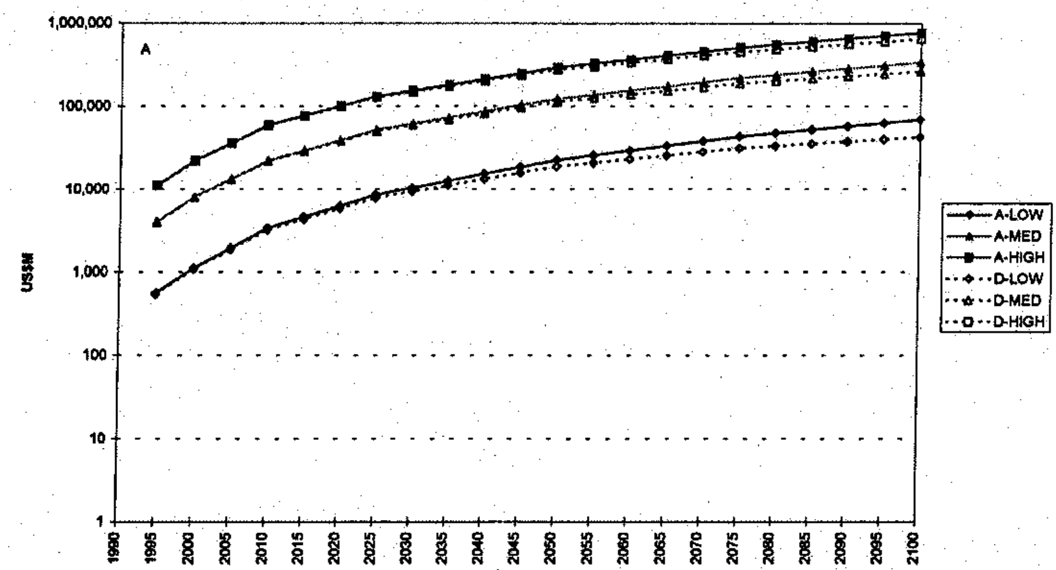
The above rates are used to set a reasonable global range for the annual cost per migrant (Table 5). These rates are scaled according to the per-capita gross global product (GWP) in order to project into the future for the two scenarios. No attempt has been made in this analysis to estimate the costs of increased morbidity or mortality resulting from migration, nor for migration resulting from extreme events. The underlying assumption is that migration of this kind is very gradual, and therefore not subject to the stresses of migration resulting from extreme events such as storm, flood or drought.

Migration from coastal areas and land no longer suitable for agriculture is expected to increase in line with increased population densities. It may be that the IS92a scenario would anticipate higher levels of population displacement, due to resource conflicts, population pressure, lack of economic investment, etc. The risk of such widespread migration is included in the discussion of other sectors below.

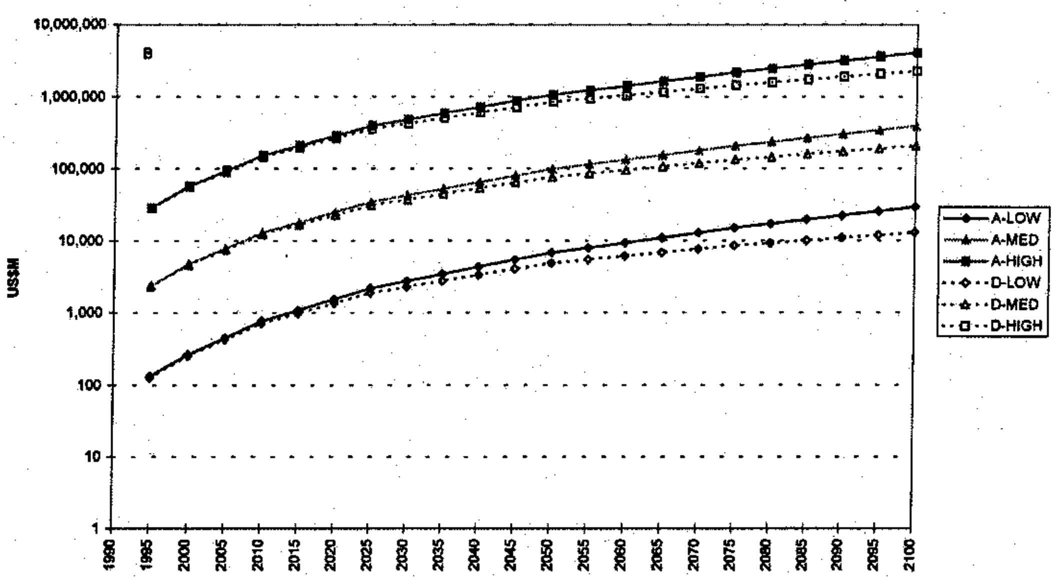
Results

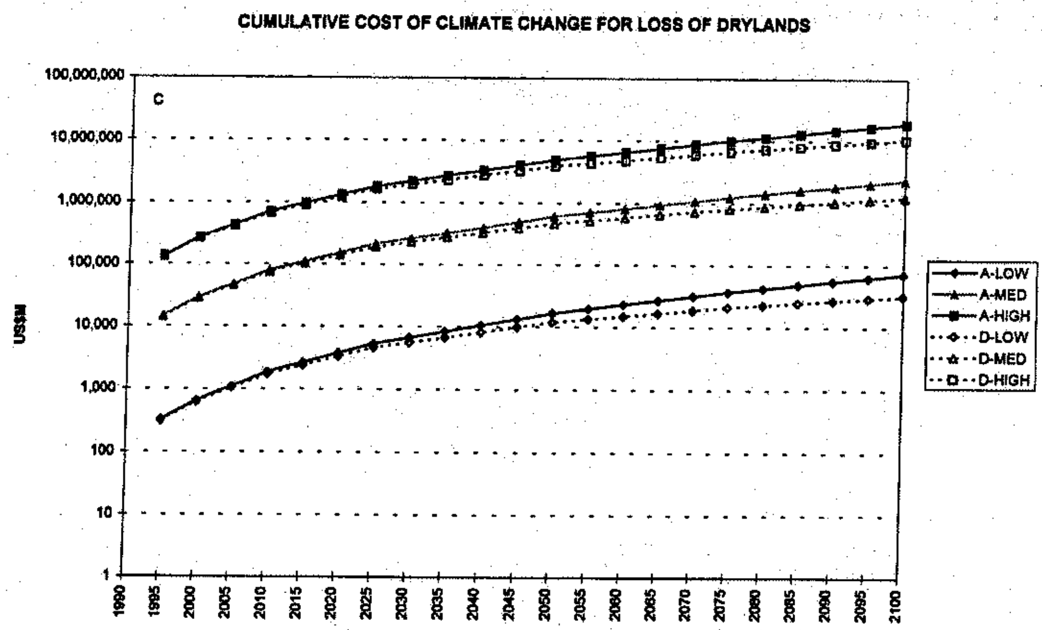
The resulting costs are highest for the loss of drylands, in the medium estimates exceeding $\$10^{13}$M (Table 6). The loss of wetlands is also large, but an order of magnitude less than for drylands. In contrast, the cost of coastal protection is relatively small. The difference between the IS92a and IS92d scenarios is relatively small (compared to the size of the damages). This is partly due to the weighting by sea level rise rather than by global temperature change.

CUMULATIVE COST OF CLIMATE CHANGE FOR COASTAL PROTECTION



CUMULATIVE COST OF CLIMATE CHANGE FOR LOSS OF WETLANDS





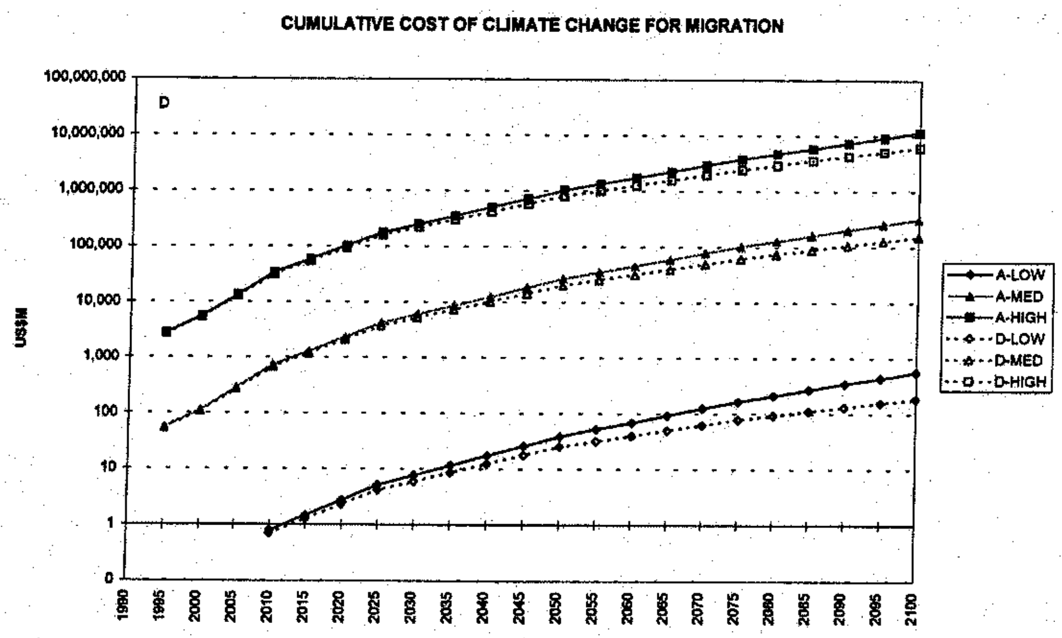


Figure 11. Cumulative Cost of Climate Change for the Coastal Zone, Comparing the IS92a and IS92d Scenarios. (a) Coastal Protection; (b) Wetlands; (c) Drylands; (d) Migration. Note: all sectoral costs are zero in 1990, and for migration are zero until 2010 in the low case.

Table 6. Cumulative Cost of Climate Change for Coastal Resources

CP	Unit	1990	2000	2010	2025	2050	2075	2100
Coastal Protection								
A-LOW	$M	0	1,119	3,359	8,557	22,643	43,520	69,256
A-MED	$M	0	8,024	22,257	52,182	123,662	220,452	336,486
A-HIGH	$M	0	22,312	59,594	132,306	294,180	508,098	772,550
D-LOW	$M	0	1,091	3,214	7,848	18,953	31,490	42,947
D-MED	$M	0	7,980	21,982	50,659	114,438	188,242	264,191
D-HIGH	$M	0	22,257	59,116	129,627	277,996	452,433	645,471
Wetlands								
A-LOW	$M	0	264	764	2,186	6,791	15,076	29,222
A-MED	$M	0	4,751	12,944	34,687	98,883	206,986	388,356
A-HIGH	$M	0	58,013	153,463	394,097	1,068,872	2,182,777	4,083,106
D-LOW	$M	0	254	708	1,889	4,892	8,549	12,987
D-MED	$M	0	4,648	12,299	31,345	77,048	133,584	207,535
D-HIGH	$M	0	56,884	146,313	358,681	846,588	1,455,616	2,290,579
Drylands								
A-LOW	$M	0	650	1,884	5,387	16,740	37,162	72,034
A-MED	$M	0	29,087	79,247	212,365	605,389	1,267,229	2,377,630
A-HIGH	$M	0	269,444	712,762	1,830,395	4,964,406	10,137,970	18,964,104
D-LOW	$M	0	626	1,746	4,657	12,059	21,073	32,014
D-MED	$M	0	28,454	75,297	191,905	471,713	817,842	1,270,592
D-HIGH	$M	0	264,199	679,557	1,665,905	3,932,000	6,760,652	10,638,659
Migration								
A-LOW	$M	0	0	1	5	39	167	563
A-MED	$M	0	111	715	4,103	26,315	101,208	319,647
A-HIGH	$M	0	5,510	33,504	176,585	1,023,619	3,737,924	11,706,287
D-LOW	$M	0	0	1	4	25	79	188
D-MED	$M	0	109	679	3,686	20,295	61,840	154,173
D-HIGH	$M	0	5,388	31,847	159,979	812,242	2,434,065	6,225,741
Total: Coastal Resources								
A-LOW	$M	0	2,033	6,008	16,135	46,212	95,925	171,075
A-MED	$M	0	41,974	115,167	303,360	854,361	1,796,063	3,421,936
A-HIGH	$M	0	355,279	959,322	2,533,383	7,351,076	16,566,769	35,526,047
D-LOW	$M	0	1,971	5,669	14,399	35,930	61,190	88,136
D-MED	$M	0	41,190	110,256	277,595	683,495	1,201,509	1,896,492
D-HIGH	$M	0	348,728	916,833	2,314,192	5,868,826	11,102,766	19,800,450

5. Impact on Heating and Cooling Demand

Methodology and assumptions for estimating energy demand and impacts

The methodology is better developed for specifying energy demand and prices than for any of the other impact sectors. There seems no reason to suppose that the way energy use for space heating and cooling responds to climate change will be qualitatively different under the two reference scenarios. It is therefore assumed in both cases that:

- Space heating and space cooling are the dominant energy services affected by climate change.
- Within the major regions of the world, energy use for each activity is apportioned according to the product of GNP and degree days.
- In any given economic and cultural conditions, space heating demand remains a simple linear function of degree days (base 15°C).

- In any given economic and cultural conditions, both the market penetration of space cooling equipment and the energy use of that equipment are linear functions of cooling degree days (base 20°C), with a minimum energy use corresponding to 30 annual degree days.

Space heating and cooling baseline scenarios for the IS92d reference are based on the energy end use scenario to the year 2100 developed by the Stockholm Environment Institute (SEI, 1993). This scenario is used not only because of the detailed energy use data contained therein, but also because it is broadly consistent with the economic and environmental changes underlying the IS92d scenario. Ideally, a similar end use projection should be used for the IS92a scenario. However, no such projection has been identified in a review of the global energy scenarios literature (e.g. WEC, 1993; EC, 1992, 1995). It appears that detailed end use projections are restricted to the consideration of low energy, environmentally sensitive futures.

In the absence of a detailed end use scenario, specific projections for space heating and space cooling in the IPCC 92a scenario are developed from the projections in the IS92d scenario by modifying the demand parameters using the differences between the scenarios. This approach has the advantage that the differences between the two scenarios are introduced deliberately rather than appearing as unintended consequences of assumptions from other researchers.

For energy modellers, the most usual parameters of concern in projecting a demand for energy are prices and income/output. In this case, price effects have been neglected, because of the small differences in energy supply prices projected between the IS92a and IS92d scenarios. Fuel costs differ by only 25% (and electricity costs by less) even at the end of the 110-year period considered (Pepper *et al.* 1992). For usual values for long term price elasticities of energy demand (approximately 0.4), the impact on energy demand is 10% or less over the whole period. The impact of differences in energy taxes could be more significant (although it would work in the opposite direction raising prices more in the IS92d scenario), but is difficult to quantify. The impact of environmentally motivated energy taxes over the long term is more realistically addressed through looking at rates of technical and behavioural change induced under different social conditions.

The impact of output and income on energy demand is generally modelled as a single parameter, with the assumption that the underlying nature of the population is stable. For long term global assessments, this is not valid. Changes in income/output are more realistically modelled as separate effects of population and per capita income/output. Ceteris paribus, energy demands are always proportional to population. Per capita income/output effects are more complex and need to be addressed individually or each category for energy demand.

Econometric modelling of energy demand has shown that energy use cannot adequately be projected with reference to price and income/output alone. Over the long term, technical and social trends which are not reflected in price or income usually have a major effect. To resolve this, modellers frequently introduce an additional parameter, the autonomous energy efficiency improvement (AEEI), which represents the rate at which energy efficiency improves without any price induced effect (see Manne, Mendelsohn and Richels, 1993).

The use of an AEEI is both a misnomer and potentially misleading. The social and technical changes embedded in the index are merely independent of price and income; they are not autonomous of all socio-economic factors. Indeed, the AEEI is driven by social and technical developments – it is the modelling parameter most open to policy influence. Its usual treatment, as an exogenous parameter, is therefore inappropriate. In this work, it is not treated in that way but used as an indicator of energy efficiency improvements driven by policy, technical and social changes, and therefore different in different scenarios. The practical problem for scenario development is that the AEEI is a conflation of factors which are complex, inter-related and difficult to foresee. It cannot be predicted with accuracy and will not be constant over time. Estimates of its likely average value over the period considered can only realistically be made with reference to historical rates and by common sense judgement. These are the approaches taken here.

