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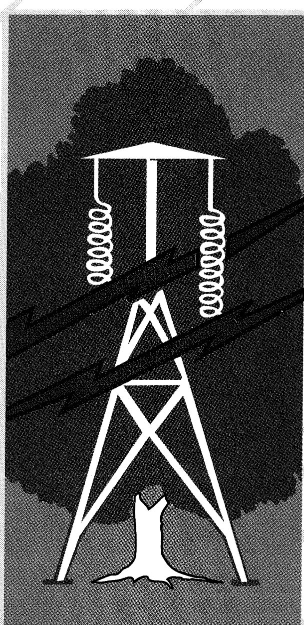

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ExternE
Externalities of Energy

GLOBAL WARMING DAMAGES

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EXECUTIVE SUMMARY

Methodology

This paper reports the results of the Global Warming Sub-Task of the ExternE Project, which has sought to apply and extend the established ExternE methodology for marginal external costs to the climate change damages of greenhouse gas emissions.

Some modifications of the ExternE methodology have been required to allow for the high level of aggregation which is necessary in addressing complex, global, long term effects. There is no dependence on emission location. We use global emission scenarios defined by the IPCC and calculate greenhouse gas concentration, radiative forcing and consequential changes in global mean temperature, precipitation and sea level rise. Site specific impact analysis is infeasible. Instead we rely on analyses of impact at a highly aggregated level (national or higher) as an input to climate change damage models.

Existing climate change models FUND and the Open Framework have been used. The models have some common features, both calculating greenhouse gas marginal damages. But FUND's strengths are in dynamic and integrated analysis, whilst the Open Framework concentrates on first order impacts and spatial issues. Comparing results to improve understanding of the issues has therefore been the goal of the exercise, not model convergence.

Key Issues

Some key issues have been identified which potentially have very important effects on the assessment of climate change damages - equity, discounting, socio-economic conditions, climate and impact uncertainties, and the treatment of sustainability problems. These have been reviewed. In some cases no approach can be recommended as uniquely correct, and instead we adopt a "base case" against which to measure sensitivities.

Equity issues have been controversial in the political discussions of climate change damages. "Willingness to pay (WTP)" is the standard measure of value in environmental economics, adopted throughout the ExternE Project. However, WTP is a function of income and therefore lower in poorer countries, so there are equity objections to simple additive aggregation. We reject the approach of using common values for all countries. Instead we prefer to adopt WTP values but to address equity concerns in the aggregation process, using weighting factors to account for declining marginal utility of income. Results are presented for both equity corrected and simple additive aggregation.

The discount rate has a very large effect on the net present value of damage incurred in the far future, and therefore on the marginal costs of current emissions. We have surveyed the arguments for using different discount rates. There are some arguments that "pure time preference" is not an admissible factor in assessing inter-generational damages, and therefore that the rate adopted should be equal to the long term per capita growth rate. This would imply scenario dependent discounting which we have not implemented. There is broad agreement that a low positive discount rate should be used, but not its exact value. We present results at a number of discount rates - 0%, 1%, 3% and 10% - but do not recommend the use of the extremes of this set.

The future damages imposed by climate change due to current emissions will depend on the socio-economic conditions in future generations, in particular the capacity of those societies to adapt to the impacts of climate change. Marginal damages of emissions are therefore dependent on socio-economic as well as climatic scenarios. We have adopted two IPCC scenarios for examination - IS92a and IS92d - which may be thought of as representing "trend projection" and "more sustainable development" respectively. However, both are under-specified for assessing climate change impacts. The additional assumptions required may be critical, especially the regional climate changes and socio-economic development patterns for those societies most vulnerable to impacts of climate change. In these cases, there are potentially some additional damage categories - like famine and conflict - the risk of which will depend largely on the underlying socio-economic conditions, but which climate change could exacerbate. We call these "socially contingent damages" and note that they are difficult to estimate.

Uncertainties arise at all stages of the analysis. The sensitivity of global climate change to greenhouse concentrations is still rather uncertain. The pattern of expected regional climate change is even less well established. The climate change impact literature is still in its infancy, especially with respect to adaptive capacity, so that impact assessments are incomplete and have large uncertainties. Accurate damage assessment is not therefore feasible. In the Open Framework model some estimates of uncertainty have been made carrying through upper and lower estimates. A formal uncertainty analysis has been undertaken with the FUND model. Both analyses rely on expert judgement of levels of uncertainty. In addition, some of the most important uncertainties are not statistical, but depend on ethical/political choices (e.g. treatment of equity, discount rate). In these cases we examine the sensitivity of marginal damages to different choices.

The assessment of external costs lies explicitly in the paradigm of weak sustainability. For climate change damages, as in the rest of ExternE, it can prove difficult to place marginal values on natural systems, in particular where they are not substitutable and/or the environmental problem is better characterised by scale limits. It can be argued that the concepts of strong sustainability are more applicable in these cases. The potential for developing an intermediate framework based on "safe minimum standards" has been explored in co-operation with the ExternE Sustainability Indicators Task.

Key Impacts

Climate change has a very large number of impacts. The literature has been reviewed to identify those impacts which are of most interest to policy-makers and most likely to result in significant damages. We conclude that these are likely to be the impacts of sea level rise and extreme weather events as well as impacts on human health, agriculture, water resources and ecosystems. We have concentrated on these impact categories, as well as some others already included in the FUND and Open Framework models such as energy demand and migration.

Health impacts have been reviewed in some detail. Heat stress and cold stress impacts will be influenced in opposite directions so that the net impact (globally) of direct temperature changes may be quite small. The area amenable to parasitic and vector borne diseases, notably malaria, will expand and impacts could be large. Other direct impacts, such as effects on air pollution, are likely to be smaller. Socially contingent damages to health (via other impacts such as food production, water resources and sea level rise) in vulnerable communities are difficult to estimate but potentially very large.

Agricultural impacts depend upon regional changes in temperature and rainfall, as well as atmospheric carbon dioxide levels. Bio-physical models can identify areas suitable for crops and potential yield changes, but actual yield changes will depend on many factors. Climate variability, as well as mean climate change, is an important consideration. Adaptive responses will be important - choice of crop, development of new cultivars and other technical changes, e.g. irrigation. Impacts of production do not fully determine damages - these will also depend on changes in demand and trade patterns driven by socio-economic factors. The models used in this work take contrasting approaches. In FUND damages are scaled according to global climate from damage estimates obtained using complex models of world agricultural change. Open Framework damages are based on changes in national agricultural GDP scaled from spatial assessments of land suitable for agriculture.

The literature on water supply impacts includes studies at the regional (catchment level), but there has been only one global scale study. Hydrological simulations can predict changes in water resources. Impacts and damages also depend on demand changes, including those driven by climate change. The water demand of biological systems is affected by various climatic factors, including temperature and humidity. Water supply systems are usually sized to meet (currently) extreme supply/demand conditions and the costs of shortage can be very high. Climatic variability is therefore important in determining damages. The easiest approach to valuation relies on consumer prices to calculate welfare. But in extreme cases, there may also be socially contingent damages.

Sea level rise leads to costs in additional protection, loss of dry land and wetland loss. The balance will depend upon future decisions about what protection is justified. There is no guarantee these will be economically optimal. Costs of protection are relatively well-known, but other costs, in particular valuation of wetland losses, are more uncertain. In addition to these direct costs, land losses will produce migration effects, the costs of which depend on diverse social and political factors.

Impacts on ecosystems and biodiversity are amongst the most complex and difficult to evaluate. Most of the major ecosystem types are likely to be affected, at least in parts of their range. Some isolated systems are particularly at risk. However, there is no comprehensive or reliable assessment of the impacts of climate change on ecosystems. Most valuations rely on *ad hoc* estimates of species loss and contentious valuation studies. The value of ecosystem function may be important, but has received less attention. Even where valuation has be attempted is difficult to apply to marginal changes. There is therefore widespread agreement that accurate valuation of ecosystem impacts of climate change is not possible.

Hazards of extreme weather events raise challenges for climate modelling. Cold spells, heat waves, drought, floods, storms and tropical cyclones may all be affected. The frequency and severity of extreme events may not be linearly dependent on average climate. Climate variability will also be important and there is no consensus on how this will change. Impacts and damages will also depend on the location and timing of the hazard and adaptive responses. For example, cyclone damage to property will tend to rise with wealth, but mortality effects may fall considerably. The Open Framework uses subjective assessments to test the sensitivity to each of the major hazards. FUND concentrates on hurricanes, storms and floods.

Results and Conclusions

Results of FUND and the Open Framework are presented separately and then compared to the extent allowed by the different model structures. For all of the reasons outlined above no single value of marginal greenhouse gas damages is adequate to capture the complexity of problems faced. A common "base case" for damage assessment is therefore defined - using the IPCC IS92a scenario, with equity weighted regional damages over the period 1990-2100 aggregated at a number of discount rates.

For both models the net present value of the damages is presented with a breakdown of these costs by region and by impact sector. In addition the marginal damages are calculated for the three major direct greenhouse gases (CO_2, CH_4 and N_2O) as a function of discount rate, time of emission and equity weighting assumption. The results of uncertainty analysis are presented for both models. In addition the effects of key sensitivities are examined using FUND.