Over a long period, even very modest differences in the size of this parameter can have a significant effect (Ekins, 1995), far outweighing likely price effects. The size of the parameter is unknowable with any great accuracy, and will vary from end use to end use, but it is clearly scenario dependent. Most importantly from our perspective, efficiency improvements will be most evident in the conditions of environmentally sensitive, economic development characteristic of the IS92d scenario. Estimates can only be made with reference to broad scenario outlines and historical trends.

Baseline energy use for space heating and cooling over the world is modelled starting with the IS92d scenario. Corrections for differences in population, income and rates of technical change are introduced. Separate calculations are undertaken for each world socio-political region (USA, Western Europe, other OECD, former USSR, East and Central Europe, Africa, Latin America, Middle East and South & East Asia), then attributed to countries in those groups based on the individual country's portion of regional GNP*Degree Days.

Space heating demand is not expected to be very dependent on GNP. Most space heating energy is used in the residential sector. Reasonable comfort levels are a basic necessity and overheating has negative utility. Income elasticities are therefore low. In the OECD countries only Japan and the UK have a significant un-met space heating need (Schipper and Meyers, 1992). In the economies in transition, heat is usually provided at very low (or zero) marginal cost and with very low efficiencies, and therefore any increases in comfort demands can be met by achieving current Western European technical standards. Of the developing nations, only China has a large population living in climatic conditions with big space heating requirements.

Historically, domestic space heating consumption in developed countries has changed little over the last century. From UK data, an income elasticity of 0.2 is estimated (Hodgson and Miller, 1995). This is at income levels characteristic of those global average levels in the IS92a scenario in the next century. Of course, the form of development and technologies available will be very different from those in which this elasticity is calculated, and therefore we cannot be certain it is transferable. However, the arguments adduced above would indicate that the income elasticity for space heating will be small and common sense suggests it will be positive. A value of 0.2 is therefore used here. It should be noted that the resulting difference in energy use between the IS92d and IS92a scenarios is not sensitive to the exact value.

Space cooling demand is expected to be far more dependent on GNP than space heating demand. Space cooling is closer to a luxury than a basic necessity. This implies that the related energy demand can be very income sensitive at some stages of development. Most space cooling energy is used outside the residential sector, mainly in large commercial buildings. For a given standard of design, energy use is therefore likely to be largely proportional to the output of the commercial sector.

Energy use in the residential sector for cooling is likely to reach saturation levels in the warmer developed countries before 2100. Historically, domestic space cooling energy consumption is very culturally dependent. For example, demand is far larger in the USA than in Japan even under similar climatic and economic conditions. In cooler developed countries, the growth in air-conditioning energy demand currently exceeds GDP growth rates, but saturation is expected in the first half of the next century (UKDTI, 1995). On the other hand in developing countries, market penetration remains far from complete in the 92d scenario (SEI, 1993). It is clear that the overall global picture at any one time is rather complex, but over a period of a century, rising incomes will have a major effect, unless technical or cultural factors alter development paths. An income elasticity of about one is therefore a reasonable assumption. However, there are significant uncertainties in this.

The broad description of the IS92a scenario indicates lower levels of environmental awareness and legislation than for the IS92d scenario. This may be expected to produce lower levels of energy efficiency. In addition the lower levels of per capita income in the IS92a scenario would be expected to result in less investment in energy efficiency throughout the economy and reduced rates of all forms of technological improvement. As a result autonomous rates of energy efficiency improvement are expected to be significantly lower.

The UK has some of the longest data series on domestic energy use of any country. Per capita energy use in the domestic sector has actually fallen over the period 1920-85 by 8%, whilst real incomes have risen substantially more than three-fold (Evans and Herring, 1989). Allowing for income induced increases in demand (with an elasticity of 0.2) the average AEEI over the period has been 0.5%/year. This coincides with a period of economic growth at an average rate higher than that projected for the IS92a scenario. In addition there has been a significant growth in environmental awareness affecting space heating techniques over the period. The AEEI in the IS92a scenario is therefore expected to be less than 0.5%/year.

Examination of the IS92d scenario projection shows that per capita space heating energy use falls from 12.9 GJ to 8.3 GJ from 1990 to 2100. If the 2100 consumption data is corrected to allow for the growth of incomes over the period (with an income elasticity of 0.2) the 2100 income adjusted per capita space heating energy use is only 43% of the 1990 value. This implies an average AEEI over the period of 0.8%/year.

As expected the AEEI calculated for the IS92d scenario is slightly higher than the trend over this century. The argument above indicated that the trend in the IS92a scenario will be lower, but still positive. A reasonable estimate is 0.3%/year (i.e. 0.5%/year less than the IS92d scenario). This is adopted for the impact calculations.

Whereas the AEEI for space heating can be quantified historically, widespread application of space cooling is too newly developed and culturally specific to allow reliable extrapolation of existing trends. Examination of the IS92d scenario data shows that per capita space cooling energy use rises from 129 kWh/year to 258 kWh/year from 1990 to 2100. If the 2100 consumption data is corrected to allow for the growth of incomes over the period (with an income elasticity of unity) the 2100 income adjusted per capita space cooling energy use is only 27% of the 1990 value. This implies an average AEEI over the period of 1.2%/year. Such a rate is quite high, but not unreasonable for a relatively inefficient and immature technology such as space cooling.

Speculation about how this AEEI may differ between scenarios is difficult. Clearly, we would expect a lower rate in the IS92a scenario because of lower rates of technological change and lower environmental concern. Because space cooling is not widely adopted and is relatively immature as a technology a wider spread of technical futures is possible than for space heating. It is far from clear that compressor driven refrigeration systems will retain their dominant position. Moreover, there is a range of passive cooling options.

Social trends will be at least as important as technical developments. Current residential practice in the warmer parts of the USA is the use of whole dwelling air conditioning, whereas in Japan room air conditioners with much lower electricity consumption are more normal. The extent to which these different practices are adopted in rapidly growing air conditioning markets will be critical. In the commercial sector, air conditioning has become standard in "high quality" developments throughout the world. However, there are some recent counter trends in cooler countries, driven by environmental concerns. The development of conflicting trends such as these over 110 years is obviously a matter of speculation, but it is reasonable to assume that there will be significant differences between the two scenarios. We therefore expect the AEEI between scenarios to differ by more than the 0.5%/year adopted for space heating. To establish a best estimate for how much more requires a more detailed look at space cooling end use.

Closer examination of the assumptions made in deriving the IS92d scenario space cooling energy projection shows that they are very different from what would be expected in the close to "business as usual" assumptions of the IS92a scenario. The SEI work assumes residential ownership levels of only 20-30% in Europe, Asia and Africa in 2100, despite income levels reaching close to existing OECD levels in even the poorest countries. Moreover, specific energy use is assumed to follow Japanese patterns. More reasonable assumptions for the IS92a scenario would have nearly complete penetration of domestic space cooling outside cool temperate regions at consumption levels intermediate between existing US and Japanese levels. In this event, the technical and cultural differences between the scenarios would contribute a factor 10 increase in energy demand for domestic space cooling.

In the commercial sector, the IS92d scenario assumption is that space cooling takes a constant share of electricity demand over the period. With increasing penetration of air conditioned buildings, higher cooling loads and less rapid compensating efficiency improvements, the share is judged more likely to double in the conditions of the IS92a scenario.

The combined effect of these technical and social differences between scenarios is likely to produce a factor 5 increase in energy demand for space cooling by 2100 in the IS92a scenario over the IS92d scenario. This is equivalent to an AEEI which is lower by 1.5%/year. Recalling that the IS92d AEEI for cooling is 1.2%/year this implies a negative AEEI of 0.3%/year in the IS92a scenario. In other words the space cooling energy demand grows at a rate modestly higher than proportional to population and income. In view of existing trends, this assumption does not seem unreasonable, and therefore is used in the impact calculations.

Total energy use for space heating grows by a factor of about three over the period 1990-2100 in the IS92a reference, in contrast to the IS92d scenario in which space heating energy use is virtually the same at the end of the period. The difference stems largely from the larger population in the IS92a scenario and the reduced rate of technological and environmental improvement, which results in lower energy efficiency. Total energy use for space cooling grows by a factor of about 17 over the period 1990-2100, in contrast to the results of the IS92d scenario (a factor of 2.5 growth). The difference between the scenarios in the year 2100 is therefore a factor of 7, due to the larger population in the IS92a scenario and the reduced rate of technological and environmental improvement, which results in lower energy efficiency. This does not imply that the technical efficiency of cooling falls, rather that the social trends towards greater use of air conditioning outweigh the technical improvements This factor far exceeds that for the difference in primary energy consumption between the scenarios, reflecting the fact that space cooling is a "discretionary" demand sensitive to scenario assumptions.

For space heating, it is assumed that demand in proportional to the heating degree days (base 15°C). For space cooling, it is assumed that both the market penetration of cooling equipment and the specific energy demand in operation are proportional to the cooling degree days (base 20°C).

Results for heating benefits and cooling costs

Table 7 presents the costs of climate change for changes in heating demand supplied from fuel (oil, gas and coal) and electricity. Warming would reduce the amount of heating required, therefore the numbers are negative costs, or benefits. Figure 12 shows the cumulative cost of heating, where the value in 2100 is the total projected benefit from 1990 to 2100 without discounting.

The cumulative heating benefit is almost $40,000,000M for the IS92a-medium scenario, with a range from an order of magnitude less to 5 times greater. In comparison, the benefits of the IS92d scenarios are much lower, about one-fourth of the benefits of the IS92a scenario in the medium estimate. The chief differences between the two scenarios are the differences in population and specific energy efficiency, with a smaller effect due to lower energy prices.

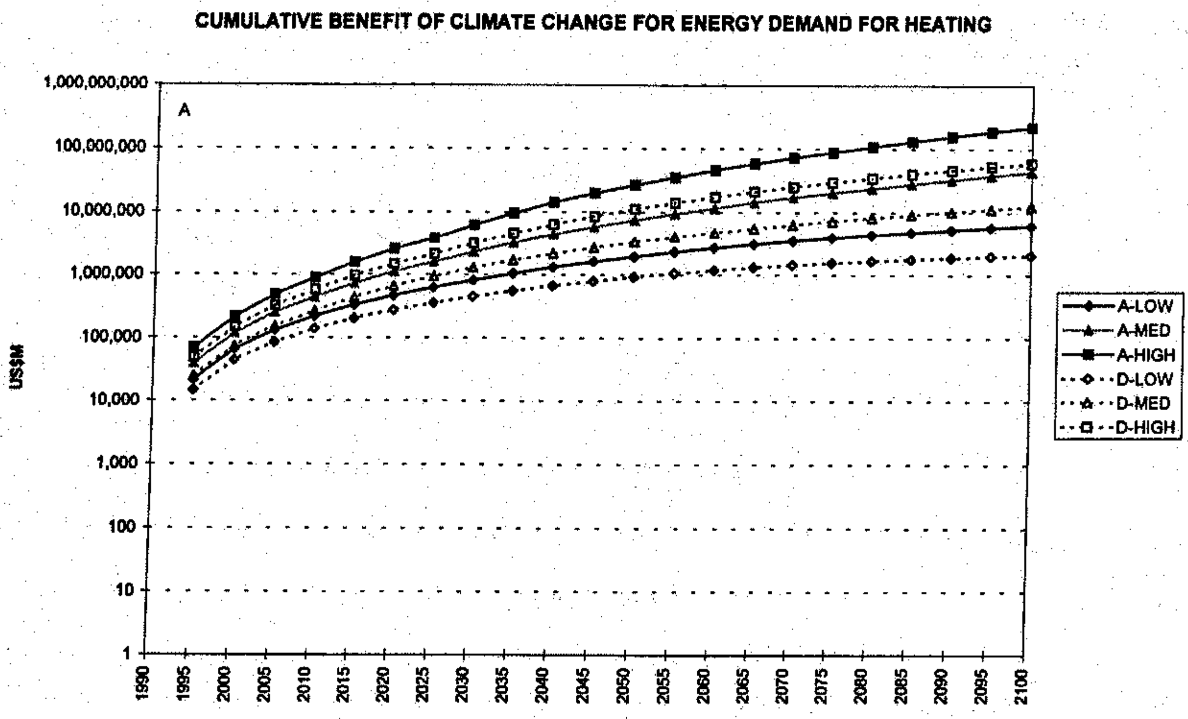
Table 7 also shows the results for the increased cooling costs associated with global warming. The medium estimate for the IS92a scenario is over $25,000,000M, almost an order of magnitude greater than the IS92d scenario. The increased cooling demand is much less than the heating benefits, implying that the aggregate cost of climate change on energy demand would be positive. With such large benefits from heating, further economic analysis of the price of energy would be warranted. The saving in fuel would lead to lower prices. These are estimates of the direct costs, and not impacts associated with greater heat stress.

The net effect is a significant savings with energy demand for space heating dominating the costs associated with cooling.

Table 7. Cumulative Cost of Climate Change for Space Heating and Cooling Demand, $M

	Unit	1990	2000	2010	2025	2050	2075	2100
Heating: Fuel								
A-LOW	$M	0	-22,772	-80,207	-248,062	-838,728	-1,759,329	-2,932,555
A-MED	$M	0	-40,971	-161,613	-660,232	-3,338,369	-9,555,334	-21,735,842
A-HIGH	$M	0	-76,407	-349,524	-1,720,155	-13,829,660	-46,196,695	-115,748,903
D-LOW	$M	0	-15,089	-49,611	-136,356	-373,206	-646,697	-891,885
D-MED	$M	0	-26,377	-94,295	-364,478	-1,360,802	-3,057,800	-5,567,564
D-HIGH	$M	0	-52,198	-217,093	-898,876	-5,197,261	-14,111,789	-28,596,860
Heating: Elec.								
A-LOW	$M	0	-42,868	-138,126	-372,950	-1,134,110	-2,179,009	-3,299,835
A-MED	$M	0	-77,248	-276,977	-928,069	-4,127,676	-10,753,879	-22,058,273
A-HIGH	$M	0	-134,877	-535,816	-2,085,871	-13,112,094	-41,937,876	-103,858,366
D-LOW	$M	0	-29,036	-88,695	-218,875	-556,589	-917,188	-1,202,332
D-MED	$M	0	-48,907	-169,301	-574,493	-1,985,207	-4,173,587	-7,001,632
D-HIGH	$M	0	-95,725	-355,694	-1,227,233	-5,974,214	-15,666,669	-31,479,164
Cooling: Elec.								
A-LOW	$M	0	17,629	65,225	221,710	925,639	2,104,843	3,701,172
A-MED	$M	0	34,895	145,038	629,136	3,946,498	12,283,050	30,239,195
A-HIGH	$M	0	70,139	325,746	1,663,839	15,003,228	56,783,567	169,365,045
D-LOW	$M	0	10,419	34,470	96,556	282,119	489,670	662,519
D-MED	$M	0	20,763	76,611	259,047	1,068,287	2,425,273	4,275,939
D-HIGH	$M	0	41,542	169,045	679,867	3,886,700	10,596,409	22,106,111
Total Energy								
A-LOW	$M	0	-48,011	-153,107	-399,302	-1,047,199	-1,833,495	-2,531,218
A-MED	$M	0	-83,323	-293,552	-959,165	-3,519,547	-8,026,163	-13,554,920
A-HIGH	$M	0	-141,145	-559,595	-2,142,188	-11,938,526	-31,351,003	-50,242,225
D-LOW	$M	0	-33,706	-103,836	-258,675	-647,675	-1,074,214	-1,431,697
D-MED	$M	0	-54,521	-186,986	-679,925	-2,277,722	-4,806,114	-8,293,257
D-HIGH	$M	0	-106,381	-403,743	-1,446,242	-7,284,775	-19,182,049	-37,969,914

Notes: Negative numbers indicate benefits. The two heating estimates refer to different energy sources: coal and gas (fuel) and electricity. Cumulative totals are slightly different from sectoral NPV for 0% discount rate due to interpolation and rounding errors.



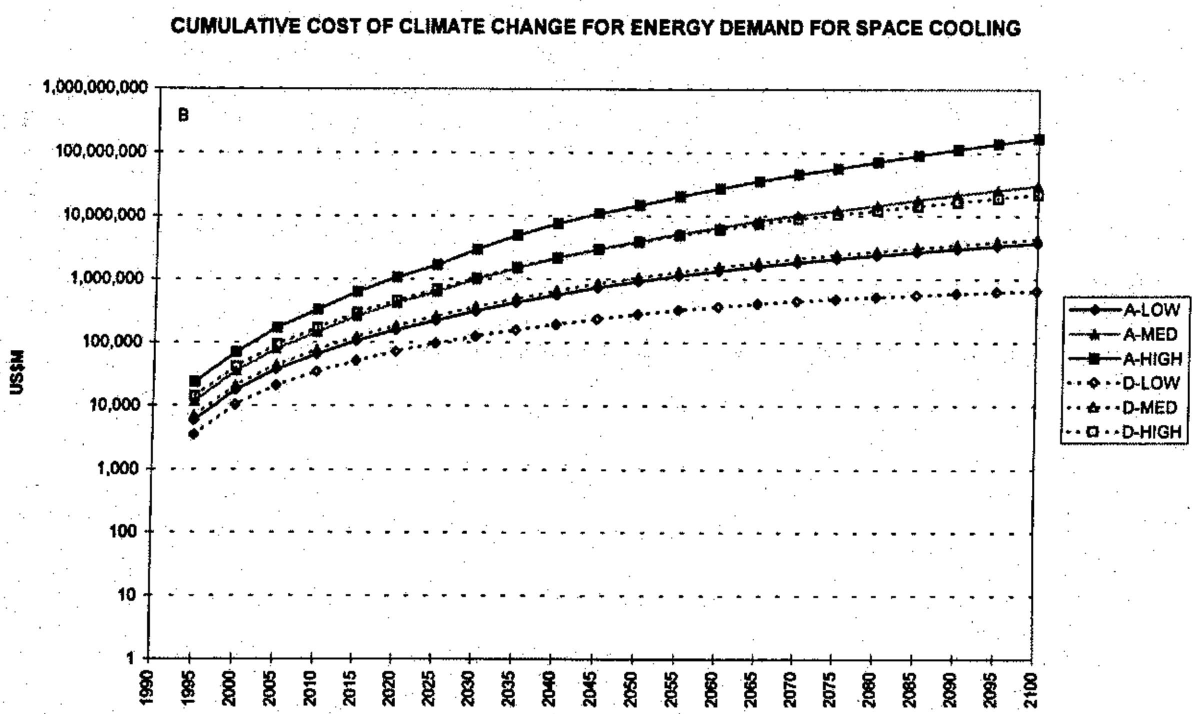


Figure 12. Cumulative Costs of Climate Change for Heating and Cooling. (a) Heating from Fuel and Electricity; (b) Cooling.

6. Impact on Agriculture

Methodology and assumptions

Agriculture is highly sensitive to climatic fluctuations, at least in the short term. The most critical factors are temperature, precipitation, solar radiation, and CO_2 concentration. Increased temperatures expand the limits of agriculture toward the poles and higher elevations. Increased solar radiation enhances prospects for photosynthesis. Higher concentrations of CO_2 increase the rate of photosynthesis and improve water use efficiency in all crops, but to differing degrees. The beneficial effects may be limited by nutrient and water stress. A key uncertainty is whether precipitation will compensate for increased evaporative demand, or even decrease.

It is likely that agricultural impacts will be varied – with increases in productive potential at northern mid-latitudes and increased drought stress in drier regions. However, agriculture has the ability to adapt to new conditions through new crops, switch in cultivars, and improved agronomic management. This is particularly so for the IS92d scenario, where incomes are higher and climate change is less rapid or severe than in a business as usual scenario. Between regions, trade can compensate for local deficits in production, although with some cost and depending on the ability of consumers to purchase imported products. Thus, economic analysis of agriculture is more complex than for energy demand or water resources because of the close relationship between supply and price and the linkages between supply and demand in different regions.

Valuing the impact of climate change (or climatic variations for that matter) on agriculture is difficult. To compile a robust assessment of global impacts four steps are essential:

1. Delineate current and future agricultural area, including the effects of markets, technology and climate change.

2. Estimate changes in yields due to markets, technology and climate change.

3. Estimate changes in production, the area cultivated multiplied by yields.

4. Value the changes in production, accounting for local and international trade and the different effects on producers and consumers.

Global studies with this sort of rigour have not been published. A fundamental problem is calculation of global changes in welfare for commodities that are traded. To what extent should a change in production in the US, for example, be counted as a decrease in consumer welfare in Egypt or other countries highly dependent on food imports? If global prices increase, how should the implied change in producer welfare, consumer welfare and investment be counted? In most sectoral models, the effect of increased prices on other sectors is not modelled. This is a central issue for economic evaluation of climate change. Rather than counting costs for individual sectors, what are the costs of shifts in internal rates of return, risk premia and patterns of regional investment?

The two major studies (including their many versions) provide some insight into the sensitivity of agriculture to climate change. Both used the same scenarios of yield changes, without explicit modelling of the agricultural area. Both have relatively disaggregated regional representations: over thirty countries or world regions are included.

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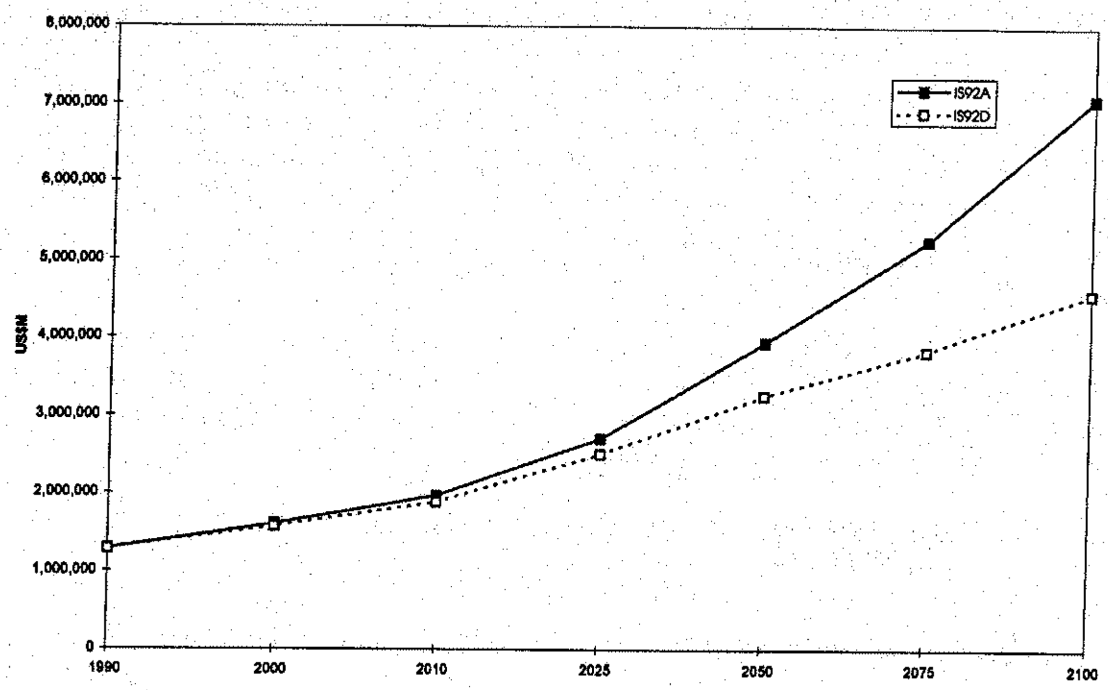

Figure 13. Projected Gross World Product in Agriculture

The first-order impact model used in this study provides a broad assessment of agricultural sensitivity to climate change based on the area suitable for rainfed agriculture. The index has been applied in climate change studies to delineate natural vegetation from agricultural areas (Hendersen-Sellers and McGuffie, 1994). It is relatively simple to compute at the global level, comprising two dimensions:

- Biotemperature between 5°C and 25°C, where biotemperature is the accumulation of monthly mean temperature over 0°C divided by 12 (the number of months); and
- Precipitation greater than 500 mm per year and less than 2500 mm per year.

For economic analysis, the most appropriate indicator to link to the first-order impact model is the change in the total area suitable for agriculture in each country. This assumes that yields can be maintained if agricultural land is still available. The resulting map of present agricultural suitability matches world vegetation models such as Prentice *et al.* (1992) to delineate the world's zones of major production. With climate change, the balance of increased temperatures and varied precipitation tends to lead to a poleward expansion of agriculture and some retreat in drier areas. This closely matches the conclusions of the IPCC (Tegart *et al.* 1990; Watson *et al.* 1996).

Because of the many determinants of agriculture, we have adopted a wide range of estimates of the sensitivity of changes in the agricultural component of GNP to changes in the area suitable for agriculture in each country (Table 8). The medium case assumes that there is a strong relationship between the area suitable for agriculture and its value in the national economy. That is, the effect of climate change will be reflected in expanding or shrinking areas suitable for intensive agriculture, leaving unspecified what would be the optimum crop combinations for future climates.

For the low estimate, the relationship between the area suitable for agriculture and its value in the economy is considered to be weak. The negative impacts are assumed to be ameliorated by the beneficial effects of carbon dioxide enrichment and adaptive responses with little economic costs. On the other hand, the high estimate of costs assumes that large decreases in suitability are not compensated for by agricultural technology, irrigation or other means. Thus, for example, if the area suitable for agriculture decreases 20% (given the projected climate change in a specific country), then, in the medium case, the decrease in agricultural GNP is assumed to be half of 20%, or 10% over the reference period to the year 2100. Or, in the low case, agricultural GNP would decrease by only one-tenth of 20%, or 2% between 1990 and 2100. These assumptions are global, although there is some argument for regional differences. For example, African agricultural technology may be less adaptive than agriculture in the OECD. At the global aggregate level, this is not likely to make much difference.

The resulting proportions are then applied to the agricultural component of GNP in each country. The estimates are annualised using the annual estimates of temperature rise. The differences between the IS92a and IS92d scenarios result from different impacts on global climate and national agricultural suitability and different growth rates of agricultural GNP.

Table 8. Assumptions Regarding Agriculture and Water Resources

	Unit	Low	Medium	High
Agriculture				
Sensitivity of agricultural GNP to first-order agricultural index				
IS92a or IS92d	%	10%	50%	90%
Water Resources				
Water deficit elasticity of supply (α_d):				
IS92a		0.00	-0.10	-0.20
IS92d		0.00	-0.10	-0.20
Water deficit elasticity of demand (α_d):				
IS92a		0.10	0.30	0.50
IS92d		0.10	0.30	0.50
Income elasticity of supply (β_s)				
IS92a		0.50	0.25	0.00
IS92d		0.40	0.20	0.00
Income elasticity of demand (β_d)				
IS92a		0.50	0.60	0.70
IS92d		0.40	0.50	0.60
Price elasticity of supply (ε_s)				
IS92a		0.65	0.33	0.00
IS92d		0.60	0.30	0.00
Price elasticity of demand (ε_d)				
IS92a		-0.65	-0.45	-0.25
IS92d		-0.60	-0.40	-0.20

Notes: 1990 Water prices for individual countries are used where available; world price is a global average for other countries.

Results

For each scenario, the global effect of climate change on agriculture is a cost. For the medium case of the IS92a and IS92d scenarios, the costs are about $500,000M, although the IS92a scenario is 50% larger (Table 9 and Figure 14). This is primarily due to the greater warming and higher demand for agriculture in the IS92a scenario. The low estimates of impacts are negligible, less than $100,000M. Even the high estimates are also relatively modest in comparison with other sectors.

Table 9. Cumulative Cost of Climate Change for Agriculture

	Unit	1990	2000	2010	2025	2050	2075	2100
A-LOW	$M	0	633	1,767	5,215	18,044	41,740	84,269
A-MED	$M	0	2,743	8,139	25,263	92,386	220,086	453,890
A-HIGH	$M	0	3,113	10,841	38,557	160,737	406,003	873,484
D-LOW	$M	0	783	2,101	5,702	16,526	30,698	50,238
D-MED	$M	0	3,965	11,126	31,536	96,248	185,226	311,355
D-HIGH	$M	0	5,492	16,670	51,088	172,234	351,264	616,080

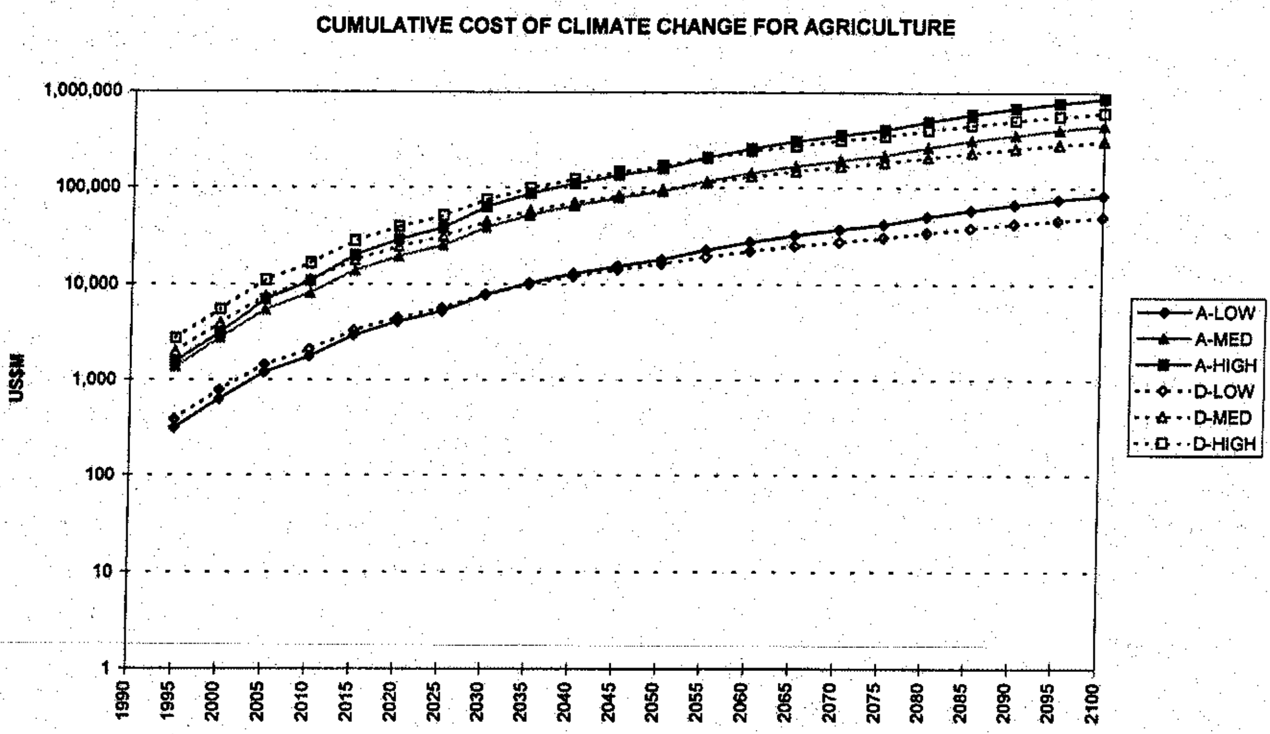

Figure 14. Cumulative Cost of Climate Change for Agriculture.

7. Impact on Water Resources

Methodology and assumptions

The supply of water resources is quite uneven across the world, as is water use per capita. Water surpluses and deficits delineate the major hydrological regimes of the world. For example, the Congo River basin in Africa is a region of great water surpluses, while the semi-arid fringe of the Sahara is chronically short of water.

Global climate change will affect both supply and demand for water. The balance of precipitation and atmospheric demand for moisture (potential evapotranspiration, PET) is directly related both to the long-term availability and to the use of water for domestic, municipal, industrial and recreational use. Sea level rise would affect some aquifers and management of some river basins. However, global data on salt water intrusion and coastal water resources are not available. The impacts would amplify the costs shown under coastal protection above. Some of these uncertainties are captured in the "other sectors".

The impact measure for modelling the effect of climate change on water resources is based upon precipitation (P) minus potential evapotranspiration (PET). PET is calculated based on the Thornthwaite equation, modified to correct for overestimates at poleward latitudes. Mean monthly temperature is the primary variable in the Thornthwaite equation, making it suitable for broad-scale analyses and amenable to climate change impact studies.

The balance of monthly P-PET is accumulated over the year, providing annual estimates of water surpluses (months where P exceeds PET) and water deficits (PET exceeds P). As for energy demand, the index is weighted by the geographic area affected. The outcome is an index measuring the percentage change in water deficit for each country between 1990 and 2100.

Scenarios of climate change alter both P and PET (through the effect of temperature). In many places, water surpluses are reduced and water deficits are increased with the effects of climate change. However, where precipitation increases above the increase in PET, water resources will benefit from climate change. For example, northern Europe tends to get wetter and southern Europe drier with many GCM scenarios.

The current rates of water withdrawal by country have been taken from per-capita rates quoted by Gleick (1993). An increase in the net water deficit would be expected to exert an upward pressure on the demand for water, and a downward pressure on the supply of water. The extent to which the supply will decrease (proportionally) and the demand increase (proportionally) has been assumed to be related in a linear way to the net water deficit index (the percentage change in the area experiencing water deficit less the percentage change in the area experiencing water surplus).