The marginal damages calculated using base case assumptions are as follows:

Greenhouse Gas	Damage Unit	Marginal Damage from Model			
		FUND		Open Framework	
		1%	3%	1%	3%
Carbon Dioxide, CO_2	ECU/tC	170	70	160	74
	ECU/tCO_2	46	19	44	20
Methane, CH_4	ECU/tCH_4	530	350	400	380
Nitrous Oxide, N_2O	ECU/tN_2O	17 000	6 400	26 000	11 000

Source: FUND v1.6 and Open Framework v2.2
Basis: IPCC IS92a scenario
equity weighted
no socially contingent effects
emissions in 1995-2005
time horizon of damages 2100

For the base case assessment there is close agreement between the results of FUND and the Open Framework. Given the differences in model structure and assumptions, this is to some extent fortuitous. Analysis of the breakdown of damages by sector and region shows reasonable agreement in some cases, but divergence in others.

Uncertainty analysis indicates that the range of uncertainty is very large. In addition, not all uncertainty is statistical - even the choice of a base case represents a subjective (and often political) view of future economies and societies. Both discount rate and choice of aggregation rule (equity weighting) have large effects on the results. Furthermore, some potentially important issues - socially contingent damages and ecosystem damages are not fully included. The base case values therefore should not be treated or quoted as best estimates.

1. INTRODUCTION

The damages of climate change have not previously been addressed systematically within the ExternE Project. In the initial work, under the auspices of the EC/US Project 'External Costs of Energy', climate change impacts were explicitly excluded. Subsequent work has included some estimates of climate change damages (CEC, 1995a; CEC, 1995b; CEC, 1995c, CEC, 1995d). But these estimates were based on work outside the ExternE Project, using a variety of methods and assumptions, not all of which are consistent with those of ExternE.

This report seeks to develop an ExternE methodology for the damages of global climate change. In spirit, the approach is similar to that taken for other air pollution damage categories (CEC, 1995b), in that we use a "bottom-up" methodology, considering the effects of emissions on atmospheric concentrations, then the physical impacts produced in the natural environment and finally the monetary values of those impacts. However, the nature of global climate change makes it impossible to be true to a 'bottom-up' methodology, for a number of reasons:

- the relevance of concentrating on a single emission source is limited as most greenhouse gases are globally well-mixed,
- the impact complexity makes a comprehensive disaggregated assessment infeasible,
- impact and damage modelling requires tools outside the scope of those traditionally used in ExternE, and
- the valuation of very long term, global, macroeconomic effects introduces some new challenges.

The methodology adopted is described in Section 2. It is an extension of the traditional benchmark of climate change impacts where damages are calculated for an equilibrium climate change scenario at a concentration of greenhouse gases equal to twice the pre-industrial level of carbon dioxide ($2xCO_2$). It uses models developed by two of the collaborating institutes (FUND from IVM and the Open Framework from ECU) specially re-configured with assumptions consistent, as far as possible, with the ExternE approach and reviews undertaken in our research. The methodology is described in more detail in the following section and Appendices describing FUND and the Open Framework.

Section 3 of the report concentrates on some of the key problems. Many of the issues have been addressed in the context of other environmental impacts within ExternE and elsewhere. Nevertheless, climate change has some special characteristics which highlight some of the most difficult issues, e.g.:

- discount rate,
- assumptions about future socio-economic change,
- the treatment of uncertainty,
- intra-generational equity, including the value of life outside the EU, and
- valuing ecosystems and biodiversity.

In many cases there is no single correct approach which can be universally agreed. We therefore concentrate on making transparent the assumptions used and the sensitivity of the results to those assumptions.

Placing monetary values is not the only approach to assessing climate change impacts - indeed for a problem as long term and complex as climate change it is naïve to think that simple cost benefit analysis will identify an optimum strategy around which the international community can unite (Arrow, 1996). However, it is clear that monetary valuation is an important and influential approach to climate change impact analysis (e.g. Nordhaus, 1991; Cline, 1992; Fankhauser, 1994; Pearce et al, 1996; Tol, 1996a). Even within more complex decision analysis frameworks, it can be shown that economic valuation of the impacts of climate change is an important component (Tol, 1997; Rennings, 1996). But there are potential impacts upon which we cannot, in practice, place monetary values upon and, at least in some paradigms, this is not even an appropriate goal. These issues are explored in more detail in Section 3.5 and Appendix 3.

Section 4 of the report considers the key impacts of climate change. These have been identified by a systematic review of the literature as being potentially of the greatest importance, both in terms of general perception and economic cost. These are:

- health,
- agriculture,
- water supply,
- sea level rise,
- ecosystems and biodiversity, and
- extreme events.

The assumptions adopted and their basis in the literature are presented. Other impacts are included only to the extent they are modelled in earlier versions of the FUND and Open Framework. There is no attempt to do a complete review as this would have been outside the scope of the work possible under this project. Instead we rely on the major review undertaken by the IPCC (Houghton et al, 1996; Watson et al, 1996; Bruce et al, 1996) and subsequent important changes identified in our own review of more recent work. The details of the impact models used in our calculations are given in Appendices 1 and 2.

Section 5 presents the numerical results, estimates of their uncertainty and their sensitivity to important assumptions. The results of the two models are compared. Section 6 draws together the conclusions of the work.

2. METHODOLOGY

2.1 General Approach

The general methodological approach is based on the standard 'bottom-up' ExternE approach to measures marginal damages (CEC, 1995b). However, it is substantially adapted for climate change damages to allow for:

- the very limited site dependence which is expected,
- the state of the art of impact assessment which focuses not on marginal effects but on expected impacts at $2xCO_2$,
- the high level of aggregation in most relevant impact and damage studies,
- the assessment of damages using well-established, integrated, global scale models rather the EcoSense software which is designed for regional scale impacts, and
- more detailed investigation of some sensitivities which are important for global scale and very long term environmental and health impacts.

The functional unit used in the assessment is unit mass of a greenhouse gas rather than a unit of power generated at a fixed point. The damages per unit of emission are independent of location (at least for the important, long-lived, well-mixed greenhouse gases). Conversion of the results to damage per unit of power generated (and other functional units) is straightforward, involving only multiplication by the emission factor.

Emissions are converted into incremental concentrations using atmospheric models. The change in level and rate of climate change are then assessed using the climate sensitivities found by the IPCC using state of the art climate models (Schimel et al, 1996). The marginal effects of incremental emissions depend on the underlying scenario of greenhouse gas emissions. To test the sensitivity of this assumption we use two different IPCC scenarios, IS92a and IS92d (Pepper et al, 1992), representing assumptions which might be described broadly as a 'trend projection' and 'more sustainable development' respectively.

The models which have been used are the FUND model (version 1.6) at IVM Amsterdam and the Open Framework for Climate Change Impact Assessment (OF) model (version 2.2) at ECU Oxford. Marginal impacts are calculated by running a perturbed scenario to calculate the incremental effect of emissions at any date on future climate change. Calculating marginal damages involves making additional assumptions about the functional relationship of impacts and damages on the level and rate of climate change. The most common approach in the past has been a static equilibrium analysis based on a climate scenario of a doubling of CO_2-equivalent GHGs and relatively course representations of world regions. The two models used here extend this approach in two ways. The FUND model adopts a dynamic, transient approach incorporating sensitivity to both the level and rate of climate change, while preserving the 2xCO2-equivalent benchmark damages found in the literature (summarised in Pearce et al, 1996). The Open Framework uses country-level analyses in a coupled framework that links scenarios of climate change, first-order impact models and economic valuation. It is also transient, but considers sensitivity to the rate of climate change only in a subjective manner. The assumptions about population and economic development used in assessing the damages are compatible with those of the emissions scenarios.

Damage assessment involves placing monetary values on the physical and biological impacts assessed. In doing this we use the values agreed by ExternE where available. The range of affected receptors is, of course, very large, and therefore new valuations have to be included. In addition some of the valuation methods are necessarily approximate and preliminary.

As in the rest of ExternE, valuation of marginal impacts on ecosystems has proved very difficult. In the case of climate change, it is clear that there are some potentially significant impacts for ecological stability and biodiversity, but there is no comprehensive quantification of these effects (see Section 4.5 and Appendix 8). Even if reliable descriptions of the ecological impacts of climate change could be established, valuation would be problematic. Much of the ecosystem damage literature focuses on loss of individual species and aesthetic concerns. However, it has been argued that impacts on ecosystem functions may be of greater concern (e.g. Barbier et al, 1994). Recent work to value these functions (Costanza et al, 1997) indicates that total values may be very large, but provides no indication of the value of marginal changes in function of the type needed for our purposes. Thus, credible estimates of the marginal damages of climate change on ecosystems are not available.

The problem of how to address ecological impacts has been reviewed in collaboration with the sustainability indictors task. The weak sustainability paradigm in which ExternE operates is most problematic where large scale issues of ecological stability are concerned. In the ecological economics literature, these impacts are often addressed via a "safe minimum standards" approach. For conventional pollutants the thresholds are set from critical loads and levels observed in the field and these are now widely accepted. Similar approaches have been suggested for climate damages, but the evidence for critical levels is inevitably speculative, and therefore any "safe minimum standard" adopted is largely subjective. Alternative methods of addressing the climate change problem, in which cost benefit analysis plays a key role in a wider integrated assessment, are considered in Section 3.5 and Appendix 3.

Even where potential impacts can reasonably be valued, the uncertainties associated with climate change make estimation of expected values difficult. The potential surprises of major changes in ocean currents or positive feedbacks in greenhouse gas releases are obvious examples. In addition, the more obvious impacts of climate change on agricultural and water systems have potential effects on migration, public health, social unrest and conflict, which are difficult to estimate, and probably will be highly dependent on socio-political conditions. Apart from the migration costs of sea level rise, other socially contingent effects are not formally modelled. Thus they are largely excluded from the FUND damage estimates and included in the Open Framework only as very subjective estimates.

As with many other pollution problems, health damages, and particularly mortality, are found to be significant. The assessment of these damages in different regions has been very controversial. We have reviewed this problem and propose a way forward which is numerically equivalent with ExternE practice to date of using common unit values in all countries, but which provides a proper welfare economic justification (see Section 3.1 and Appendix 5).

In valuing mortality, two different approaches have been used in ExternE: based on the value of statistical Life (VOSL) and the value of life years lost (VLYL). The former was the basis of earlier ExternE reports (CEC 1995a-d), whereas the latter is now preferred. This change in view is reflected in the detailed discussion on health damages (Appendix 7), but it has not proved possible to incorporate it into the models. However, apart from direct effects of heat and cold, the important mortality damages - infectious diseases, storms and socially contingent effects of resource loss - will tend to result in large losses in life expectancy, and the therefore the change from a VOSL to a VLYL base will not be as large as for some other categories of air pollution.

2.2 Modelling Methodology

FUND and the OF pre-date this ExternE work and have been used extensively in climate change analysis. In each case, the model has been updated and parameters re-set to adopt common assumptions where possible. The models have radically different structures and strengths. At this stage of the development of climate damage modelling, convergence among models is neither a realistic nor a desirable aim. Their combined use gives greater assurance that potentially important issues are addressed. Comparison of results helps to promote the ongoing process of improving our understanding in this complex field.

2.2.1 Comparison of FUND and the Open Framework

The two models used in this assessment have distinct features, although they share a number of common features. Both models calculate damages over time: from 1950 to 2200 for FUND and 1990 to 2100 for the Open Framework. Both share origins in the sectoral damage calculations pioneered by Fankhauser, Nordhaus, Cline and others. Both report damages in monetary units.

However, the models were designed with different purposes in mind. FUND is more dynamic and integrated; the Open Framework concentrates on spatial issues. FUND has relatively modest computational requirements that allow formal uncertainty testing; the Open Framework generates large data sets, with a focus on a range of potential damages. FUND draws upon published literature to provide a benchmark of damages for 2xCO2; the Open Framework constructs a simplified climate change impact assessment with a linked chain of models. FUND has nine regions; the Open Framework has a mixture of country-level analyses and global impacts. To make comparisons even more difficult, the models report damages in different terms. FUND reports average annual damages corresponding to a 2xCO2-equivalent climate change. This provides comparability with other damage models used by the IPCC, whereas the Open Framework reports cumulative damages over the period 1990-2100. The two models do not represent the wealth of damage assessments currently available - hence comparison of their results should not be taken as a necessary sign of either consensus or disagreement regarding the cost of climate change.

The details of the models are provided in Appendices 1 and 2. The following sections seek to outline the general approach taken.

2.2.2 Greenhouse Gas Concentration Modelling

Both FUND and the Open Framework model the concentration of the three principal direct anthropogenic greenhouse gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These are all long-lived in the troposphere and therefore relatively well-mixed, so that a single average global concentration is an appropriate input to radiative forcing calculations. Other short-lived, secondary pollutants are neglected, e.g. ozone (O_3) and sulphur dioxide (SO_2), which contribute with opposite signs to climate change.

The details of the atmospheric modelling are different in the two models. The Open Framework uses MAGICC (Raper et al, 1995). This is a well-established global climate model which has been thoroughly reviewed for this type of application and used by the IPCC. In contrast FUND uses its own parameterisation of atmospheric lifetime for each species. For CH_4 and N_2O, the anthropogenic emissions are assumed to be depleted geometrically with life times of 8.6 years and 120 years respectively. For CO_2 a more complex five box model is used, to represent the interchange of carbon between different reservoirs into the ultimate sink in the deep ocean.

The dynamics of all these gases are now sufficiently well-known that the differences between the two models in this respect are unlikely to cause any significant difference in the final results.

2.2.3 Climate Modelling

Greenhouse concentrations are used to calculate the radiative forcing, which is then used to assess global average temperature and sea level rise. The Open Framework uses MAGICC, calibrated to the IPCC range of climate sensitivity (1.5°, 2.5° and 4.5° C for equilibrium 2xCO2-equivalent global mean temperature change).

In the latest version of FUND, the radiative forcing of each gas is modelled according to formulae derived by the IPCC. Equilibrium temperature is determined by radiative forcing and actual temperature is modelled to converge geometrically on the equilibrium value. The sensitivity of sea level rise to temperature is equivalent to the IPCC best estimate and, again, the actual value is modelled to tend geometrically to this limit. This modelling procedure reproduces fairly well the outputs of more complex models with a physical representation of the lags.

The Open Framework incorporates a more detailed description of regional climate change. This is achieved by scaling the spatial predictions of a general circulation model 2xCO_2 equivalent experiment by the global average values from MAGICC. The GISS scenario is used in this assessment. The spatial analysis, at a 0.5 ° latitude by longitude resolution allows more realistic descriptions of future climate change impacts at the country level.

Both models include some description of climatic hazards. FUND allows changes in storm intensity and river floods using an accounting procedure. The Open Framework reports a subjective assessment of hazards based on temperature, precipitation and sea level rise.

2.2.4 Impact Modelling

The approach to impact modelling is divergent between the two models, because of their different structures and emphases.

FUND concentrates on the sectors which have been identified in the literature as being likely to suffer the greatest damages. Impacts and damages are assessed from literature estimates. There is a high level of geographical aggregation - to nine world regions - but there is good linkage of the impacts to the key socio-economic parameters (e.g. per capita income) of the scenarios. Rate and level dependency of damages and the functional form of the temperature/damage curve are treated in detail.

The Open Framework has greater geographical detail working on a national basis, using spatially disaggregated climate change. There is more emphasis on the physical indicators of damage, with use of first-order impact indicators such as degree days, area suitable for agriculture and water surplus. These then are used as the drivers of impacts and damages. In contrast with FUND, the relationship between damages and the rate of climate change is reflected only in assumptions of sensitivity, e.g., the lower projection of climate change also assumes lower estimates of economic sensitivity to climate change.

Table 2.2.1
Attributes of FUND (version 1.6)

Sector	Climate Change Forcing			Impact Variables			Outcomes		
	Temper-ature	Precipi-tation	Sea Level Rise	GDP	Income	Population	Tangible	Intangible	Mortality
Coastal Protection.			√	√			√	√	
Wetland loss			√	√			√	√	
Dryland loss			√	√			√	√	
Migration			√		√	√	√	√	
Agriculture	√			A	√		√		
Species	√			√				√	
Heat stress	√				√	Urban			√
Cold stress	√				√	√			√
Hurricanes				√	√		√	√	√
River floods		Winter		√	√	√	√	√	
Winter storms					√		√	√	
Malaria	√					Susceptible			√

Notes:
Income is per capita income (i.e. GDP/population).
FUND distinguishes between tangible and intangible damages. Both are calculated for each impact sector that reports monetary costs other than mortality. The share of costs between tangible and intangible depends on per capita income. Mortality is calculated as separate impacts for some of the sectors.
A = agricultural GDP

Table 2.2.2
Attributes of the Open Framework

Sector	Climate Change Forcing			Impact Variables			Outcomes		
	Tempe -rature	Precipit- ation	Sea Level Rise	GDP	Income	Popula -tion	Direct	Indirect	Mortality
Coastal Protection			√				√		
Wetland loss			√	A			√		
Dryland loss			√	A			√		
Migration			√		√	Coastal	√		
Agriculture	√	√		A			√		
Water	√	√		√	√		√		
Energy demand	√			√	√	√	√		
Biodiversity			√		√	√	√	√	
Disaster	√	√	√		√		√		√
Other indirect								√	√

Notes:
Income is per capita income (i.e. GDP/population).
The Open Framework distinguishes between direct and indirect impacts, but these are treated as separate sectors. Mortality is calculated in disasters, although some excess deaths contribute to the "other indirect" sector.
A = agricultural GDP.

Given the different purposes and structures, it is difficult to compare the sectoral coverage of the two models. Tables 2.2.1 and 2.2.2 summarise their main attributes. Both have sea level rise impacts (coastal protection, wetland, dryland and migration), agriculture and biodiversity. The Open Framework's disaster module covers heat stress, cold stress, hurricanes, river floods and winter storms (as well as avalanche, drought, hail, landslide, lightning, and tornado). FUND's estimates of malaria are included in an approximate fashion in the Open Framework's "other indirect" sector.

2.2.5 Damage Assessment

The principles of valuing impacts have been well established in ExternE and elsewhere. Willingness to pay for a change in risk is the preferred basis (CEC, 1995b). This is most difficult to implement for non-marketed goods (intangibles) where prices are not immediately apparent. The valuing of climate change impacts is not different in principle, but the problems of valuing across all countries and long into the future makes prices and preferences uncertain. It is assumed that WTP is related to per capita income.

Marginal damages in each region are calculated as the discounted sum of monetised impacts in all future years. Different discount rates are used (0%, 1%, 3% and 10%) to reflect the range of current practice, although a low positive rate is believed to be most reasonable in this context (see Section 3.2).

3. KEY ISSUES

3.1 Equity

Issues of intergenerational equity proved to be the most controversial in the assessment of climate change damages. In particular, the damage costs assessment chapter of the IPCC Report (Pearce et al, 1996) provoked considerable opposition (e.g. Meyer and Cooper, 1995) on the grounds of its perceived implication that lives lost in developing countries are of less value than those in the developed world. The subsequent debate has proved more fruitful. It has drawn attention to the normative content of any aggregation of individual preferences (Fankhauser et al, 1997). Different assumptions about aggregation have been shown to have important consequences for climate change damages (Fankhauser et al, 1997).