There is clearly considerable uncertainty as to how sensitive these two quantities will be to the net deficit index (Table 8). Thus, for example, if the net water deficit index is 20% over the reference period to the year 2100 (indicating a 20% increase in net water deficit), then in the medium case, the decrease in the water supply is assumed to be 2%, and the increase in water demand is assumed to be 6% (given constant price and income). The price would then adjust in order to bring demand and supply into line.

The current water prices by country have been taken from Gleick (1993) (where quoted), largely reflecting charges by water utilities in market economies. The average value globally is $0.55 per cubic metre, and this value has been used for countries where there is no data. Fankhauser (1992) used much lower values for middle and low income countries. These assumptions are not justified by the price levels quoted by Gleick. It could also be argued that the implicit cost of water in many third world countries is high. It is often the case that poorer people living in remote areas have to expend large amounts of time and energy in order to obtain water.

The change in prices over the reference period will respond both to supply and to demand in each country. The global supply will change by a small amount (less than 2%), while the demand will change in response to the assumed increases in aggregate income in the IS92a and IS92d scenarios, and to changes in price.

This analysis proceeds from the assumption that both supply and demand will respond to the net water deficit, the average income, and the water price according to constant elasticities. This means that the percentage change in either supply or demand is simply proportional to the percentage change in water deficit, income and price, the effects being added together.

The assumption of constant elasticities is a standard economic approach. In this context, this is equivalent to an assumption that the underlying perceptions of the relative value of water resources will not change significantly during the next century. Within the ranges used, this assumption should be reasonably robust, although it should be borne in mind that this is not more than a projection of current social valuations into the future.

In equation form, the quantity supplied (Q) is related to the water deficit index (W), the income (Y) and the price (P) by the relation:

$$\frac{\Delta Q}{Q} = \alpha_s \frac{\Delta W}{W} + \beta_s \frac{\Delta Y}{Y} + \varepsilon_s \frac{\Delta P}{P}$$

where Δ means "change", α_S is the water deficit elasticity of supply, β_s is the income elasticity of supply, and ε_s is the price elasticity of supply.

The quantity demanded (Q) is related to the water deficit index (W), the income (Y) and the price (P) by the relation:

$$\frac{\Delta Q}{Q} = \alpha_d \frac{\Delta W}{W} + \beta_d \frac{\Delta Y}{Y} + \varepsilon_d \frac{\Delta P}{P}$$

where α_d is the water deficit elasticity of demand, β_d is the income elasticity of demand, and ε_d is the price elasticity of demand.

The change in the total value demanded is given by:

$$\frac{\Delta(P.Q)}{(P.Q)} = \frac{\Delta P}{P} + \frac{\Delta Q}{Q}$$

Combining the above three equations to solve for the total change in value demanded, we get:

$$\Delta(P.Q) = (P.Q)\left\{\left[\alpha_d - \frac{(1+\varepsilon_d)(\alpha_d - \alpha_s)}{(\varepsilon_d - \varepsilon_s)}\right]\frac{\Delta W}{W} + \left[\beta_d - \frac{(1+\varepsilon_d)(\beta_d - \beta_s)}{(\varepsilon_d - \varepsilon_s)}\right]\frac{\Delta Y}{Y}\right\}$$

Hence, the change in total value can be calculated from the proportional change in aggregate income (from the scenario assumptions) and the proportional change in the total water withdrawal (from the net water deficit index).

The term involving Y alone corresponds to the change in value of water use resulting from the scenario assumptions, but not including the effect of climate change. The term involving W gives the effect of climate change, and these are the results which have been quoted.

The sensitivity to these two changes is determined by the long run income and price elasticities, and by the sensitivity of supply and demand to the water deficit index. Note that the quantities α_s and ε_d are both negative. In the case of inelastic demand (i.e. when ε is between 0 and -1), the *value* demanded will actually increase when the water deficit increases, even though the *quantity* demanded will fall. This is because inelastic demand will cause a large price rise.

A cross-sectional analysis between countries of the per capita water withdrawal and per capita GNP indicates an appropriate value for the income elasticity of 0.56, and for the price elasticity of -0.43. This is likely to vary somewhat from country to country however, and it seems prudent to take a range of possible values around these. It would also be expected that both the income and price elasticities would be lower in a richer world (i.e. the IS92d scenario). The values used are shown in Table 8.

Results

The cumulative cost of climate change for water resources varies considerably between the low, medium and high estimates, by over four orders of magnitude (Table 10 and Figure 15). This reflects the sensitivity of water use to both supply and demand variables. The IS92a scenario is more costly, reflecting higher demand with more people, and larger impacts on water supplies. The IS92d scenario, however, also has significant damages, in part due to the higher per capita incomes. While these costs may be large in the high estimate, none of the estimates include the indirect or welfare values of water as an amenity.

Table 10. Cumulative Cost of Climate Change for Water Resources

	Unit	1990	2000	2010	2025	2050	2075	2100
A-LOW	$M	0	12	26	59	136	246	395
A-MED	$M	0	80	207	555	1,509	3,159	6,010
A-HIGH	$M	0	699	3,391	26,047	285,533	2,816,357	29,721,760
D-LOW	$M	0	11	25	51	103	156	212
D-MED	$M	0	83	210	526	1,235	2,109	3,257
D-HIGH	$M	0	877	4,481	37,734	379,062	2,928,947	23,532,265

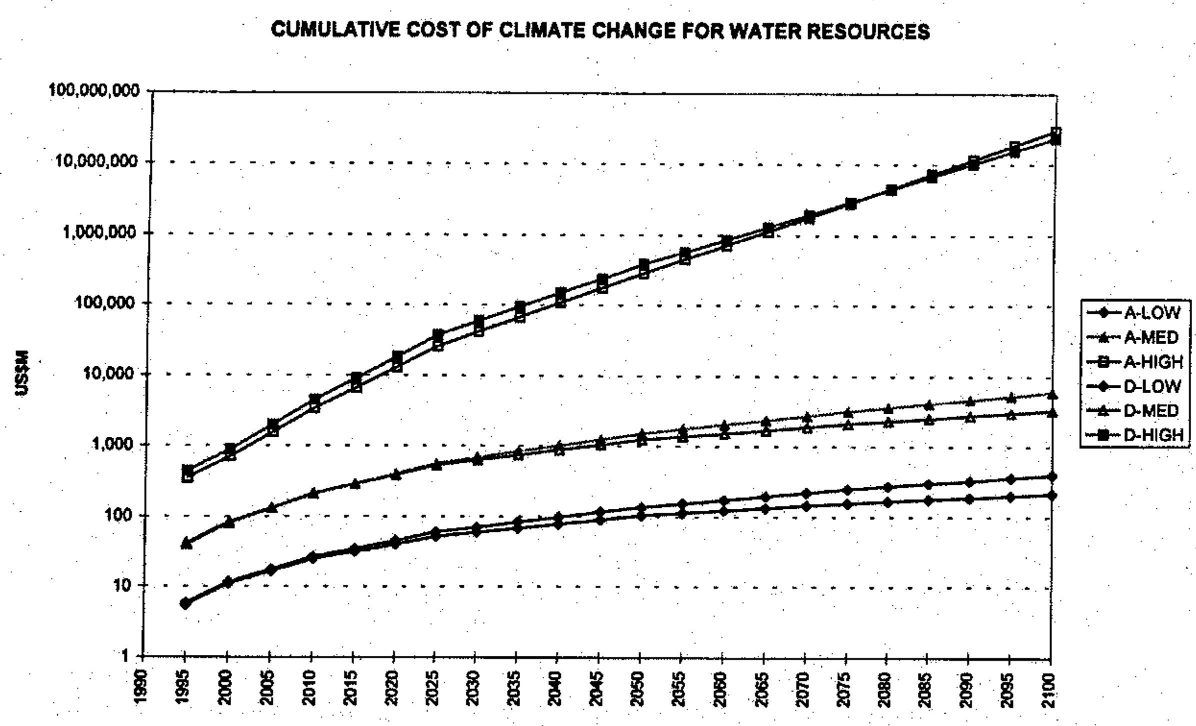

Figure 15. Cumulative Cost of Climate Change for Water Resources.

8. Impact on Biodiversity

Background to economic valuation of ecosystems

Changes in habitat due to temperature change, or to the loss of habitat such as coastal wetlands may lead to the reduction, or even extinction of species. Biodiversity changes tend to happen on a longer time scale than the forecasts for climate change. As habitats change or relocate, the species which inhabit them may not be able to follow sufficiently quickly. It is therefore extremely unlikely that there will be any increase in biodiversity as a result of climate change.

Since loss of biodiversity is one of the largest impacts of climate change, this section reviews the literature and state-of-the-art. The analytical methods adopted below, however, follow the approach suggested by Fankhauser (1992) and others. While this species-oriented approach is unsatisfactory, there does not yet exist a more robust data base and valuation methodology that will reduce the uncertainty regarding biodiversity values and losses due to climate change.

There is now a considerable literature on the economic value of ecosystems (for example, Pearce and Moran, 1994, Barbier *et al.*, 1994, UNEP, 1995). Much is devoted to valuation studies of individual areas, systems or species, usually using the contingent valuation method (CVM). The remainder is more theoretical and, perhaps inevitably, indicates all the problems involved in valuing such complex and poorly understood systems, thereby shedding doubt on the usefulness of those studies which do exist. They are representative of two schools of thought, generally known as environmental economics and ecological economics respectively. However, any approach to valuing ecosystems is controversial.

A conventional approach to natural resource valuation in environmental economics (e.g. Pearce *et al.*, 1989) distinguishes between different types of economic value, so that the total economic value (TEV) of the resource is given by:

$$TEV = UV + OV + EV$$

where UV is the use value of the resource, both direct and indirect,
OV is the option value, that is the willingness to pay (WTP) to have future use of the resource, and
EV is existence value, that is the value not related to any direct economic use.

In principle, there is no reason this taxonomy does not apply to natural ecosystems, and contrasting recent texts on the valuation of biodiversity use the approach (Pearce and Moran, 1994; Barbier *et al.*, 1994).

However, there are various problems in applying the approach to natural ecosystems. First, ecosystems are highly complex providing a large number of services, most of which are not fully understood. Secondly, ecosystems cannot simply be valued reductively as the sum of its component parts. The various life support systems provided by ecosystems are generally neglected, and therefore conventional economic valuations are underestimates (Pearce and Moran, 1994). Moreover, it is the diversity of the system which is widely believed to be critical to its resilience, and therefore its value in providing these functions under stress. It has been argued (Barbier *et al.*, 1994) that there is a total primary value (TPV) of the system which exceeds the TEV, because of synergies between the different characteristics in providing these services.

Neglecting these concerns, valuation may be achieved by summing use, option and existence values. It is widely agreed that option and existence values of ecosystems are difficult to establish, given the very limited state of knowledge we have of most systems. Most attention is therefore paid to use values.

One analysis of ecosystem characteristics and the way they relate to economic analysis is sketched in Table 11 (Barbier *et al.*, 1994). In current economic practice it is usually the stocks, such as timber, which are generally the economic motive for development of ecosystems - a sort of "natural asset stripping". As a result the use of natural ecosystems is frequently unsustainable. In a sustainable development (i.e. one where the options of future generations are not compromised), the assets are held constant, at least in total value. It is therefore the environmental functions which are the facets of use value in this development mode. Many of these services are often unpriced, but not of no value. It is the valuation of these functions which is difficult, but critical to an understanding of the real value of ecosystems.

Table 11. Ecosystem Components and Economic Valuation

General description	Ecological description	Economic description
Stocks	Components	Assets
Flows	Environmental functions	Services
Organisation	Diversity	Attributes

Source: after Barbier *et al.* (1994).

This classification of ecosystem characteristics help explain the important, but complex, role of diversity in ecosystem valuation. Similarly, the environmental functions generated by an ecosystem are a complex property of it organisational structure and diversity. Under conditions of environmental stress (such as those potentially produced by rapid climate change) an ecosystem could conceivably collapse. In both cases, it is the system resilience which is critical to the ability of the system to adapt and maintain value under stress.

Whilst this approach gives a useful way of thinking about the value of biodiversity, it is does not provide any easy quantitative solution to problems of valuation. The diversity only has use value (as opposed to existence value) because of its role in reducing the risk of system failure. Biodiversity valuation therefore necessarily requires ecosystem function valuation, coupled to risk analysis.

There are a large number of ecosystem functions. One list sub-divides the functions into production, carrier, information and regulation functions (Barbier *et al.*, 1994). Production functions generate resources of direct use to human beings; carrier functions provide the physical space and suitable conditions for various activities; information functions provide a variety of information benefits; regulation benefits concern the operation of a wide range of biogeochemical cycles (Table 12).

Table 12. Ecosystem Functions

Production Generate direct uses	Carrier Provide physical space	Information Provide indirect benefits	Regulation Operate biogeochemical cycles
Oxygen	Human habitation	Aesthetic	Climate
Food	Agriculture	Spiritual	Watershed
Water	Forestry	Artistic	Soil
Fabrics	Fishing	Scientific	Waste recycling
Building materials	Industry	Other	Organic matter cycling
Fuel	Infrastructure		Mineral nutrient cycling
Minerals	Recreation		Biological control
Medicines	Nature conservation		Genetic diversity control
Genetic materials			

Source: Barbier *et al.* (1994)

It is clear that the valuation is increasingly difficult as we move from left to right across the table. Resources produced by ecosystems are usually traded in markets and, where they are not (e.g. water, oxygen), other valuation techniques can be applied. The conditions appropriate for the variety of activities supported by carrier functions are not usually priced and often are difficult to separate from related production functions of the system. Information may have some (usually small) existence value, but the potentially larger use benefits are in the future and, by definition, not quantifiable. Some of the information "uses" are of debatable instrumental value, and arguably the subject of existence values. The regulation benefits are the most problematic. In many cases, they concern crucial life support systems, which are invariably unpriced, but obviously very valuable. It is these benefits, rather than the more commonly understood production functions which are potentially the largest particularly under conditions of rapid system change, where "shortages" of these functions could occur.

The total use value of an ecosystem should include all the aspects listed above and any synergies between them. This is rarely achieved in practice, so that published values are expected to be partial summations, and therefore less than the total use value. Where important regulation functions are omitted, the values may be significantly underestimated.

In the context of climate change impacts, the total value is of interest for systems that are likely to disappear, such as wetlands and small islands liable to marine flooding, montane and polar ecosystems, and fragile nature reserves encapsulated in other land uses that prevent their migration. In other cases, it is the difference in value between the original system and the system produced by climate change which is of greater interest. Marginal changes of this type may be difficult to quantify.

Option and existence values are introduced into the calculus of environmental economics to take account of the fact that humans value things which are not instrumentally useful to them, and therefore do not improve their welfare in any easily measurable way. There are some criticisms of the this concept - essentially that these values are not the business of economic analysis. However, it is clear that if wider human concerns about the natural environment are to be introduced directly into economic analysis, some valuation along these lines is required.

Non-instrumental values are difficult to measure. Ecosystem existence is a classic public good – if they exist for one individual, they exist for us all – and therefore cannot be sold in conventional markets. Environmental economists generally measure these values using the contingent valuation method (CVM) – essentially a questionnaire-based technique in which people are asked for their willingness to pay (WTP) to preserve a given environmental asset in a hypothetical market. Studies involving individual endangered species are the best known – typically rendering values of a few dollars per person per head for species preservation.

CVM raises theoretical and practical concerns too numerous to consider here. The underlying concerns are that monetary payments for the environment – treating the environment like a package of goods – is both unethical and insufficiently plausible to generate meaningful responses. The meaning of preserving a species outside the context of an ecosystem is not entirely obvious. Large, well known species tend to produce higher valuations than little known, smaller or obnoxious species. What is being valued may be an ephemeral product of the media rather than deeply held environmental ethics. Biodiversity existence value – the number and variety of species as opposed to their characteristics – has never been measured, but is unlikely to be very significant.

CVM is also used to measure total economic value. This has the apparent attraction of circumventing all the problems of measuring the use values of ecosystem functions identified above. However, as an approach to use values, CVM is inappropriate. Markets, whether real or hypothetical, need well informed purchasers if prices are to reflect values accurately. Whilst there may be good information about the existence of various ecosystems, the average CVM respondent has virtually no knowledge of the relevant ecosystem functions, and therefore cannot be expected to value them.

From the argument above it is concluded that ecosystem economic value should be measured as a sum of the existence value (measured by CVM) and a large number of use values, related to different environmental functions. The value of biodiversity is principally related to the latter and the stability of the system under stress. CVM, although contentious, is the only technique for placing an economic value on ecosystem existence. More robust methods are available for valuing specific functions of ecosystems.

Ecosystems are likely to be severely affected where climate change makes their existing locations unsuitable and isolation prevents ecosystem migration. Obvious examples are montane and island ecosystems. In general, these occupy rather small areas and, certainly compared to tropical rain forests, they have rather low genetic diversity. On the other hand they are highly specialised - many small areas contain large number of unique species. In many cases, because they exist in relatively inhospitable areas, the system may have limited resilience.

Valuation of these types of systems is problematic since they are so diverse. Productive use values are probably relatively small, but recreational values may be high. A study of the unique Galapagos ecosystems indicate a use value of $600/ha, but, as usual, this omitted regulation use values. For a globally important area like this, the existence value measured over the world's population may be quite large. Where existence values of important nature conservation sites have been measured, answers can be spectacularly high. For example, a study of the Kakadu nature reserve in Australia implies a value of $1-3M/ha. This is derived from a CVM study, but because of the problems with CVM it is highly improbable that it could be extended to larger areas, and therefore its meaning is not clear.

Forests, as a semi-managed ecosystem, are potentially affected by climate change, because the climatic zones suitable for forest of different types are expected to move as the climate changes. Zones suitable for some forest types, such as tropical rain forests, are expected to expand, although of course other stresses, notably deforestation make it unlikely that this will result in globally increased forest cover. Other forest types, notably sub-tropical and boreal forests, will face reductions in suitable land areas. However, a steady state analysis is misleading. Where the rate of advance of climate zones exceeds the rate of forest migration, forest area at the poleward edge may be unable to occupy the climatically suitable zone. This effect is of particular concern for the boreal forests of northern Eurasia and North America. For these reasons, forest impacts of global warming might be expected to be concentrated in the boreal forests and isolated areas of forest in other regions.

Forest valuation studies tend to have concentrated on the tropical rain forests, because of their high biodiversity, current deforestation rates and interest in financial incentives to developing countries to conserve them. Valuation have again concentrated on productive and recreational values, which are obviously different from those of boreal forests. Recreational benefits studies of forests have focused on heavily used locations and are not generally applicable to the vast tracts of forest in Canada and Siberia.

However, it is clear that carbon fixing is a significant component and, because this is a global benefit, it is transferable. Some authors (e.g. Pearce and Moran, 1994) ascribe a value to carbon fixing. In the context of our study of global warming damage costs this would clearly be illogical. The value of carbon fixing is an output of our study not an input to it. However, net changes in forest area are part of the emission scenarios.

To implement a methodology based on the value of ecosystems would require a typology of major world ecosystems, their sensitivity to climate change (both the area changed, area remaining and quality of the ecosystem), and damage functions that relate ecosystem changes to values for their direct use, option use and existence value. As reviewed above, some of these estimates have been attempted, but they are not sufficiently well-established to provide a global estimate of ecosystem value (see UNEP, 1995). Also, modelling ecosystem changes is at a relatively early stage. While equilibrium models such as the Biome model assess changes in the areal distribution of biomes, they do not provide a good indication of ecosystem quality or the primary products that may be available. Given this state of affairs, the project adopted the existing approach to biodiversity valuation.

Methodology and assumptions

Despite theoretical frameworks, there is very little information upon which to base quantitative estimates of the extent of biodiversity or species loss. Previous studies have estimated the costs due to loss of biodiversity based upon a list of species presently at risk of extinction (from the World Resources Institute, 1990). The global sum of such species is about 5,200 endangered species at present, out of a total of possibly 30 million species (UNEP, 1995). It is not clear that the species on this list are those which will be threatened by global climate change in particular. Nevertheless, Fankhauser (1992) used this list as a starting point, adding an assumption about the proportion of these species which would be forced to extinction as a result of climate change. He assumed a 2% loss, based on the $2xCO_2$ scenario. Some current estimates suggest that the current rate of species loss is some 0.2% per year of all species in existence, or about 20% over the reference period for this study. This amounts, by the above estimate, to some 60,000 species lost per year, an order of magnitude higher than the specified number of endangered species. This discrepancy arises from difference in estimating the total number of species on Earth, as opposed to the total known species. Set in this context, Fankhauser's assumption that only 2% of the now endangered species would be lost as a result of equilibrium climate change seems very conservative.

The approach taken is to expressly project the frequency of climatic hazards, average property damages, and average lives lost per event. This was done at the global-average level, although disasters are local events. As a first attempt to systematically estimate disaster costs, it was not deemed warranted to make detailed country estimates.

Various sources are used. The two most thorough global data bases of disaster events are the listings maintained by Centre for Research on the Epidemiology of Disasters (CRED) (cited in IFRCRCS 1993) and the US Office of Foreign Disaster Assistance (M. Dilley, personal communication). These have been supplemented by reports from the Red Cross (IFRCRCS, 1993), Munich Re (e.g., 1993), and other sources. The global prevalence of climate-related disasters is shown in Appendix 4. The list of disasters follows conventions used by CRED. Disasters not directly related to climatic triggers are not included (e.g. earthquakes). Changes in temperature affect avalanches, cold waves and (in the opposite direction) heat waves. Related to water resources are: insect infestations, fire, drought, flood, landslide, and food shortage and famine. Storms include cyclones, hurricanes, and typhoons. Finally, complex disasters that are less directly related to climatic extremes are: civil strife, displaced persons, and epidemics.

To project the average cost of disasters in 2100 without climate change, it is assumed that there would not be any changes in the number or magnitude of climate events. However, property and lives at risk would change. For the low estimate in both the IS92a and IS92d reference scenarios, a reasonable decline in hazardous conditions is assumed – consistent with higher incomes. The largest potential for disaster is in the IS92a world, where economic growth implies greater property at-risk and population growth would lead to more people living in disaster-prone regions.

The value of statistical life reflects a range quoted in the literature. For example, Fankhauser (1992) cites $0.15 to 0.3M for developing countries and $1.5M for developed countries. The EU uses ECU 6M, while transport planning in the UK is based on £750,000 (about $1.125M). There is considerable disagreement as to the valuation of statistical life: whether a global average should be used, how to calculate economic and "human" values, and how to scale values in the future. The range adopted here represents the broad spectrum: $0.5M, $1.5M and $5M for the low, medium and high estimates. The value of a statistical life would be valued more highly in the future, as incomes increase. They are scaled upward according to per capita GNP in this assessment.

Including economic losses and lives lost, the current average annual cost of disasters averages $200,000M, $775,000 and $4,500,000M for the low, medium and high estimates. For the medium case, 10% of the cost is direct economic damages, the remainder reflects the value of statistical life. In the IS92a reference projection (without climate change), the cost of disasters increases substantially for the high estimate: four times the present costs. However, the more likely outcome is a reduction in costs, as more is spent on mitigation. In the low case, the costs could be a tenth of the present costs. The projections are similar for the IS92d scenario, although somewhat lower.

With climate change, the individual climatic events would change in their frequency and magnitude. For each type of disaster a multiplier is chosen for the low, medium and high estimate of the average number of events. Changes in magnitude are assumed to affect the average cost in terms of property damage and lives lost. For cold events, fewer disasters would occur, while the opposite is true for warm events. For water-related episodes and storms, it is possible that fewer events would occur (the low estimate), or a fairly large increase in events and their magnitudes could be realised. The largest increases are for fire and heat waves – a doubling for the high estimate in the IS92a scenario. Most changes for the medium estimate are in the range of 10-15%.

The impact of climate change is then the difference between the reference scenarios and scenarios with climate change. It is important to note that these estimates do not include potential effects on health other than the value of lives lost, impacts (or benefits) on economic systems other than the direct effects, and values for changes in ecosystems. For example, one potential outcome would be such an increase in tropical storms that island resorts would be abandoned as uninsurable and too risky for development. The regional economic effects of this sort of collapse are not included.

Results

The cost of disasters, without climate change, continues to increase, due to greater property at-risk and higher values placed on lives lost with greater per capita wealth. Climate change in 2100 represents a fairly modest fraction of the total cost, for the low and medium estimates (Table 15 and Figure 17). In the IS92a scenario, the medium estimate is for accumulated costs of near $15,000,000M by 2100, an order of magnitude greater than for the IS92d scenario. The potential for catastrophic losses, however, builds up when considering the high estimate in the IS92a scenario. Although this still does not include radical changes in disaster occurrences and costs, the annual average damages could reach $1,000 trillion, or some 7% of accumulated Global World Product (from 1990 to 2100).

Table 15. Cumulative Cost of Climate Change for Disasters

	Unit	1990	2000	2010	2025	2050	2075	2100
A-LOW	$M	0	448	1,711	5,132	14,906	29,772	49,728
A-MED	$M	0	134,227	512,501	1,537,504	4,466,082	8,919,961	14,899,142
A-HIGH	$M	0	9,429,195	36,002,381	108,007,143	313,735,034	626,612,868	1,046,640,645
D-LOW	$M	0	-1,015	-3,874	-11,621	-33,755	-67,418	-112,610
D-MED	$M	0	12,329	47,074	141,223	410,219	819,318	1,368,519
D-HIGH	$M	0	2,103,294	8,030,759	24,092,277	69,982,328	139,773,447	233,465,634

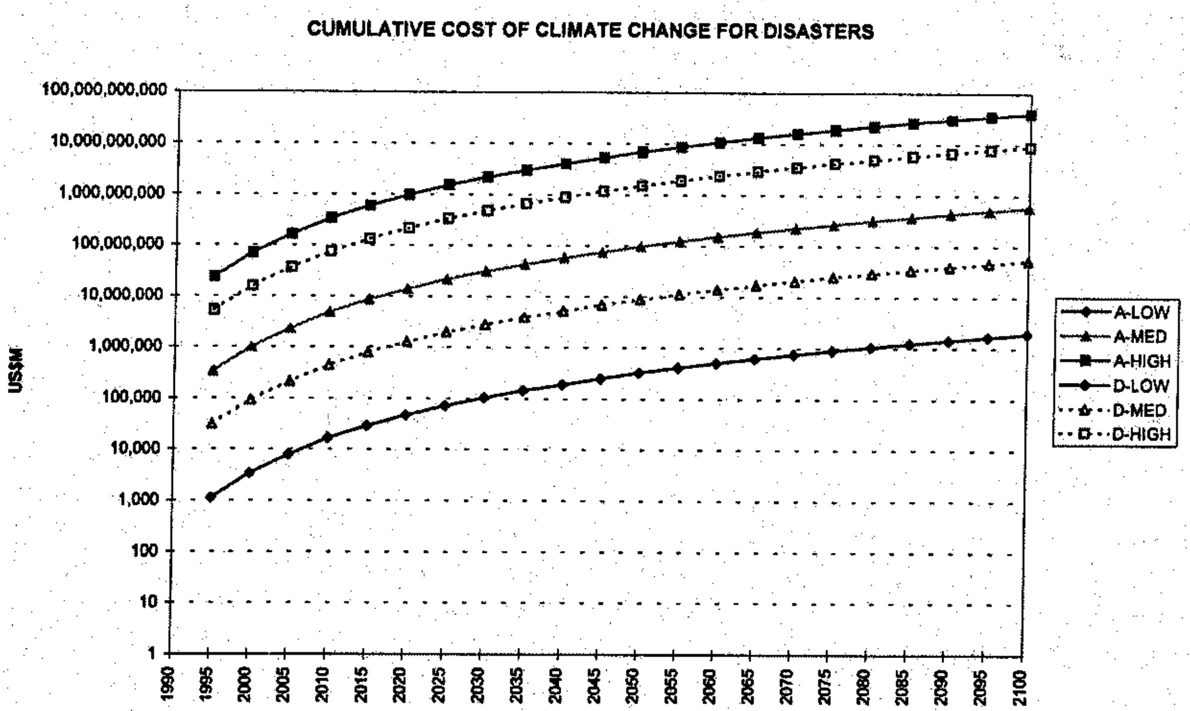

Figure 17. Cumulative Cost of Climate Change for Climate-Related Disasters. Note that the slight benefits in the IS92d-Low scenario are not shown.

10. Impact on Health, Welfare and Other Sectors

In the above sectoral analyses, we sought to review and where possible improve the methods for calculating potential costs of climate change. Specific results are shown for the direct cost sectors -- coastal resources, agriculture and water resources, energy for space heating and cooling -- and for loss of biodiversity and disasters, which require indirect means of economic valuation. The next section summarises these estimates.

However, before presenting a global total, it is important to get a sense of how large the damages might be from sectors not included above. As noted in the introduction, the damages accruing to individual fuel cycles should be calculated on the basis of total potential global costs, not just sectors for which we (or any analysts) find convenient data and methods. This chapter fulfils this requirement. First, we review some of the other potential damages. Then we present a method for scaling from the impacts counted above to a global total that reflects the range of estimates published in the literature. The review of other potential damages is based on the IPCC inventory (Pearce *et al.* 1995).

Other sectors

Effects on coastal resources are counted as direct costs. The loss of amenity as natural coastlines are replaced by engineering structures or as land becomes derelict due to periodic storm surges and erosion are not valued. The amenity changes due to rapid sea level rise could be substantial, as protection structures become more common.

Perhaps the largest uncounted impacts are on human health, related to stress and vector-borne diseases. The benefits accruing through reduced heating costs (implying reduced cold stress) are not directly offset by increased cooling requirements: heating is widespread in developed countries, space cooling is not as common in developing countries. Therefore, large populations would find living conditions are hotter, although they would not be able to benefit from air conditioning in offices, factories, stores, homes and vehicles. This change in welfare could be quite significant. For example, Tol (1994) estimates increased mortality of 215,000 world-wide, valued as $188 billion, over half of his estimate of the total cost of climate change. Increased effects of malaria, yellow fever, dengue fever and other diseases could far exceed the direct health impacts. While some of the direct effects of heat waves are included under natural hazards – widespread changes in mortality and morbidity, and changes in living conditions are not.

For agriculture our evaluation is based on the fraction of agricultural GNP at-risk. This does not include many of the multiplier effects of agricultural development on regional economies. While the effect of drought on food crises is estimated under natural hazards, long-term, recurrent poverty and food deprivation are not. An increase in global food prices and a decrease in local production may further marginalise large populations in developing countries. It does not include fisheries and forests, although some of these costs would be included under the loss of endangered species. The direct changes would be both negative and positive, probably not dramatically affecting the global total. However, the degradation of forests and effects on poverty could be widespread and significant. The secondary effects of loss of agricultural regions (or forest and fishing economies) on migration are not included in this study. The migration estimates provided relate to dryland loss due to sea level rise, not the more widespread loss of regional production systems due to drought and desertification. As for diminishing water resources, significant internal and external social strife would be associated with large-scale migration. Few places in the world would be able to absorb new populations without disruption to existing land tenure and production systems or urban infrastructure and economies.

As for heating and cooling, market changes in water supplies do not cover all of the amenity values associated with water. Widespread changes in the natural and managed landscape due to greater water extraction and restrictions on irrigation would affect regions where water resources decrease. An obvious example would be a decrease in golf courses (or their green areas) in sub-humid regions. Entire landscape cultures of home gardens would change. More importantly, major water resources are shared between countries and are recurrent sources of political conflict (Gleick, 1992; Homer-Dixon *et al.* 1993). Including increased costs of defence, resource transfers between regions, and (if negotiations are unsuccessful) regional wars might be warranted in the economic valuation of climate change.

Above, the effects of climate change on endangered species are valued. However, additional use and option values are likely to be invested in whole ecosystems. As noted above, these costs are impossible to calculate with our present knowledge of ecosystem functions, sensitivity to climate change, and economic valuation techniques.

The effects of natural hazards are based on additional economic costs and lives lost. Even though the resulting numbers are quite large, no attempt has been made to account for the social stress of disasters. In addition, changes in the distribution of hazards would imply widespread changes in some resource activities. Recurrent drought in semi-arid areas would require significant new investment in urban water supplies, increased efficiency of irrigation schemes, and preparedness planning. Individual droughts can be costly: up to 10% of GNP in some developing countries (Benson and Clay, 1994). If such events became more common, the costs could constrain economic investment for large regions.

Some studies have suggested quite widespread changes in tourism as a result of regional changes in climate (e.g., Rotmans *et al.* 1994). Warmer conditions in "home" countries might stem the flow of tourists to warm destinations such as the Mediterranean and Caribbean. Loss of beaches and coral reefs would further deter coastal tourism. Reduced snowfall or a shorter snow season could affect winter tourism in mountain regions. These effects are likely to be regional, to some extent compensated by gains in tourism in other areas. For example, Florida's loss as a major destination might be compensated by a longer season and increased camping, hiking and water sports in the lakes of Minnesota.