These issues are explored in more detail in Appendix 5. Consideration of equity is necessary given the commitments of signatories to the FCCC. This implies that potentially serious impacts in developing countries should not be undervalued. The practice of the ExternE Project has therefore been reassessed in this context.

ExternE to date has used "common unit damages" reflecting average WTP in Europe, for regional scale damages which are largely confined to Europe. Whilst equity considerations make it attractive to carry over this approach to global damages, it is inconsistent with the methodological individualism of welfare economics. Instead, in this paradigm, income dependent WTP values should be accepted and equity issues addressed in the normative process of aggregating individual preferences into the social welfare function. By applying equity weightings to observed (income dependent) WTP values, the social welfare function which is constructed is sensitive to equity concerns.

"Equity weighting" is not an optional extra, but an essential part of cost-benefit analysis. There is no single correct way to aggregate. Even calculations which are referred to as "not equity corrected" make an implicit normative judgement - that WTP reflects marginal utility and that income distribution does not matter in aggregation. But declining marginal utility of income is a more common, and reasonable, assumption. If it is utility which is to be optimised, WTP values need to be weighted by marginal utility of income. If, as commonly assumed, marginal utility of income declines logarithmically, then the appropriate weighting is the inverse of income. This approach is used in this work as the baseline assumption, with "no equity correction" (i.e. constant marginal utility of income) as a sensitivity. The numerical results are equivalent with those obtained using a "common unit damages" approach, but are more soundly based in economic theory.

Damage calculations are based on valuations at the income level applicable in the relevant country or region. When the equity correction factor described above is applied, the utility loss for any impact is the same in all countries. For mortality, this utility loss - the equity corrected values of statistical life (VOSL) - is about 1 MECU. These equity corrected damages are therefore not strictly comparable with other ExternE results based on "uncorrected" European valuations (e.g. VOSL of 3.1 MECU). An internally consistent set of damages due to all types of European emissions can only be obtained by adding all the (uncorrected) damages in Europe before aggregating with non-European damages using whatever aggregation rule is preferred.

3.2 Discounting

The discount rate is a contentious issue in environmental cost benefit analysis. It raises not only complex theoretical questions in the context of sustainability, but also has important influences on results where there are long term effects.

In ExternE, discount rates of 0%, 3% and 10% have typically been used to reflect an adequate range. With regard to climate change, none of the three rates is entirely satisfactory: while rates of 3% or 10% lead to negligible discounted damages for significant long term impacts, a rate of 0% may lead to infinite damages if impacts persist over all time.

There is a variety of approaches to resolving the issue. It can be avoided by rejecting economic valuation as an appropriate tool for the assessment of long term effects. Of course, some other assessment framework is needed in which long term issues are integrated with economic assessment. This is discussed further in Section 3.5 and Appendix 3.

A less radical approach is to use time dependent discount rates. There is now a reasonable theoretical basis for this, based on work both in ExternE (Rabl, 1996) and elsewhere (e.g. Heal, 1996). This is based on theoretical considerations of the discount rate as the social rate of time preference, STP. It is widely agreed (see e.g. CEC (1995b)) that:

$$STP = ITP + W \times U$$

where ITP is the individual rate of pure time preference due to impatience, W is the growth rate of real consumption per capita and U is the elasticity of the marginal utility of consumption.

The elasticity, U, is frequently assumed to be unity and the long term sustainable growth rate, W, is typically expected to be 1-2% (CEC, 1995b). If the precautionary principle is invoked, the lower end of this range is appropriate. The social rate of time preference is very dependent on ITP. The observed value of this can be quite high, justifying high discount rates. Typically values of around 2% are assumed (CEC, 1995b). But, it can be argued that, individual time preference is not an appropriate consideration in inter-generational assessments, where what is at stake is distribution between people in different generations rather than allocation by an individual over a lifetime.

If sustainable development is a guiding principle, it is clear that discount rates for long term damages should be low. Future generations would prefer us to discount damages to them at the long term per capita growth rate (Rabl, 1996). This has an average value of 1.6% and 1.8% in the two scenarios we consider (IS92a and IS92d respectively). The growth rates are somewhat higher in the countries currently facing the highest risks and lower in those responsible for most current emissions. They also vary over time. Discount rates which are time and region specific might therefore be appropriate, but this would require models with an endogenous discount rate, and therefore we have not adopted this approach.

In practice we have not departed from the existing ExternE practice of using a number of fixed discount rates. Much of the damage which will be experienced as a result of greenhouse gas emissions will affect generations other than that of the emitters. There is therefore a strong case for using a low positive discount rate. However, it is clear that the choice is political rather than technical. We therefore use a range of values to represent reasonable choices and to illustrate the discount rate dependence. We adopt rates of 1% and 3% for the baseline assessment on the grounds that these are closest to the long term per capita growth rate. A 1% discount rate implies a low negative rate of pure time preference, whereas a 3% rate implies a positive time preference exceeding 1%. We also report the sensitivity to other discount rates used in ExternE - 0%, and 10%, although these are outside the range commonly considered to be applicable.

It should be noted our assessments use a genuine discount rate, not an 'effective discount rate' (an amalgam of discount rate and growth of valuations over time), which is the basis of results reported in earlier ExternE work (e.g. CEC, 1995a). The FUND and OF models explicitly allow for valuation to change over time in line with changing per capita incomes. The long term 'effective discount rate' which is appropriate from the sustainability arguments above is zero. Results calculated at a discount rate equal to the long term growth rate (i.e. between the 1% and 3% discount rates reported), are therefore comparable with those calculated at 0% effective discount rate elsewhere in ExternE.

3.3 Socio-Economic Factors and Socially Contingent Damages

A wide range of future societies is possible on the timescale affected by impacts of greenhouse gases emitted today. The future impacts depend upon how societies develop, for example, on population growth, technological advance, income and its distribution, and our effectiveness in adapting to and mitigating climate change. The damage is therefore a function of future socio-economic change. Clearly this is uncertain and the uncertainty grows over time. If the damages are dominated by impacts in the far future, the uncertainty can be very large.

This effect has been obscured by the dominant methodology for evaluation of climate change impacts which considers benchmark damages on a world with the current socio-economic characteristics (which is not done in FUND and the OF). The result is a view of climate change damages as something we impose on future generations fixed in the present. Damages should be viewed as dynamic interactions between socio-economic and climatic changes.

The only sensible tool for addressing these issues is the use of scenarios. The scenarios developed for the IPCC provide a range of assumptions about population, income, energy use and land use (Pepper et al, 1992). However, they were developed to analyse greenhouse gas emissions, not their impacts, and therefore some key issues for impact adaptation are not considered, including:

- criteria for protection of coastlines,
- numbers at risk from hunger, drought and storm,
- development of public health and education programmes, and
- policies for ecosystem protection

Nevertheless, we use the IPCC IS92a and 92d scenarios as the most suitable ones available.

For many 'first order impacts', the scenario does not influence the impacts by a large factor. However, more complex impacts may be more significantly affected. For example, where it is impossible or uneconomic to protect low-lying land against sea level rise, it is clear that refugees will be created. The numbers will depend on population, but the costs to society will be determined by other more complex factors. In a rich and equitable world, it might be expected that the refugees would be relatively easily accommodated in other areas and the costs restricted to the expenses of resettlement and integration in a new community. In a less optimistic scenario, the same number of refugees might join a growing dispossessed group, suffer great hardship, increased mortality rates, and even contribute to international conflict. The consequential loss of utility might be orders of magnitude larger than the resettlement cost. This category of damages is largely dependent on the underlying social, economic and political conditions - we therefore refer to them as socially contingent damages.

The treatment of these socially contingent effects of climate change (migration, hunger, conflict etc.) is responsible for the biggest divergence in estimates of damages in the climate change literature. Most of damage studies reviewed by the IPCC (Pearce et al, 1996) exclude socially contingent effects. In some studies this exclusion is made explicit (e.g. Tol, 1997). In others, it is not clear whether the authors do not believe such impacts will occur, find the impacts difficult (or impossible) to quantify, do not believe the impacts should be quantified, or are unhappy with the range of uncertainty that would result from quantitative assessments. The result is that these potential impacts, although addressed in the IPCC review of impacts (e.g. McMichael, 1996), are not reflected in the damage review. In contrast, studies which include rough estimates of socially contingent damages tend to find high values (e.g. Hohmeyer and Gärtner, 1992; Ferguson, 1994; Kuemmel and Sørensen, 1997).

An estimate of the potential socially contingent damages of climate change is presented in Appendix 7, based on reviews of additional numbers at risk of food insecurity due to climate change. It is not sufficient to aggregate the changes in agricultural production that will result from climate change. The distribution is also potentially important in assessment of damages.

Climate change may increase the numbers of people at risk of food shortage by many millions, even if overall food production is increased. It is estimated in Appendix 7 that plausible changes in mortality rate to these populations, under adverse scenario assumptions, could lead to additional annual deaths in the range 0.04 to 3 million. The upper end of the resulting damages is an order of magnitude larger than the total damages in most studies reported by the IPCC. The potential for socially contingent damages is therefore a key sensitivity.

3.4 Uncertainty and Sensitivities

Analysis of uncertainty has typically been rather poor in the external cost literature. In many cases, uncertainty is not addressed at all, with the result that spurious certainty has been accorded to values which are little better than order of magnitude estimates. Where uncertainty is addressed, e.g. in the ExternE Project (CEC, 1995a-d), it is generally only qualitatively, as quantitative assessments of uncertainty are unavailable for many of the impact pathway steps. However, it is clear that many of the steps have significant uncertainty, and therefore that the confidence range for the final value is large.

The treatment of uncertainty in much of the climate damage literature is even worse than in the general external costs literature. Many studies have concentrated on finding a 'best estimate' for global damages. This has sometimes been quoted to two or three significant figures although no serious investigator would claim that the results were anything better than a very approximate estimate. The often quoted range of the IPCC damage survey - $5/tC to $125/tC - (Pearce et al, 1996) is frequently misinterpreted as an uncertainly estimate, whereas in fact it is only the range of 'best estimates' from cited studies. It is clear that more work on uncertainty is needed.

Our efforts to quantify uncertainty are, like others, constrained by both the available data and our modelling capability. In general, the literature, from which the parameters used in the damage calculations are derived, does not provide probability distributions. Expert judgements and our own *ad hoc* assumptions have therefore to be used. The results should be treated as indicative rather than definitive.

The Open Framework model does not allow a formal uncertainty analysis, as the level of spatial disaggregation makes this computationally impossible. An indication of the uncertainty range is therefore obtained by carrying through high and low estimates. The FUND model handles uncertainty more formally: many parameters are given explicit probability distributions and Monte Carlo experiments then allow an estimate of the probability distribution of global damage. Results of the full approach are presented in Section 5.

The FUND model makes some advances in our understanding of climate change damage uncertainty. However, it is not possible with this type of statistical exercise to capture all, or even the most important, sources of uncertainty in climate change. Damage estimation is an exercise in both futurology and value judgements. There are several assumptions which can critically affect the results and which not amenable to resolution by scientific study. These include:

- the discount rate,
- the underlying socio-economic development scenario,
- the method of aggregation of individual utilities (treatment of equity), and

- the value of ecological stability and biodiversity, as well as
- the likelihood of serious socially contingent impacts described in the previous section.

These all involve ethical judgements and/or predicting the future. It would be wrong to think that meaningful probability distributions could be placed on any of them. But clearly they are potentially important issues in the interpretation of any result presented. We have therefore chosen to address them, not probabilistically, but by sensitivity analysis.

In addition, it should be noted that we work within what might be called the dominant paradigm of climate change established by the IPCC. Whilst this clearly represents the best available judgement of the world scientific community, it does not mean it is necessarily correct. The science of climate change, in particular the assessment of its environmental and economic impacts, is in its infancy and may well change significantly. Whilst the most vociferous groupings which reject the IPCC consensus represent a vested interest rather than an intellectually dissident minority, few climate scientists would exclude the possibility of significant negative feedbacks. Similarly, there are potential climate surprises which might dramatically increase the impacts of climate change. These include:

- positive feedbacks in greenhouse gas emissions,
- ice sheet disintegration, and
- 'sudden' modifications to major ocean currents.

Current evidence indicates these are unlikely and therefore probably have only a small effect on expected damages. However, unwelcome climate surprises, by definition, cannot be excluded, and therefore are relevant to a wider integrated analysis.

3.5 Sustainability

It has been shown that the outcome of estimating damages in monetary units is very uncertain for many categories of impact. Moreover, calculating the marginal damages of some ecosystem impacts is hardly viable at all. However, it is important that environmental impacts are not excluded from assessment simply because they are difficult to place monetary values on. Alternative approaches to integrated assessment are therefore required.

Much of the problem underlying monetary valuation arises because of three attributes of environmental impacts:

- they are often better characterised by limits of scale not marginal effects,
- they are frequently very long term, and
- they often affect critical natural systems for which there is no substitute.

Welfare economics was not designed to address issues of this type. In this context, sustainability and sustainable development, although imperfectly defined, are more helpful concepts than the aggregated net present value of future individual utilities.

The relationship between sustainability and monetary valuation of environmental impacts in general has been addressed in a different task of ExternE concerning sustainability indicators (Atkinson et al, 1997). This has considered both the weak sustainability paradigm which implicitly underlies ExternE and the strong sustainability paradigm which is better geared to issues of scale, i.e. limits on the overall magnitude of environmentally damaging activities. Climate change impacts and sustainability have been considered jointly with this task. A detailed description of the work on climate change and sustainability is given in Appendix 3.

Neither weak nor strong sustainability provides a wholly satisfactory framework. And uncertainties do not disappear simply because the framework is altered. Whilst the weak sustainability framework has problems with scale issues, ecological impacts and very long term effects, a strict strong sustainability framework does not allow any trade-offs between environmental damage and the economic costs of greenhouse gas mitigation, even though it is apparent that this will be necessary.

Appendix 3 argues for a middle course, based on 'safe minimum standards' in which targets for tolerable climate change are evaluated based on ecological and economic assessments. This clearly implies some normative judgement of what is tolerable, but any decision making involves normative action. An 'inverse scenario' approach based on earlier work for the German Government (WBGU, 1995) is described in Appendix 3. This is broadly consistent with the approach implied by the Framework Convention on Climate Change. Monetary valuation of damages plays an important role in the integrated assessment. Approaches of this type could be adopted in using climate change damage estimates for policy.

4. ASSESSMENT OF IMPACTS

4.1 Health Impacts

Climate change can influence human health in various ways. The IPCC (McMichael, 1996) identifies:

- heat stress,
- cold stress,
- vector-borne and parasitic diseases,
- air pollution and pollen related asthma and allergic effects,
- socially contingent effects, such as malnutrition and conflict,
- direct injury, infectious diseases and water contamination due to sea level rise, and
- extreme event and storm damage effects,

These impacts are very different in character and geographical distribution. No comprehensive study of them all has been undertaken and therefore damage assessment is inevitably *ad hoc*. The first five impacts are reviewed in Appendix 7 in the context of the ExternE methodology. Effects of the other two are included in other sections.

Much of climate change damage literature to date has concentrated on heat stress effects as the most obvious effect of global warming. In general, there has been an assumption that increases in heat stress will outweigh the reductions in cold stress. This is obviously true in tropical and sub-tropical regions. But in most temperate countries there is a significant excess winter mortality, and therefore a *prima facie* case that warming will reduce mortality rates in these regions. The extensive literature on this topic is largely neglected in most climate change damage assessments. Studies of acute weather effects are difficult to apply to climate change. Re-examination of heat and cold stress indicates that, overall, increased heat stress mortality and decreased cold stress mortality may be broadly comparable globally, although the distributions will be very different.

The potential for vector-borne diseases to extend their ranges outwards from the tropics is well-established. Our review finds that malaria is the most important. Impacts of climate change will be very dependent on the progress made in controlling the disease through public health measures. Mortality mainly affects children. Effects on life span and therefore estimates of the damages are greater than those of the direct effects of temperature.

Health damages of air pollution (via increased ground level ozone impacts) are also potentially significant, although very uncertain because of the difficulties in modelling tropospheric ozone concentrations.

The socially contingent damages resulting from public health effects of food and water shortages are potentially the most important, but also the most uncertain. They depend critically on future social development in the poorest countries where food security is likely to affect mortality rates. Estimates made in Appendix 7 indicate that these could lead to a utility loss of as much as $10,000 billion (5% of global GDP) at benchmark warming in a scenario where sustainable development is not achieved.

4.2 Agricultural Impacts

The effect of climate change on agriculture has been a major concern, with roots in crop-climate studies going back at least a century. Impacts are generally construed as a series of linked assessments:

1. Climate change → Crop suitability → Potential crop yield
2. Potential crop yield → Actual agricultural production
3. Actual agricultural production → Economic impacts → Social impacts

The relationships are, in some cases, complex and non-linear.

The biophysical linkages, between climate change (or its variation), the area suitable for different crops and potential crop yield, can be addressed through a range of models. At the simplest level, temperature and precipitation constraints delineate the area suitable for cultivation. Mechanistic models simulate plant photosynthesis, partitioning of plant growth, water and nutrient balances, and crop yield. In the past few years, the importance of CO_2 enrichment has been stressed. Current transient scenarios of climate change are not as severe as earlier equilibrium scenarios. When CO_2 effects are included, many crops show net benefits from climate change, particularly in temperate regions. Even in the tropics, the effects may not be as severe as once believed, although they are more likely to remain negative.

Major methodological problems at this stage include parameterising the CO_2 effect and scaling up from site-level process models to spatial patterns of changes in potential (and actual) production. While technically possible, a global assessment that couples site-process models and spatial suitability does not exist. Another key difficulty is breadth of coverage. Perhaps twenty major crops account for the majority of food consumption and trade. However, each crop has many varieties, new varieties are released every year, and alternative crops may be common in the future. It is impossible for crop-climate models to keep up, and extremely difficult even to guess how different crops and varieties will respond to climate change.

Most scenarios of climate change have looked at changes in mean values, especially of monthly temperature and precipitation. Yet, crops are known to be sensitive to these factors at different timescales: both to daily weather and to climatic variability. Especially in regions of moisture stress, changes in the number of rain days and drought would have major effects.

Most impact assessments have assumed that changes in potential crop yield (or area suitable for cultivation) will map directly onto changes in actual production. This neglects the fact that actual productivity can lag behind the potential. Crops that perform close to their potential may be more sensitive to climate change than crops where the gap is large. In the latter case, the present scope for improved management could outweigh the effects of climate change. Future production will therefore depend on the social and economic status and expectations of the relevant actors. The gap is largest in developing countries in the tropics, which are often characterised as being inherently more vulnerable to climate change. The pattern of impacts of climate change on agriculture will therefore depend on agricultural management practice.