Other market sectors would be affected by climate change. Construction may benefit from reduced frost, but be hampered by more heat waves and rainfall. Urban infrastructure costs could rise as different building materials and standards are required to cope with heat stress, more runoff, and changes in humidity.

Air pollution would be aggravated by climate change: low-level ozone concentrations rise with temperature. Estimates of the cost of stabilising ozone within present standards in the US range from \$3.5 billion (Cline, 1992) to 27.2 billion annually (Titus, 1992), perhaps 5 to 10% of the global cost of climate change.

Finally, it is impossible to estimate the likelihood that climate change will cause the collapse in a regional economy. For example, the conjuncture of drought, desertification, reduction in water supplies, increased health stress and disease, and loss of pasture and woodlands in northern Africa, combined with higher food prices, decreased tourism, and decreasing foreign aid could lead to widespread collapse of rural economies in the region. Urban immigration could be compounded by recession, followed by civil strife, and potentially international conflicts that reach into Europe. Such scenarios cannot be discounted (Myers, 1995). Neither can their economic effects reliably be calculated.

It may be rash to presume a global accounting is possible or reasonable at this time. Even the IPCC (Pearce *et al.* 1995) does not attempt a global total of all of the potential costs. A key issue is the value of a statistical life (VSL). In this study, it is used in the estimation of losses due to natural hazards. However, to calculate further mortality and morbidity changes, country-level VSLs would be required, and would significantly affect the total costs.

Scaling up to a global cost

The goal of this study is to assign a cost to individual fuel cycles and to compare the costs between two reference scenarios. To do this, it seems prudent to use global estimates of the cost of climate change. However, global figures based on evaluation of all of the affected sectors are not available at present. As a rough approximation, to complement the costs counted above, we have adopted the following to scale up to total, global costs.

The IS92d, "resilient development" scenario implies a reasonably high value on environment and somewhat less pressure on resources as population growth and climate change stabilised. Assuming the costs for "other sectors" are not net benefits, they are estimated as multiples of the positive direct costs:

- For the low estimate, the "other sectors" would be equal to the positive direct costs.
- For the medium estimate, the costs might be twice the positive direct costs.
- For the high estimate, the costs could reach four times the positive direct costs.

For the IS92a scenario, lower scalars are used, such that the IS92d scalars are 50% greater than the IS92a scalars. This 50% difference between the two scenarios reflects higher per capita incomes (about 30% greater in the IS92d world by 2100), as well as a shift in values towards the environment. As such, the two sets of scalars are consistent with our logic of two reference scenarios and the difference between them is relatively modest. Thus, in calculating the IS92a global totals:

- For the low estimate, the other sectors would be 67% of other positive costs.
- For the medium estimate, the costs would be 133% greater than the other positive costs.
- For the high estimate, costs could be 267% greater than the other positive costs.

This range of scalars for other sectors corresponds to published estimates for "other sectors". For example, Nordhaus (1991) calculated a cost of 0.26% of GDP for the US, but set 1% of GDP as a central estimate taking into account additional sectors that are not directly estimated. Tol's (1994) estimates for human amenity, morbidity and mortality are over two-thirds of the total costs for the U.S. Nevertheless, scaling up by a factor of 1, 2 or 4 is simply a device to represent these other costs. It does preserve the notion of a range of estimates and provides a global total that is not inconsistent with the published literature.

Results

The resulting costs for other sectors are large, from less than $1,000,000M to three orders of magnitude greater, in excess of US$3,000,000,000M (Table 16). The IS92a scenario is over twice as costly as the IS92d scenarios, in spite of the higher values associated with the IS92d scenario.

These costs dominate the world total. Further research on these costs could refine the estimates. To the extent possible, specific evaluations can be attempted. For example, the range of health effects can be subjected to methods of direct and contingent valuation. Bounds might be placed on some of the estimates, such as ecosystem functions. Regional and sector-specific scalars might then be introduced to provide improved estimates.

Table 16. Net Present Value of Other Sectors

	Unit	LOW	MED	HIGH
IS92a	$M	2,481,120	66,715,556	3,542,564,395
IS92d	$M	767,599	19,880,865	1,317,788,167

11. Global Costs of Climate Change

Global costs

The aggregate global costs of climate change for the two reference scenarios are shown in Table 17, while Figure 18 charts the breakdown between sectors. Without discounting, the global cost of climate change ranges from a slight benefit, over $\$5x10^5$M, to a very substantial cost, almost $\$5x10^9$M. Expressed in terms of GWP, this range is from a very small benefit (less than 0.01%) to almost 42% (Table 18). The two medium estimates are $\$76x10^6$M (0.7% of GWP) for the IS92a and $17x10^6$M (0.2%) for the IS92d scenarios.

The global totals for the two scenarios are quite distinct. For the low estimate, the IS92d total is a net benefit, dominated by the benefits from heating with quite low costs in other sectors. For the medium case, the IS92a is four times greater than the IS92d total. This difference between the two scenarios is slightly less in the high estimate. The difference between the two scenarios is accentuated by discounting, with the IS92a being more than twice as costly as the IS92d scenario with a discount rate of 10%.

Higher discount rates result in lower net present values, as expected (Table 19). It might be desirable to discount market values at one rate and indirect values at another. For example, changes in heating and cooling energy costs might be discounted at market rates (typically 3 to 10%), while losses of environmental goods, such as species, would be discounted at much lower rates (perhaps 0 to 1.5%). The choice of discounted values might reflect subjective values of uncertainty and risk.

The distribution of costs between sectors is broadly comparable between the two scenarios. That is, heating and cooling dominate the global costs for the low estimate. Disasters and "Other indirect" costs assume a larger portion of total costs in the medium and high situations. Biodiversity follows in importance behind energy and disasters. The effect of "Other indirect" sectors deserves comment. For each of the scenarios, these costs are substantial. In the low case, they offset the net benefit accruing from heating savings. For the middle and high estimates, these other costs are the largest contributor (over three-fourths) to the global total. Since these are subjective estimates derived from scalars, the final numbers are clearly subject to considerable uncertainty.

The total cost presented here is still within the range cited in the literature (Table 20). Based on the medium estimate for the IS92a, the present study is two-thirds of the estimates for the US (Cline and Nordhaus) and half of Fankhauser's global total. The real difference between the present study and others cited by the IPCC is in the high estimate of potential damages. The sizeable damages accruing in the Non-intervention scenario (almost half of GWP) and even in the Resilient Development scenario (over 15% of GWP) are alarming. It must be borne in mind, however, that GWP is an indicator of market flows whereas most of the damages in the high estimate are in non-market resources – environment, amenities, and human life. If GWP are revised to include these values, the percentage of damages would likely be quite modest.

Of related interest are the subjective estimates based on a poll of experts conducted by Nordhaus (1994a, cited in Pearce *et al.*, 1995). The reference warming is 3°C by 2090, about half-way between the IS92a medium and high projections used here. The average among 19 experts, from physical and economic sciences, is global costs of 3.6% of GWP, while the median is less, 1.9%, in a range from 0 to 21%. Almost all of the respondents felt that more than half of the costs would be in market sectors. More interesting for high estimates of warming, when asked the probability of damages exceeding 25% of GWP, the average of the expert group is 4.8%, with a range from 0 to 30%.

Cascade of uncertainty

For each scenario, we follow through a range of uncertainty. This consistently tracks a low, medium and high estimate of climate change, impacts and economic evaluation. For example, the low estimate of climate change is derived from MAGICC's assumption of a low climate sensitivity (1.5° C). This is then matched with low estimates of how sensitive economic impacts are to changes in climate, for example the elasticity of agricultural GNP to the index of agricultural suitability, or the low values of the impacts of heating demand and fuel prices. Within MAGICC, the low and high estimates are intended to bracket the 80% confidence interval, while the medium corresponds to an average or "best guess" estimate. The subsequent ranges of economic values also are intended to reflect the range from 10% to 80%. If all of the sources of uncertainty are known and their distributions are similar, the confidence interval for the final results would be relatively greater, perhaps 1% to 95%.

However, given the ad-hoc, subjective methods used to model the uncertainty and the very real potential for surprise and discontinuous impacts (i.e. not marginal changes from the reference scenarios), we have avoided a statistical definition of the confidence interval. What can we say about the cascade of uncertainty? Two extremes have been emphasised:

- IS92a-high: Approaches a surprise scenario of high climate change, high impacts, and high valuation of those impacts. The economic values themselves may be somewhat lower than in the IS92d case (due to lower GNP per capita), but the impacts are larger due to a higher sensitivity to adverse impacts.
- IS92d-low: Effectively most climate change impacts can be coped with due to increased incomes and low estimates of climate change.

In fact, a third world-view might be warranted: The IS92f has high population growth, with most of the other features of the IS92a scenario. This might be used to characterise a "fragile scenario" where regional collapse is a distinct possibility due to the systemic effects of climate change and continued sensitivity to its impacts.

Several integrated modelling groups, such as at Carnegie Mellon University (CMU) (Kandliker and Morgan, 1995; Morgan and Keith, 1995) and the Dutch Ministry of Environment and Public Health (RIVM) (Rotmans, 1995), have adopted different ways to evaluate perceptions of future worlds and to generate a range of results that reflect not only scientific uncertainty but cultural perceptions of future values. CMU use a risk profile approach, while RIVM have embodied egalitarian, individualism and heterogeneity from cultural theory. While stimulating, these approaches may not be appropriate at this point in modelling fuel cycle externalities.

However, further work could propose combinations of the scientific uncertainty, impact sensitivity and economic evaluation that reflect different decision-makers' (assumed) perceptions of the future. As a starting point, these might be:

- Scientific uncertainty: maintain MAGICC's range of results for temperature and sea level rise; possibly add a second GCM scenario with a different regional pattern of impacts. This provides a continuum of time slices, a range of uncertainty in climate change (Low, Medium and High), and various spatial patterns (e.g., GISS, GFDL and UKMO).
- Impact/climate sensitivity: this is the source of our context-rich scenarios. For the moment, we have labelled these as Non-intervention (IS92a) and Resilient Development (IS92d). Non-intervention follows current trends with increased incomes stimulating development but not solving all of the resource constraints and climate sensitivity, with trade-offs between exposure (for instance to hurricanes) and benefits (coastal access).
- Economic valuation: the more subjective estimates of value may not be inherent in the perceptions of either resilient development or projected trends. So it seems best to handle these separately, corresponding to our current assumptions about the range of economic impacts (i.e., value of statistical life that corresponds to developing countries, developed countries or EC policy). Three labels might be: Market-valued: values of life and species as measured in current (national) micro-economic analyses; Progressive: for example, values are currently inequitable, but approach a global average in 2100; and Egalitarian: values are high, such as the EC recommended rate, and equal globally.

Current analysis of the IS92d scenario is egalitarian – all VSLs are global averages – but with three ranges for low, medium and high estimates of value. However, the range of economic assumptions might vary across both the impact sensitivity and scientific uncertainty. For example, the highest impacts would come from high climate change, IS92a impact sensitivity (assumed to have higher world costs than IS92d) and egalitarian (high) economic evaluation. This option is not particularly logical – we would assume that high values placed on species and lives would prevent the Non-intervention world from becoming a reality. At the other extreme, a resilient development world, with low climate impacts due to mitigation and adaptation, is consistent with high economic valuation, and less so with presumptions of low economic values. Such risk profiles should help to clarify the combination of assumptions on value of life and species, welfare, and trade-offs between winners and losers.

Risk

The range of uncertainty remains quite large. Even within individual sectors, the difference between low and high estimates is one or two orders of magnitude, and usually larger than the difference between the IS92a and IS92d reference scenarios. The choice of valuation technique contributes a further uncertainty. In our own calculations, we have seen orders of magnitude differences between assumptions regarding what is a cost, the benchmark reference assumptions, and how to scale costs into the future, among other parameters.

Climate change over the next Century is almost certain to occur. The present value of those changes may be unknowable. Beyond the present absence of data and robust techniques, the global total depends largely on indirect values. For future generations, these values are not knowable. The extent to which they can be projected and estimated is an open question.

Given the uncertainties and unknowable nature of environmental economics, is it reasonable to calculate a global cost-benefit analysis? Quite possibly, the better approach is to pose a different question: How much should we pay (or set aside) to reduce (or prepare for) the risk of adverse climate change? This questions puts the focus on the high numbers presented below (rather than the medium estimates). It also allows the analyst to directly address risk premia in calculating expected damages.

Regional distribution of impacts and multiple effects

The methodology developed for this research is designed to provide a global estimate of the potential impact of climate change. However, the first-order impact models are based on 0.5° latitude x 0.5° longitude data, while the economic valuation is based on country-level projections of demand, economic growth, population, and impacts. This provides greater spatial realism than is currently available in most economic valuations of climate change. This also provides an opportunity to investigate the regional impacts. Two questions are important: Where are the net costs likely to be greatest? How great is the implied trade-off between winners and losers?

Note, however, that the present methodology can provide only partial insight into these questions. Many of the key assumptions are global: energy prices and value of statistical life, for example. Some sectors are only calculated at the global level, notably disasters and "other indirect" costs. The value of biodiversity is a hybrid, based on the global loss of species with a global average value scaled into the future by per capita GNP, which differs among countries. In addition, data for many countries are missing, especially for the first-order impact models and economic indicators.

The distribution of impacts for coastal resources, agriculture, water resources, and energy can be assessed since their estimates are based on national data. All of the impacts are expressed in the value of the impacts ($Million), to illustrate the patterns of relative damages. They are not intended to assign thresholds of acceptable or unacceptable costs relative to GDP or stakeholders within each country. Only the IS92a scenario (medium estimate) has been evaluated. Since the IS92d uses the same global climate model, the relative differences between countries can be expected to be similar.

For agriculture, a third of the countries would benefit from increased agricultural suitability. These are mainly in the temperate climates of the world. Conversely, the countries with the highest losses are in the tropics, notably in Subsaharan Africa. The situation for water resources is more disparate. Most of the world suffers a cost, with modest benefits accruing in parts of the tropics and Europe, among other regions.

The cost for coastal resources includes the impacts on coastal protection, loss of wetlands, loss of drylands and migration as coastal areas are lost. All of these sectors are costs in affected countries. The assumption of partial retreat handles the balance of coastal adaptation. Moderate costs, over $10,000M would occur in almost 50 countries. The countries with relatively large losses are not geographically distinct. Significant losses would occur in Asia, North America, New Zealand, Scandinavia and some of the African countries.

The benefits from reduced heating demand, for both electricity and fuel sources, are quite large – over 1% of GNP for 24 countries. Five countries account for 70% of the heating benefit, in term of total savings (in decreasing order): US, China, Canada, Russian Federation and Australia. The smallest benefits accrue to tropical countries, particularly in Africa. In contrast, cooling costs are highest in Subsaharan Africa and parts of Asia, although most of the world has at least moderate costs. Some 37 countries would have costs exceeding 1% of GNP. Adding the heating benefits and cooling costs together, poleward countries have net benefits, while tropical countries suffer net losses. Some 25 countries have either net benefits or net costs in excess of $10,000M.

How great is the implied trade-off between winners and losers? The global totals presented above are the sum of country costs, whether they have benefits or costs. In most economic appraisals, it is assumed that the benefits can be used to compensate the losses. However, for understanding the global commons and equity issues, it is important to assess the magnitude of the difference between benefits and losses. (It may also be important to do this within a country, but this is not feasible with the current methodology.)

For agriculture, in the IS92a-Medium scenario, the global net cost is almost $500,000M. Yet the global benefit is over three-fourths of this amount. Thus, if just the negative consequences of agriculture are included the global cost would be 80% greater. The situation is similar for water resources, but the global benefit is less than 10% of the global total, which is less than $10,000M for the IS92a-Medium scenario.

The balance of heating and cooling impacts is a net benefit at the global level of some $10,000,000M (for the IS92a scenario, medium estimate, without discounting). Almost 100 countries have a net cost (cooling demand exceeds heating benefit), while some 60 countries have a net benefit (heating benefit exceeds cooling cost). Thus, more countries are losers than are winners, in terms of changes in energy demand. However, the winners win 50% more than the losers lose. If only the net losses are used in the global cost of energy impacts, the total would be a cost of the same magnitude as the reported benefit.

Fankhauser and Tol (1995) comment on the IPCC assessment of economic costs of climate change (Pearce *et al.*, 1995). Of particular interest are options for aggregating regional costs to a global figure. If equity is a significant consideration, then country-level damages might be weighted, perhaps by their per capita income:

$$D_{world} = \sum_{regions} D_{region} \left(Yreference / Yregion \right)^{E}$$

Damages (D) for the world are the sum of regional damages weighted by per capita income (Y), for example the ratio of a reference (global average) to the regional value, raised to the power of E. A value of 0 for E results in equal weights for each region. For E=1, weighted damages would be on the order of 50% higher than the unweighted damages. Further research is required on how to include equity in calculating the global cost of climate change.