A major methodological issue is therefore how to handle adaptive responses. Some assessments have constructed yield scenarios for different levels of adaptation. The farm-level assumes low-cost strategies, such as changes in cultivars and agronomic practices, are adopted. More costly adaptation would include expanded irrigation and therefore depends on water resource changes. No study has included potential changes in crop genetics (e.g. reduced costs for pesticides, enhanced yield and yield quality) or changes in the farm enterprise (e.g. including demand for biofuels as a mitigation response to climate change).

The link from changes in actual production to regional and global economies has been addressed through agricultural trade models. Regional production functions are subject to global clearing rules, based on commodity demand and price. The effects on national food balances (the need for imports and exports) are included. Such models are well developed for negotiations on agricultural policy.

However, they have some serious constraints when applied to the long term evolution of agriculture. Much depends on consumer demand. Many models assume that rising per capita income fuels a switch from coarse grains to meat, but few have experimented with behavioural changes in consumption. The role of investment and agricultural technology is often ignored, or treated as an exogenous variable. As such, the agricultural trade models tend to be conservative – projecting the present relationships between production, demand and technology. Large scale discontinuities, either positive (e.g. lower consumer demand) or negative (e.g. disinvestment in vulnerable regions) are not portrayed.

It is the potential for such discontinuities in the social world that generates the largest estimates of damages. Very little empirical work underlies the presumed relationships between climate change and, for example, famine, desertification, migration from semi-arid regions, and water wars. Nevertheless, such concerns are not unimaginable and may be very real outcomes of climate change in some regions (see Appendix 7 for a rough estimate of these impacts).

The easiest approach to valuing agricultural damages is to relate changes in production (or potential production) to agricultural GDP. Since agriculture is a variable proportion of GDP, it is important to construct suitable reference scenarios. More sophisticated analyses rely on consumer and producer welfare. These must be determined through assessments of global prices and trade since a large fraction of food consumption is traded internationally.

Valuing the secondary effects of agricultural impacts is more difficult. Land degradation and migration can be valued - via land markets, the social costs of displaced populations, and human mortality (subject to disagreements over the value of a statistical life). Further social effects of disinvestment, declining living standards, and regional collapse are not so amenable to economic valuation. Such social effects can generate large estimates of damages, and a large range of estimates of their importance (see Section 3.3 and Appendix 7).

In any detailed valuation is it necessary to account for the effects of international trade. The earliest global studies used the Static World Policy Simulation (SWOPSIM) model developed by the US Department of Agriculture (Kane *et al.*, 1992, Reilly *et al.*, 1996). Regional yield changes were based on a US Environmental Protection Agency (EPA) project (Rosenzweig and Iglesias, 1994). Two scenarios were tested by Kane *et al.* (1992). The modest scenario resulted in a 4.0% decrease in the composite price of primary products, an increase in net welfare of $1509m ($1986) and an increase of 0.01% of 1986 GDP. The more severe scenario reversed these estimates: prices increased 41%, welfare decreased by $75,302m and GDP decreased by 0.47%. All of the impacts fall on consumers – producer surplus increases with rising prices. Even in this more severe scenario, China is the only country to suffer losses greater than 1% of GDP.

Studies with the Basic Linked System (BLS), using the same yield changes, illustrate the scope for agricultural adaptation (Fischer *et al.* 1996, Rosenzweig and Parry, 1994). The BLS simulates annual changes in world agriculture, rather than a static, equilibrium experiment such as SWOPSIM. The annual adjustments in prices, demand and production mitigate much of the implied impacts of climate change on yields. For three scenarios of climate change, global cereal production decreases by 1–8% and GDP by 0.5–5.5%. Adaptation was tested at two levels. At the farm level, cereal production decreases up to 5% and GDP up to 4.5%. Further adaptation results in small gains in cereals and GDP (up to 1%) or small losses (around 2% for both cereal production and GDP) for two of the climate scenarios. The impacts were not uniform - losses in developing countries were serious, even with adaptation, while mid-latitude developed regions expected gains in agriculture even without adaptation. As noted above, the adverse effects in developing countries may be attributed at least in part to methodological difficulties.

A more recent study has features of the SWOPSIM study (a static equilibrium trade model), but with a spatially explicit model of crop yields and water resources (Darwin *et al.* 1995). As for the previous studies, the principal conclusion is that climate change in the next century is not likely to imperil aggregate global food production. For four scenarios of climate change, net annual impacts on World GDP ranged from –0.35% to +0.1%. Adjustments in crop selection, inputs and land under cultivation are effective, actually increasing world cereal production.

Both of the climate impact models in the ExternE project include estimates of agricultural damages. In FUND, agricultural damages are scaled to the BLS study cited above. In the Open Framework a spatial index of the area suitable for agriculture is scaled to projections of agricultural GDP. The results reflect the wide range of potential costs.

4.3 Water Supply Impacts

The effect of climate change on water has received less attention at the global level, although numerous regional studies have been undertaken. The linkages are simpler than for agriculture, since little water is traded internationally:

1. Climate change → Runoff and groundwater recharge → Water resources
2. Water resources → Economic impacts → Social impacts

The biophysical linkages, between climate change (or variations) and water resources are typically modelled using hydrological simulations that link climate, land cover, soil water balance, underground recharge, stream-flow, water supply systems (reservoirs, bore-holes, in-stream abstraction) and water demand (agricultural, municipal and industrial).

The importance of CO_2 enrichment on water use efficiency (WUE) is still a major concern. Increased WUE implies less demand for water during the growing season and more runoff. While a consensus for crops seems to be emerging, studies of landscapes and ecosystems are less clear. A recent synthesis suggests that CO_2 enrichment may have little effect on water use efficiency for natural and semi-natural areas. However, reduced demand by crops would reduce irrigation requirements. Since most of humanity's water resources are used for irrigation, future WUE is a major uncertainty in assessments of water resources and climate change.

More recent scenarios of climate change have included all of the parameters that determine potential evapo-transpiration, i.e. temperature, radiation, humidity and wind. In a recent assessment in the UK, concurrent changes in these variables resulted in far less impacts of climate change than experiments with changes in temperature alone (Arnell et al., 1997). Increased humidity reduces the atmosphere's capacity to extract moisture from plants and water surfaces.

As for agriculture, scenarios of climate change should include climatic variability. Water systems are designed to supply reliable yields. A small shift in risk could imply a costly redesign of storage and delivery systems. The effect of sea level rise on coastal aquifers and water use in coastal basins has not been included in either global sea level rise studies nor global water resource assessments.

The links from changes in water resources to regional economies and societal impacts have seldom been quantified. Global data on water supply, use, users, prices, and elasticities of supplies and demand are sparse. Considerable attention on water wars has postulated climate change as a significant threat. As for agriculture, investment, demand management and technology are often ignored. Yet, water scarcity could contribute to the scenarios of extreme damage cited above.

The easiest approach to valuing water resources relies on consumption and consumer prices to calculate welfare (ignoring the effects on water utilities). However, water has many secondary benefits that may not be reflected in marketed consumption. For example, low flows are often maintained to support valuable riverine and wetland ecosystems. It is not clear how the English would value a change from a green and pleasant landscape to parched and xerophytic vistas. Also, water resources respond to variations in supply and demand. The extent to which climate change can be mitigated by developing new resources (e.g. a reservoir) or altering demand (e.g. through pricing) is not clear. In much of the world, water use is not metered and prices do not reflect the volume of use (nor in some cases the actual market cost of water).

The only global estimate of water resources is the study by Darwin *et al.* (1995) as noted above. Changes in water resources were assessed in the context of their impact on irrigated agriculture. Water resources for four climate scenarios were found to increase for the world as a whole (by 6-12%). However, shortages would occur in some regions. For example, in Japan water supplies might increase or decrease by 10% and prices would increase by more than 75%. In contrast, the EC, Australia, New Zealand and SE Asia use less water for irrigation in most of the scenarios tested. The costs of changes in water resources for agriculture are included in the above estimates for agriculture.

In FUND, water resources are excluded from the analysis. In the Open Framework, a spatial index of the water runoff is linked to an economic assessment of supply and demand for water at a country level. The range of results in the Open Framework reflect different assumptions regarding the sensitivity of water supply to the spatial index and different elasticities for supply and demand.

4.4 Sea Level Rise Impacts

The costs of sea level rise can be divided into three types:

- capital costs of protective construction,
- the costs of foregone land services for the loss of dry land, and
- the costs of foregone land services for the loss of wetland.

The three damage categories strongly interact with one another. For example, if a section of dry land (i.e. above sea level) coastline is chosen to be fully protected, no dry land services will be forgone, but the costs of protection will be high, and the adjacent wetland may be flooded.

The total impact of sea level rise, and its distribution over its categories, thus depends on the adaptive policy chosen. For instance, the IPCC Coastal Zone Management Subgroup (IPCC CZMS, 1992) uses the *ad hoc* rule that all dry land with a population density above 10 people per km^2 will be protected. Cline (1992) bases estimates on similar assumptions that developed areas would be protected, while Fankhauser (1995) and Yohe et al. (1995, 1996) employ models which choose the economically optimal value of protection. The difference can be rather drastic as shown in Table 4.4.1.

Table 4.4.1
Estimates of Damages in the USA due to 50 cm Sea Level Rise

Category	Damages (in million US$/year)	
	Fankhauser	Cline[1]
Protection	233	600
Dry land loss	1,322	850
Wetland loss	28,705	2,050
Total	30,027	3,500

1. based on 50% of Cline's estimate for a 1m sea level rise.

The wetland losses are very variable between models and very uncertain as they depend on assumptions made about the value of natural ecosystems, which are extremely controversial (see Section 4.5 and Appendix 8).

Another effect associated with dry land loss is that the people who used to live on land that is subsequently inundated are forced to move. Forced migration may well be one of the most pronounced impacts of sea level rise (Myers and Kent, 1995), considering the fact that people tend to cluster in deltas and near shores (Vellinga and Leatherman, 1989). This aspect has not been fully evaluated, primarily because migration is highly dependent on economic and political factors.

In FUND, impacts of sea level rise are based on the average of Fankhauser's impacts under an average of the *ad hoc* and the optimal rule for the USA, extrapolated to the world using Fankhauser's *ad hoc* assessment. The costs of emigration are set to an arbitrary three times the per capita income. The costs of immigration are set to 40% of the per capita income in the host country (Cline, 1992; Fankhauser, 1995).

In the Open Framework, the IPCC CZMS (1992) and Fankhauser's *ad hoc* methods are used, based on country estimates of the amount of coastline that would be protected and lost. In contrast to FUND, migration is assumed to be contained within the host country.

4.5 Ecosystems and Biodiversity

The IPCC Second Assessment Report describes the state of the art concerning monetary valuation of biodiversity impacts of climate change as follows: "Perhaps the category in which losses from climate change could be among the largest, yet where past research has been the most limited, is that of ecosystem impacts. Uncertainties arise both because of the unknown character of ecosystem impacts, and because of the difficulty of assessing these impacts from a socio-economic point of view and translating them into welfare costs. Existing figures are all rather speculative. There is a serious need for conceptual and quantitative work in this area." (Pearce et al, 1996, p.200)

4.5.1 Biodiversity and Ecosystem Indicators

In the international discussion about environmental indicators, the Pressure-State-Response approach of the OECD is commonly used as a reference framework (OECD, 1994; Rennings and Wiggering, 1996). According to the OECD framework, indicators have to be subsumed under one of the following categories:

- Pressure: Pressure indicators try to answer the questions about the cause of problems. Biodiversity indicators in this category include e.g. stresses like land use for transport and intensive agriculture.
- State: State indicators answer questions about the state of the environment. Biodiversity indicators in this category include e.g. lost and endangered species.
- Response: Response indicators try to answer questions about what is done to solve the problem. Biodiversity indicators in this category include e.g. the size and number of protected areas.

Obviously, the damage pathway approach of ExternE and the corresponding monetary valuation needs state indicators as a basic information. But data is only available for two important state indicators (Walz, 1996):

- threatened or extinct species as a share of total species known, and
- threatened habitats.

Furthermore, for a damage pathway approach, like ExternE, causal relationships between pressure and response indicators of biodiversity cannot be quantified on the basis of present knowledge.

The effect of climate change on biodiversity and ecosystems is still poorly understood. Significant losses of species due to climate change are expected, and some experts judge them as the possibly most important impact of climate change (Kirschbaum et al, 1996a). Causal relations to climate change are only described qualitatively in the literature. For example, impacts for specific types of ecosystem are described extensively by the IPCC (Watson et al, 1996), but mainly in a qualitative way.

Generally, climate change may have an effect on biodiversity of soil microbial and faunal populations by changing soil moisture and temperature, but it is not possible to predict detailed effects. Higher CO_2 concentrations may change the composition of organic compounds in soil nutrients. However, ecosystem impacts caused by climate change seem to be much smaller than impacts caused by land use changes (Kirschbaum et al, 1996b).

Possible biodiversity impacts of global warming for specific types of ecosystems are:

- Forest – While trees are likely to benefit from warming, especially if rainfall and windstorms are not limiting factors, forest ecosystems are highly sensitive to climate change. They contain about two-thirds of all species on earth, with tropical forests alone having at least half of all species. As a consequence of a 10% reduction in the size of forest areas, about 50 % of species could become extinct. Based on this relationship, a temperature rise of 2°C could lead to a loss of 10-50% of the species in the great boreal forest (Kirschbaum et al, 1996a). A key issue is change between forest types: for example, from boreal to temperate broadleaf, from closed savannah to open savannah. Whether a change in dominant forest type reduces species diversity depends on whether species can migrate with their present habitats or adopt new habitats.
- Range land - Climatic warming may cause tundra to become a net source of carbon dioxide. Temperature increases in the tundra will reduce species richness (Allen-Diaz et al, 1996).
- Desert - Biodiversity in existing deserts may improve if rainfall increases, but these effects are poorly understood (Noble and Gitay 1996).
- Oceans - The effects are likely to be much less severe in oceans than in estuaries and wetlands. Most migratory organisms are expected to be able to tolerate a small rise in temperature. However, some sedentary species like corals will be affected, but it is expected that other environmental stresses like direct pollution are more important factors for their degradation (Ittekkot et al, 1996).
- Mountain - Climate change may exacerbate fragmentation and reduce key habitats. Mountain top endemic species are especially endangered by additional climate stress (Beniston et al, 1996).

- Coast and small island - Climate change has the potential to affect coastal biodiversity. It may lead to a change in population sizes and distribution of species, alter the species composition and geographical extent of habitats and ecosystems, and increase the rate of species extinction (Bijlsma et al, 1996).

4.5.2 Monetary Valuation of Biodiversity and Ecosystem Impacts

For biodiversity in general, an extensive economic literature with monetary valuation studies already exists. Many contingent valuation surveys have assessed willingness to pay for the protection of endangered species (for a survey see Loomis and White, 1996; Pearce and Moran, 1994; Perrings et al, 1996). In most cases, values have been derived for single species and for the recreational use of certain areas. Additionally, some estimates are available for the value of plant species for medicinal purposes (Pearce et al, 1996). Monetary estimates of species losses due to global warming have been made by Cline, Fankhauser and Tol (see e.g. Fankhauser and Tol, 1995). Due to the problems described above, all authors have used *ad hoc* assumptions about the impact of climate change on biodiversity.

In a recent study Costanza et al (1997) have estimated very high values for the current economic value of 17 services of the world's ecosystems, in particular for nutrient cycling. The eclectic range of valuations and techniques on which the study draws and the scaling up from small areas to global values makes the study results very controversial. Nevertheless it is clear from other studies that ecosystem functions are important to many human activities, and therefore that values are potentially large (e.g. Barbier et al, 1994). Valuations based on species loss alone are therefore an inadequate measure of ecosystem value.

Ecosystem damages are therefore potentially very large, but it is difficult to calculate marginal damages as the incremental impacts of small changes in ambient conditions on ecosystems are not well quantified. The marginal damages of greenhouse gas concentrations on ecosystems are therefore not computable with any accuracy.

Within ExternE, no monetary values have been recommended for impacts on water, forests or ecosystems. For acidification and eutrophication, physical indicators have been estimated (Mayerhofer 1997), but these indicators can not be transferred directly into damage costs. They indicate a certain level of risk, not damages, and neither probabilities nor scenarios for damage paths are given. Compared with the ecosystem impacts of climate change, it is at least possible to quantify the risks in physical units. For climate change, a comparable methodology measuring ecosystem risks does not exist. Future studies could apply approaches similar to the ExternE assessments for eutrophication and acidification (Atkinson et al., 1997).

The description of ecosystem impacts of climate change is largely qualitative and very uncertain. Against this background, no physical threshold or monetary indicator can be recommended for the monetary valuation. Ecosystem values reported derive from existing *ad hoc* judgements made in earlier versions of FUND and the Open Framework and are incomplete.

4.6 Extreme Events

The assessment approach for most climate change impacts is to link scenarios of climate change with impact models and then to evaluate the potential costs. However, this is not readily accomplished for disasters. Calculating the future costs of weather hazards is constrained by the lack of knowledge in three essential spheres:

- Scenarios of climate change do not yet present a consensus on the likely effects on many weather hazards,
- The present distribution of extreme events is uncertain and may not be stationary on the time scale of decades to centuries, and
- Exposure and vulnerability to weather hazards are changing, rapidly in many parts of the world. The maximum potential loss is unknown except for a few developed regions.

In addition, the imposition of incremental trends in climate (e.g. global warming and sea level rise) upon distributions of extreme events requires downscaling from the global to the local and from long-term trends to specific events. This problem may be best illustrated by an example. The impact of a major flood depends on a combination of factors - when the flood occurs (day or night, holiday season or winter, etc.) and where it occurs (e.g. major metropolitan or rural area), in addition to discharge stage, velocity and duration. The impacts will be largely influenced by the state of preparedness (including warning), exposure to losses (e.g. insurance cover, private and public assistance), and recovery time (e.g. for replacement of infrastructure). All of these factors vary over time and space. Government may be unable to respond to emerging threats just as a failure of land use controls to protect vulnerable areas increases the hazard. A shift in location and a change in land use policy could affect flood damages to a greater degree than climate change *per se*.

The differences between countries and regions and over time are remarkable. Cyclones and storm surges in Bangladesh in the 1970s killed hundreds of thousands. A recent storm killed tens of thousands, following improvements in early warning and cyclone-proof shelters. Hurricanes in North America rarely kill more than a hundred. At the same time, however, property losses due to natural hazards are increasing. As per capita income increases, the value of possessions exposed to losses increases. Development in hazardous locations has been common in many areas, especially the south-east coast of the USA.

To forecast local damages from future disasters would require solving a time-place-risk conundrum. To what extent would intensity and duration be altered? When would events occur, compared to changes in vulnerability? What areas would be affected (either more or less than at present)? The objective of most economic assessments of climate change is to derive an annual average cost. These methodological problems make this problematic for many weather hazards. Nevertheless, some insight into the range of potential impacts and their determinants can be gained through an examination of potential changes in weather hazards.