Multiple effects

Evaluation of the IS92d scenario discounted the probability that climate change would lead to regional collapse of some economies, such as the conversion of the Sahel from agriculture to a population dependent on food aid. Such a scenario has greater plausibility in the IS92a world, particularly for the higher projections of climate change and sea level rise and assuming a world with greater population pressure is prone to more intense and more frequent resource conflicts.

Analysis of the country data does not indicate particular groups of countries that experience consistently high costs for most of the impact sectors. For many countries, some benefits will accrue that might compensate for some resource losses. It is likely that many presently vulnerable countries, such as in south Asia and Subsaharan Africa, will find the threat of climate change a significant challenge to their development plans. However, a more rigorous regional model would have to be employed to provide robust conclusions regarding regional risk.

Table 17. Summary of the Global Cost of Climate Change, Net Present Value, 0% Discount Rate, IS92a and IS92d

	UNIT	LOW	MED	HIGH
IS92a - 0.0% Discount				
Coastal Protection	$M	69,256	336,486	772,550
Wetlands	$M	29,222	388,356	4,083,106
Drylands	$M	72,034	2,377,630	18,964,104
Migration	$M	563	319,463	11,706,287
Total Coastal	*$M*	*171,075*	*3,421,936*	*35,526,047*
Agriculture	$M	84,269	453,890	873,484
Water Resources	$M	395	6,010	29,721,760
Total Ag & Water	*$M*	*84,664*	*459,900*	*30,595,245*
Heat Electric	$M	-3,093,209	-20,097,286	-91,206,047
Heat Fuel	$M	-2,775,677	-19,682,082	-101,212,169
Cool Elec	$M	3,402,839	26,550,727	142,994,587
Total Heat & Cool	*$M*	*-2,466,047*	*-13,228,640*	*-49,423,629*
Total Direct	*$M*	*-2,210,308*	*-9,346,804*	*16,697,663*
Biodiversity	$M	13,187	4,706,213	72,688,518
Disaster	$M	49,728	14,899,142	1,046,640,645
Other Indirect	$M	2,481,120	66,715,556	3,542,564,395
Total Indirect	*$M*	*2,544,035*	*86,320,911*	*4,661,893,559*
TOTAL COSTS	***$M***	***333,727***	***76,974,107***	***4,678,591,221***
IS92d - 0.0% Discount				
Coastal Protection	$M	42,947	264,191	645,471
Wetlands	$M	12,987	207,535	2,290,579
Drylands	$M	32,014	1,270,592	10,638,659
Migration	$M	188	154,173	6,225,741
Total Coastal	*$M*	*88,136*	*1,896,492*	*19,800,450*
Agriculture	$M	50,238	311,355	616,080
Water Resources	$M	212	3,257	23,532,265
Total Ag & Water	*$M*	*50,450*	*314,612*	*24,148,345*
Heat Electric	$M	*-1,134,800*	*-6,803,827*	*-28,500,676*
Heat Fuel	$M	-860,424	-5,405,242	-25,843,860
Cool Elec	$M	624,339	3,934,629	19,771,458
Total Heat & Cool	*$M*	*-1,370,884*	*-8,274,441*	*-34,573,079*
Total Direct	*$M*	*-1,232,299*	*-6,063,337*	*9,375,717*
Biodiversity	$M	*4,674*	*2,426,181*	*32,261,155*
Disaster	$M	*-112,610*	*1,368,519*	*233,465,634*
Other Indirect	$M	*767,599*	*19,880,865*	*1,317,788,167*
Total Indirect	*$M*	*659,663*	*23,675,566*	*1,583,514,956*
TOTAL COSTS	***$M***	***-572,636***	***17,612,228***	***1,592,890,672***

Table 18. Summary of the Global Cost of Climate Change, Net Present Value, 0% Discount Rate, IS92a and IS92d, Percent of Gross World Product

		LOW	MEDIUM	HIGH
IS92a - 0.0% Discount				
Coastal Protection	%	0.0006%	0.0030%	0.0069%
Wetlands	%	0.0003%	0.0035%	0.0365%
Drylands	%	0.0006%	0.0213%	0.1697%
Migration	%	0.0000%	0.0029%	0.1047%
Total Coastal	%	0.0015%	0.0306%	0.3178%
Agriculture	%	0.0008%	0.0041%	0.0078%
Water Resources	%	0.0000%	0.0001%	0.2659%
Total Ag & Water	%	0.0008%	0.0041%	0.2737%
Heat Electric	%	-0.0277%	-0.1798%	-0.8160%
Heat Fuel	%	-0.0248%	-0.1761%	-0.9055%
Cool Elec	%	0.0304%	0.2375%	1.2793%
Total Heat & Cool	%	-0.0221%	-0.1184%	-0.4422%
Total Direct	%	-0.0198%	-0.0836%	0.1494%
Biodiversity	%	0.0001%	0.0421%	0.6503%
Disaster	%	0.0004%	0.1333%	9.3639%
Other Indirect	%	0.0222%	0.5969%	31.6941%
Total Indirect	%	0.0228%	0.7723%	41.7084%
TOTAL COSTS	%	**0.0030%**	**0.6887%**	**41.8578%**
IS92d - 0.0% Discount				
Coastal Protection	%	0.0005%	0.0029%	0.0070%
Wetlands	%	0.0001%	0.0023%	0.0250%
Drylands	%	0.0003%	0.0139%	0.1161%
Migration	%	0.0000%	0.0017%	0.0679%
Total Coastal	%	0.0010%	0.0207%	0.2161%
Agriculture	%	0.0005%	0.0034%	0.0067%
Water Resources	%	0.0000%	0.0000%	0.2568%
Total Ag & Water	%	0.0006%	0.0034%	0.2636%
Heat Electric	%	-0.0124%	-0.0743%	-0.3111%
Heat Fuel	%	-0.0094%	-0.0590%	-0.2821%
Cool Elec	%	0.0068%	0.0429%	0.2158%
Total Heat & Cool	%	-0.0150%	-0.0903%	-0.3773%
Total Direct	%	-0.0134%	-0.0662%	0.1023%
Biodiversity	%	0.0001%	0.0265%	0.3521%
Disaster	%	-0.0012%	0.0149%	2.5481%
Other Indirect	%	0.0084%	0.2170%	14.3825%
Total Indirect	%	0.0072%	0.2584%	17.2827%
TOTAL COSTS	%	**-0.0062%**	**0.1922%**	**17.3850%**

Table 19. Summary of Global Costs for Various Discount Rates

	Unit	Discount Rate	IS92A LOW	IS92A MED	IS92A HIGH	IS92D LOW	IS92D MED	IS92D HIGH
Total Direct	$M	0.0%	-2,210,308	-9,346,804	16,697,663	-1,232,299	-6,063,337	9,375,717
		1.5%	-897,821	-3,126,918	2,248,622	-520,317	-1,950,331	1,936,158
		3.0%	-420,974	-1,177,164	193,059	-252,516	-709,681	668,356
		5.0%	-188,581	-391,818	140,928	-117,287	-225,311	434,784
		10.0%	-50,511	-57,722	221,568	-33,108	-26,518	267,786
Total Indirect	$M	0.0%	2,544,035	86,320,911	4,661,893,559	659,663	23,675,566	1,583,514,956
		1.5%	852,777	27,464,413	1,599,084,166	269,825	8,055,646	543,283,108
		3.0%	325,635	10,157,767	647,501,973	125,764	3,205,444	220,331,504
		5.0%	112,979	3,536,682	253,136,803	55,176	1,215,625	86,402,453
		10.0%	20,423	717,971	59,397,693	14,217	276,322	20,433,038
TOTAL COSTS	$M	0.0%	333,727	76,974,107	4,678,591,221	-572,636	17,612,228	1,592,890,672
		1.5%	-45,043	24,337,495	1,601,332,789	-250,492	6,105,314	545,219,266
		3.0%	-95,338	8,980,603	647,695,032	-126,752	2,495,763	220,999,860
		5.0%	-75,603	3,144,864	253,277,731	-62,111	990,315	86,837,237
		10.0%	-30,088	660,249	59,619,260	-18,891	249,804	20,700,824

Table 20. Comparison of Cost of Climate Change between Studies

Study:	This Study	IEA GHG	Intera	Fankhauser	Cline	Nordhaus
Reference:	(1995)	(1994)	(Maul and Climent, 1994)	(1992)	(1992)	(1991)
Scope:	Global	Global	Global	Global	US	US
Emissions:	IS92a, Med.	IS92a	2xCO2	2xCO2	2xCO2	2xCO2
Coastal protection	0.003	0.006		0.007	0.021	0.154
Loss of wetlands	0.004	0.066		0.155	0.074	a
Loss of dryland	0.021	0.086	0.349[c]	0.069	0.031	0.066
Migration	0.003	0.002		0.021	0.008	a
Agriculture	0.004	0.006	0.037	0.139	0.372	0.021
Water resources	0.000	0.002		0.229	0.125	a
Energy	-0.123	-0.000	-0.001	0.113[b]	0.185	0.021
Biodiversity	0.042	0.028	0.736	0.138	0.072	a
Disasters	0.133					
Other sectors	0.597	.0220	1.174	0.629	0.210	0.738
Total	0.684	0.411	2.300	1.500	1.100	1.000

Notes: (a) Assumed together with other sectors. (b) Assessed as human amenity. (c) Total for sea level rise.

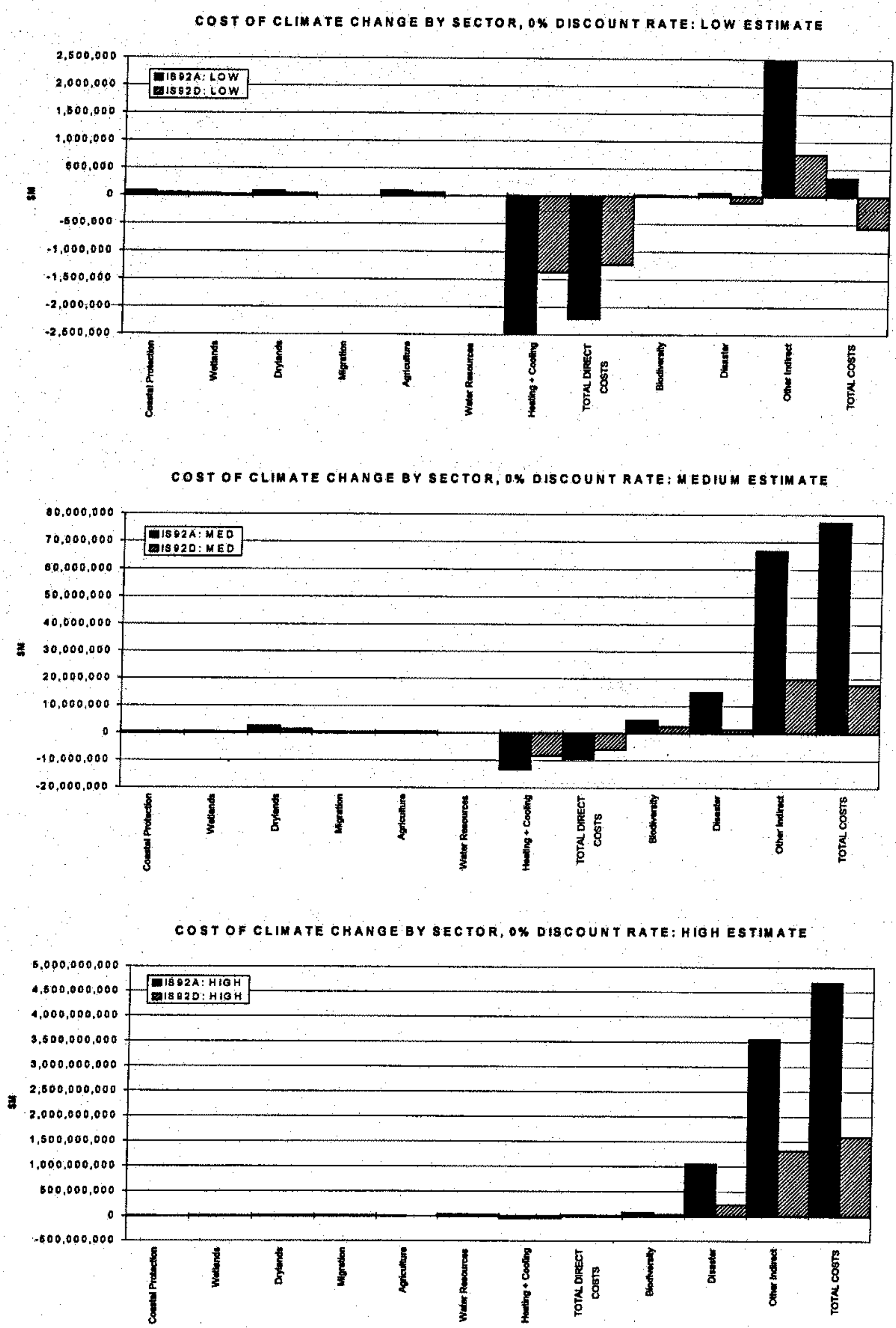

Figure 18. Cost of Climate Change by Sector: 0% Discount Rate.

12. Fuel Cycle Costs of Climate Change

Table 21 presents the portion of global damages that can be attributed to the design fuel cycles. Overall, the difference between the IS92a and IS92d scenarios is substantial, a two- to three-fold difference. As with the global damages, the low estimate for the IS92d gives a net benefit. For the medium cases, the costs range from about 0.75 c/kWh to over 3.0 c/kWh. For the high scenarios, costs attributed to individual fuel cycles would be quite large, up to over 200 c/kWh. These kinds of costs approach the highest marginal costs of electricity provision in the short-term pool.

Among the fuel cycles, the lowest costs are associated with the natural gas power station (UK Gas): about 0.5 c/kWh for the medium estimate for the IS92d scenario and 2-3 times greater for the IS92a estimates. The coal fuel cycles (Lignite and UK Coal) have higher costs, 2.5-5 c/kWh for the IS92a medium case. The Oil CC power station is slightly less costly than the UKCoal. The total costs for the peak load power station (Oil GT) are the lowest of the five fuel cycles: about $1,000M compared to 10 times that for the UK Coal. However, the externality for the electricity produced is quite high, an order of magnitude higher than the coal fuel cycles. This is due to the relatively low electricity output, although it is not clear which portion of the fuel cycle contributes to such relatively high emissions.

The cost of climate change can be calculated per unit of carbon emitted from 1990 to 2100. While this ignores the various effects of other greenhouse gases, and sulphur, it is a common yardstick for comparing fuel cycles. The two reference scenarios result in average costs of $20-50 per tonne of carbon in the medium case and over $1,000/tC in the high case (

Table 22). The range of values is substantially larger than commonly reported in the literature.

The fuel cycles vary considerably in their marginal costs – from less than $0.5/tC to over $12/tC for the medium cases. The ordering of the fuel cycles is altered somewhat compared to the c/kWh values. The peak load power station still has the highest costs, but the Oil CC and UK Gas are more costly than the lignite and UK Coal fuel cycles. This reversal reinforces the need to base economic valuation on the complete effect of emissions.

The difference between the average costs for the reference scenario and the marginal cost for individual fuel cycles in illuminating. In all cases, the fuel cycle costs are substantially lower than the average costs. Costly efforts to capture GHGs at source and dispose of CO_2 may not be as cost effective as improving energy use and carbon efficiency among other sectors.

Table 21. Fuel Cycle Costs of Climate Change, 0% discount rate

FFC	UNIT	IS92A LOW	IS92A MED	IS92A HIGH	IS92D LOW	IS92D MED	IS92D HIGH
Lignite	$M	-6.9191	4,307.6518	294,945.8035	-41.3062	1,559.9498	146,149.7786
	c/kWh	-0.0052	3.2213	220.5595	-0.0309	1.1665	109.2903
Oil CC	$M	20.4990	2,515.3130	171,111.4807	-2.4917	902.9852	86,702.9330
	c/kWh	0.0171	2.1022	143.0103	-0.0021	0.7547	72.4639
Oil GT	$M	1.4820	1,123.6338	77,632.8419	-1.0574	387.6113	41,397.7392
	c/kWh	0.0387	29.3454	2,027.5025	-0.0276	10.1231	1,081.1664
UK Coal	$M	-10.2694	11,180.8409	756,087.0398	-105.0196	3,877.8916	361,407.1913
	c/kWh	-0.0023	2.4536	165.9207	-0.0230	0.8510	79.3096
UK Gas	$M	-4.2276	2,496.0570	173,461.6384	-17.5953	876.2364	86,414.1516
	c/kWh	-0.0028	1.6357	113.6693	-0.0115	0.5742	56.6271

Table 22. Average Reference and Marginal Fuel Cycle Costs per $/tC

	IS92A LOW	IS92A MED	IS92A HIGH	IS92D LOW	IS92D MED	IS92D HIGH
Average Reference Costs	0.232	53.454	3,249.022	-0.595	18.289	1,654.092
Marginal Fuel Cycle Costs						
LIGNITE	-0.002	1.001	68.529	-0.010	0.362	33.957
OIL CC	0.010	1.206	82.053	-0.001	0.433	41.576
OIL GT	0.016	12.429	858.730	-0.012	4.288	457.918
UK COAL	-0.001	0.997	67.447	-0.009	0.346	32.240
UK GAS	-0.002	1.431	99.467	-0.010	0.502	49.552

Note: Emissions are the total from 1990 to 2100 for fossil fuels (not including deforestation), expressed in tonnes of carbon (0.27 tonnes per tonne of CO_2).

13. Conclusion and Further Research

In summary, the global cost of climate change is likely to be significant, whether for the IS92a or IS92d worlds. At the high end, it could reach well over a third of Gross World Product. The more likely, medium estimate is a potential cost of $20-75,000,000M, or 0.2-0.7% of GWP. The fraction of global costs that can be attributed to individual fuel cycles varies according to their emissions and reference global warming. Coal fuel cycles may be responsible for an externality of over 3.0 c/kWh. The switch to gas could reduce this cost by half.

However, enormous uncertainty remains in the economic analysis of the cost of climate change. Five levels of uncertainty can be distinguished:

1. Reference scenarios: The reference scenarios seek to characterise resource use and resource sensitivity to climatic variations, taking into account projections of country and global population growth, economic change, technological development, and environmental values. Considerable flexibility in individual country performance and economic values are possible even within the reference scenarios used here. Alternative visions of the future should include ones where resource conflict is exacerbated by political instability and the threat of regional collapse. This source of uncertainty is profound and likely to be relatively major. It could contribute to estimates that differ on the order of 1-2 fold.

2. Climate risk: We have tested only one GCM scenario. Impacts are sensitive to spatial distributions in climatic risk. If the US and Europe are adversely affected, large impacts can be realised at the global level. However, to some extent the distribution of impacts tends to even out, with shifts in regions that benefit and lose. Experience with other scenarios suggests that the impact of climate change could vary by several-fold up to about an order of magnitude. This estimate does not include the potential impacts of sudden climate change (for example, rapid melting of the Antarctic ice sheets) or the kinds of changes that are still speculative (such as large changes in tropical cyclones).

3. Scope of the assessment: Every evaluation of climate change is constrained in some way by the choice of impact sectors and the time horizon. More sectors can be evaluated as data become available, but there is little guarantee that the most costly impacts are adequately accounted for in any single assessment. For scenarios where climate change does not stabilise, the projections ending in 2100 are artificial and undervalue impacts, raising fundamental issues of discounting. It is difficult to estimate the magnitude of this uncertainty; it certainly could be several orders of magnitude for some assumptions.

4. First-order impact models: The first-order impact models that we have utilised are relatively simple. More elegant versions have been compiled for regional or sectoral studies. Such improvements have tested the importance of more processes and the uncertainty in the biophysical mechanisms of climate impacts. However, the range of results is not widely dissimilar to the results obtained here with simple models. Overall, the effect of better impact models on the global economic valuation is probably small, less than a 1-2 fold change.

5. Economic valuation: For the direct, market sectors the range of economic methods and resulting estimates are relatively modest and should not lead to dramatic changes in global costs. The more fundamental issues are temporal changes with dynamic adjustments to incremental climatic changes, discount rates, value of statistical life, accounting for equity between regions and

affected populations, and values places on environmental resources and amenities. Given these constraints on economic valuation, the resulting uncertainty is quite large, at least 1-2 orders of magnitude.

Despite the remaining uncertainties, considerable progress has been made over the past several years of research on a linked-model/spatial pathway approach to the economic evaluation of climate change. The most significant conclusions appear to be:

- A transient analysis explicitly evaluates the magnitude and timing of the impacts of future climate change against an explicit reference scenario of the world without climate change. This provides a more dynamic assessment than a static-equilibrium evaluation, and requires the analyst to disentangle the cost of climate change from changes in the economy that adapt to climate change without significant costs.

- The use of a reference scenario limits the analysis by discounting the extreme cases of regional environmental, economic and social collapse. That is, if climate change is not a marginal change in resource use, current economic approaches are inappropriate.

- The total cost of climate change is sensitive to the assumptions about the reference comparison. In a "resilient development" scenario (the IS92d), a world that is relatively less populated (the UN low estimate) and comparatively wealthy would suffer less extreme damage from climate change than a "non-intervention" or "business-as-usual" scenario.

- At least half of the total cost is attributed to changes in welfare, calculated by methods of contingent valuation that are subjective and sensitive to assumptions about future values.

- A large range of uncertainty results from relatively modest changes in assumptions, even within the context of the reference scenario.

- Assuming climate change impacts are marginal to a reference scenario, the relative contribution of different fuel cycles can be estimated by evaluating their time-dependent profiles of emissions and subsequent effects on global warming.

- Since the largest costs are subjective, the full cost of climate change may be unknowable: measuring subjective contingent valuation is not feasible at the global level and may not be reliable for future generations. An option worthy of greater investigation is the present willingness to pay a risk premium to avoid future damages from climate change, rather than directly estimating future costs and benefits.

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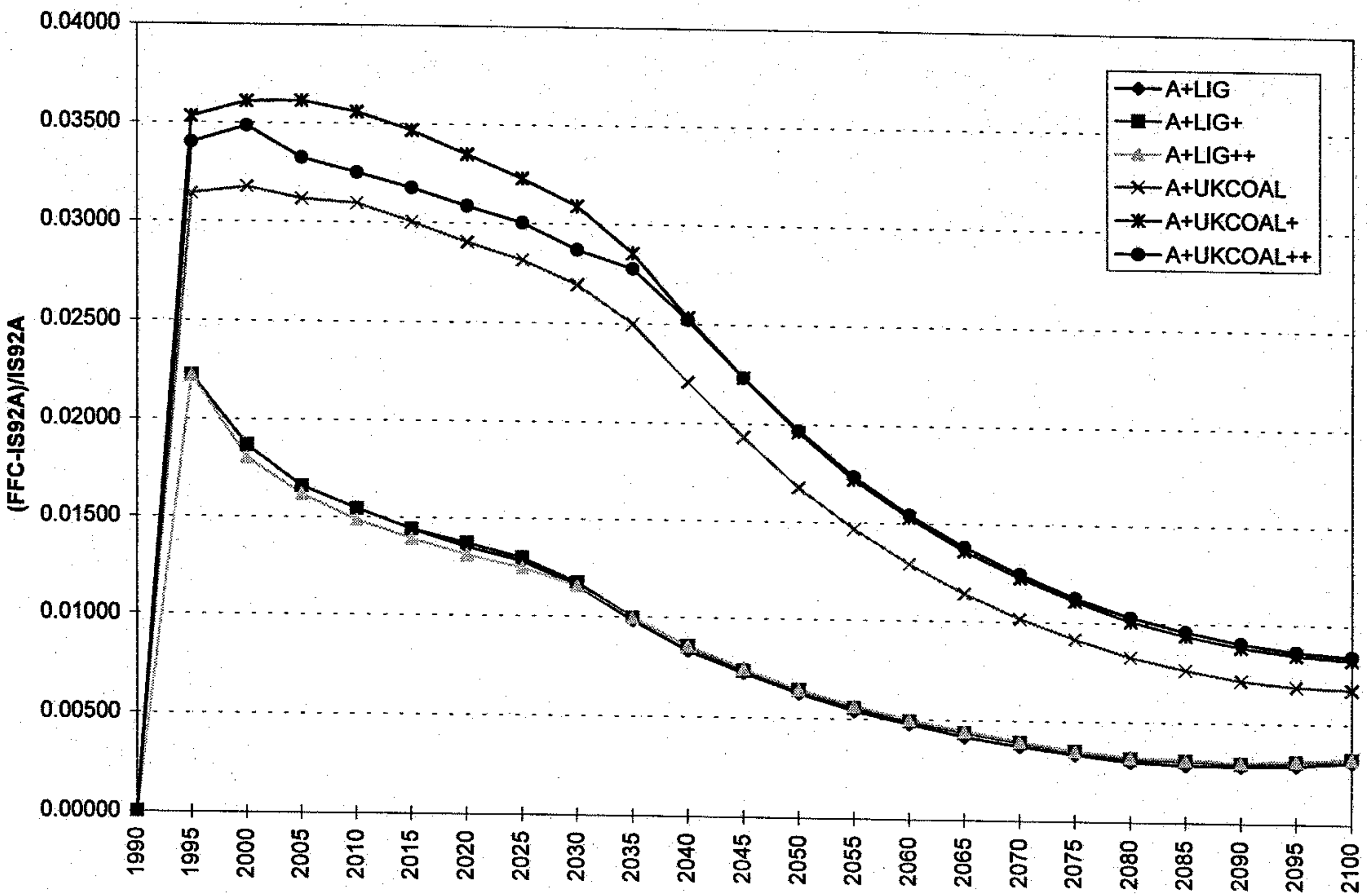
Projected Costs of Climate Change for Two Reference Scenarios and Fossil Fuel Cycles

Addendum. Incremental Effects of Greenhouse Gases on Fuel Cycle Contributions to Climate Change

Thomas E. Downing
David Blackwell

25 July, 1996

INCREMENTAL EFFECT OF GHG: COAL, T-MEDIUM



The incremental effect of greenhouse gases in each fuel cycle was evaluated. For each fuel cycle, emissions were added to the IS92a reference emissions as follows:

GHGs	Marginal Test	Code
CO_2	Carbon only	
CO_2 + CH_4, Nox, N_2O	Other GHG gases	+
CO_2 + CH_4, NOx, N_2O + SOx	Sulphur	++

The total emissions for the reference scenarios and fuel cycles are:

	Foss CO_2 (Pg C)	Defo CO_2 (Pg C)	CH_4 (Tg)	N_2O (Tg N)	CO (Tg C)	VOC (Tg)	NOx (Tg)	CFC-11 (Gg)	CFC-12 (Gg)	HFC-134a eqv.(Gg)	HCFC-22 (Gg)	SOx (Tg S)
IS92A	1440.000	86.100	81419.000	1759.200	70635.000	44024.500	8897.000	9300.000	10772.000	94461.000	92539.000	14168.000
IS92D	963.000	30.300	64239.000	1628.200	50303.000	36023.500	7607.000	4327.000	4444.000	180669.500	4469.000	8212.000
LIGNITE	4.304	0.000	1.075	0.088	0.000	0.000	9.703	0.000	0.000	0.000	0.000	4.603
OIL CC	2.085	0.000	0.457	0.118	0.000	0.000	10.772	0.000	0.000	0.000	0.000	5.244
OIL GT	0.090	0.000	0.023	0.006	0.000	0.000	0.355	0.000	0.000	0.000	0.000	0.263
UK COAL	11.210	0.000	135.454	1.783	2.202	0.747	102.758	0.000	0.000	0.000	0.000	25.690
UK GAS	1.744	0.000	4.465	0.142	0.526	2.105	11.322	0.000	0.000	0.000	0.000	0.000

The resulting charts are attached.

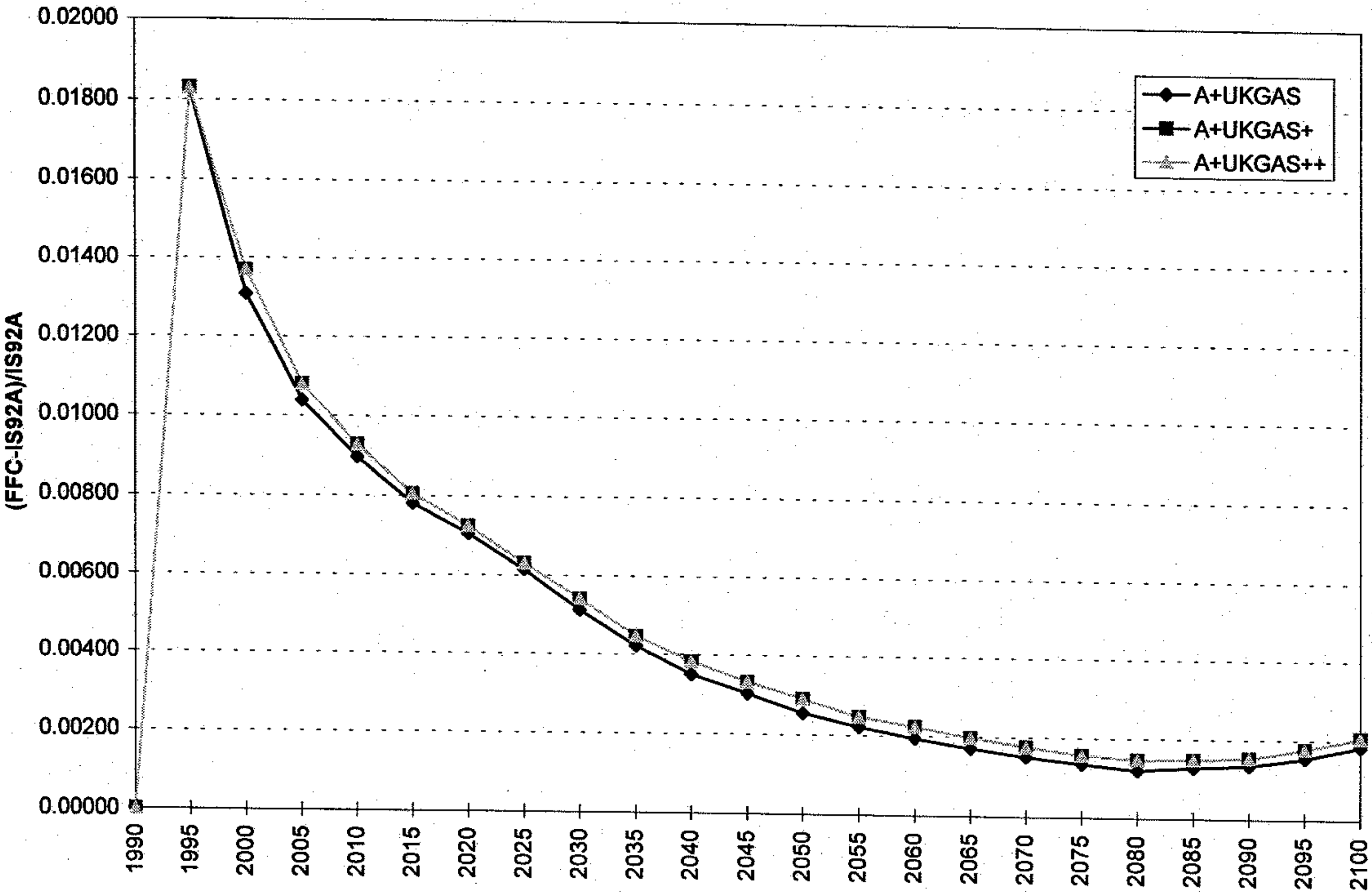
The incremental effects for the Lignite fuel cycle are negligible. Relative to the carbon emissions, CH_4, NOx and SOx emissions are quite small.

In contrast, the marginal effects for the UK Coal fuel cycle are the largest of the five fuel cycles. Adding only CO_2 results in a peak ratio of 0.032. Including the other GHGs, raises the ration by almost 0.01, over 10%. Sulphur dampens the effect during the plant's operation, but has little effect beyond 2050. This is because sulphur is quickly washed out of the atmosphere.

The two oil fuel cycles have different marginal effects. The Oil CC shows little change between the three curves. In contrast, the effect of sulphur emissions in the Oil GT fuel cycle are sufficiently strong to cause global cooling the in the first year of operation. Note that the MAGICC output is every five years, so it is not possible to tell how long the cooling would last before the other GHGs dominate the effects.

For the gas fuel cycle, there is a very modest difference between the CO_2 and CO_2 + GHG simulation. SOx emissions are not included and have no effect on marginal global warming.

INCREMENTAL EFFECT OF GHG: GAS, T-MEDIUM



INCREMENTAL EFFECT OF GHG, OIL: T-MEDIUM