Seven natural hazards can be identified that are likely to be affected by climate change (increased temperature, precipitation or wind and sea level rise for some). Direct impacts are commonly grouped as lives lost, insured property losses and economic losses (including uninsured losses, damage to infrastructure, and disruption of economic activity). Higher order effects could include changes in investment, retreat from hazardous zones, and social and psychological effects.

1. Frost and cold spells - These are likely to decrease throughout the world. Even a small increase in temperature can dramatically reduce frost risk. Winter cold stress is linked to increased mortality in many temperate countries (see Appendix 7). Reduced cold stress would

have a measurable benefit on lives lost, and some economic benefit through, for example, reductions in frozen pipes (generally insured), reduced need for road de-icing agents and fewer agricultural losses (not insured).

2. Heat waves - The converse of cold spells. Heat stress is strongly related to temperature. The health damages of heat stress may be comparable in total to the benefits from reduced cold stress, but very differently distributed. However, the other losses are relatively small. There may be some loss of quality in agriculture, damage to road surfaces and disruption of economic activity, but most of the serious economic losses during heat waves are due to drought in addition to higher temperatures (see below). Few of the effects of heat waves are insured, other than through routine health services.

3. Drought - This is essentially a prolonged lack of rainfall, although higher temperatures and wind can be major factors. For instance, the 1995 hot summer and drought in the UK was driven to a significant extent by increased demand for garden watering. Similarly dry, but cooler weather in 1997 did not result in as much pressure on water delivery systems. Very few people die of dehydration. However, a large number of people are affected by drought and can be threatened with famine if the higher order impacts are not mitigated through appropriate disasters responses. Although some agricultural produce is insured against drought (or income is maintained through subsidies), little direct insurance is available to mitigate drought impacts. The impacts, however, can be enormous – up to 10% of GDP for prolonged episodes in especially vulnerable countries.

4. Riverine floods - These are related to precipitation - both prolonged abundance and increases in intensity in smaller catchments. It may be possible to have both increased drought and increased flood. Seasonal differences may be accentuated by climate change, resulting in wetter winters and drier summers. Less rainfall and prolonged dry spells could be punctuated by more intense showers and higher runoff. However, regional projections have not been widely available. The loss of life due to floods is significant, but not very large except for coastal storm surges in developing countries (see below). Economic losses can be large, and insurance is variable. Many European and North American countries offer government-supported insurance. The UK is unique in having private flood insurance on a commercial basis. The higher order effects can be significant - disruption of infrastructure (e.g. bridges) and can lead to changes in land use.

5. Mid-latitude windstorms - These can be exacerbated by driving rain. Insured and economic damages can be huge, but few lives are lost. The higher order effects are likely to be small, although loss of mature vegetation is a major concern. If windstorms became sufficiently frequent, building standards and insurance coverage would be altered to reduce exposure.

6. Tropical cyclone -This is the most contentious area of estimates of the damages of weather hazards. The synoptic causes of tropical storms are complex, not readily related to changes in single climatic elements such as sea surface temperatures. The present and potential consequences of cyclones are larger than all of the other weather hazards - thousands of lives lost in developing countries, billions of dollars of insured and economic losses in developed countries. The socially contingent effects on GDP, investment, and even human habitability are significant. For example, the 1995 storms in the Caribbean led to a significant reduction in tourism and GDP (estimated at 18% in Antigua and Barbuda).

7. Other severe weather – Other hazards, e.g. lightning, hail, and tornadoes, have received less attention. A shift from cyclonic to convective precipitation could result in these hazards becoming common in areas that rarely experience them at present. If so, the number of lives lost and insured property losses could be significant. For example, lighting causes the most deaths in the USA among natural hazards, although it receives little media or public attention.

The likelihood of regional changes in each weather hazard is difficult to judge. Increased temperatures are most likely, leading to reduced hazards associated with cold spells and increased heat-related hazards. Hazards related to precipitation – drought and foods – are likely to increase in some regions and decrease in others. Some estimates suggest that summer droughts could increase dramatically, but much depends on precipitation and the effect of carbon dioxide enrichment on evapo-transpiration. There is little consensus at present on future distributions of windstorms and tropical cyclones. Some studies have used increases in mean wind speed as a surrogate for indices of storminess, which are less readily available from climate change models. The incidence of severe weather may increase in temperate regions where cyclonic storms are replaced by convective summer rainfall. However, the future global incidence of severe weather remains uncertain.

The impacts of climate change must be related to projections of exposure and vulnerability. Some aspects of exposure are readily projected at a macro scale, for instance population growth and per capita GDP. However, the critical determinants are more difficult: the population-at-risk is related to locale (distance from the coast); building construction and design (vulnerability to wind vortices, elevation above the flood height) determine much of the economic losses. The interactions between vulnerability and hazard are even more difficult: state of preparedness that saves lives, early warning and preparedness that reduce event damages, adoption of insurance to spread losses, state policies and enforcement of building standards and land use.

The Open Framework provides estimates of these damage categories, using subjective assessments of the sensitivity of each hazard to relevant climate parameters. FUND's analysis is restricted to hurricanes, winter storms and river floods with estimates of frequency driven by global mean temperature. More details of the calculations are provided in Appendices 1 and 2. Both analyses are based on a recent European Union research project on extreme events (Downing, Olsthoorn and Tol, 1996).

5. RESULTS

Results are initially presented separately from the outputs of the two models used - FUND and the Open Framework. Section 5.3 then compares the results.

5.1 Results from FUND

Table 5.1.1 presents the damages by region and impact category at benchmark warming from the FUND model. Damages are divided into those which are dependent on the level of climate change and those which are rate dependent. (The latter may persist for many years, so the lower numerical values in the table do not necessarily indicate lower importance.)

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Table 5.1.1 presents the damages by region and impact category at benchmark warming from the FUND model. Damages are divided into those which are dependent on the level of climate change and those which are rate dependent. (The latter may persist for many years, so the lower numerical values in the table do not necessarily indicate lower importance.)

Table 5.1.1
Damages at Benchmark Warming (in billion US$/year)

Region	Species loss	Human life	Agriculture	Sea level rise	Extreme events	Total
Level dependent damages						
OECD-America	0.0	-1.0	-5.3	0.9	2.5	-2.9
OECD-Europe	0.0	-1.1	-6.0	0.3	0.3	-6.5
OECD-Pacific	0.0	-0.5	-6.1	1.5	5.5	0.3
C and E Europe and Former USSR	0.0	3.7	-23.2	0.1	0.2	-19.1
Middle East	0.0	3.5	3.1	0.1	0.0	6.6
Latin America	0.0	67.0	7.3	0.2	0.0	74.5
South and SE Asia	0.0	81.4	15.8	0.2	0.6	98.8
Central planned Asia	0.0	58.4	-22.2	0.0	0.1	36.3
Africa	0.0	22.5	5.4	0.1	0.0	28.0
Total	0.0	233.9	-31.2	3.4	9.2	215.3
Rate dependent damages						
OECD-America	0.3	0.2	0.3	0.2	0.2	1.2
OECD-Europe	0.3	0.2	0.0	0.2	0.0	0.7
OECD-Pacific	0.2	0.1	0.0	0.3	0.4	1.0
C and E Europe and Former USSR	0.1	0.1	0.0	0.0	0.0	0.2
Middle East	0.0	0.0	0.1	0.0	0.0	0.2
Latin America	0.0	0.4	0.1	0.1	0.0	0.6
South and SE Asia	0.0	0.3	0.1	0.1	0.0	0.6
Central planned Asia	0.0	0.2	0.3	0.0	0.0	0.5
Africa	0.0	0.0	0.1	0.0	0.0	0.2
Total	0.9	1.5	1.0	0.9	0.6	5.2

Source: FUND v1.6

Level dependent damages: global mean temperature: +2.5°C; sea level: +50 cm; hurricane activity: +25%; winter precipitation: +10%; extra-tropical storm intensity: +10%)

Rate dependent damages: global mean temperature: 0.04°C/year; duration of damage memory: tropical cyclones and migration 5 years, agriculture and wetlands (tangible) 10 years, loss of life 15 years, coastal protection, dry land and wetland (intangible) 50 years, species loss 100 years

Regional definitions:

OECD-America: Canada, USA
OECD-Europe: European Union, Norway, Iceland, Malta, Switzerland, Turkey, Israel
OECD-Pacific: Japan, Australia, New Zealand
Central and Eastern Europe and the former USSR: Poland, former Czechoslovakia, Hungary, Bulgaria, Romania, Albania, former Yugoslavia, former Soviet Union
Middle East: Asian-Arabic countries, Iran
Latin America: South and Middle America, Caribbean
South and South-East Asia: Remainder of Asia (Afghanistan eastwards) and islands of the Pacific and Indian oceans
Centrally Planned Asia: China, Laos, Mongolia, Vietnam, North Korea
Africa: Africa

The damages are dominated by mortality effects. These are concentrated in the regions of the developing world and relate primarily to heat stress and malaria The modest reductions in mortality in OECD countries is due to cold stress reduction.

Global agricultural damages estimated are negative (i.e. climate change benefits agriculture), although there are large differences between regions. The temperate regions of the world experience benefits, particularly in Centrally Planned Asia and the countries in transition. On the other hand, there are significant losses in South Asia, Latin America, Africa and the Middle East.

Other impacts lead to lower totals, although the impacts of extreme events lead to significant damages in OECD-Pacific and North America. These damages relate largely to the effects of tropical cyclones. Losses are principally property in OECD countries, but mortality is more important in developing regions. Sea level rise impacts are again most significant in OECD-Pacific and American regions, where high value, susceptible coastal developments are concentrated.

Table 5.1.2
Base Case Damages

Net Present Value of Total Damage 1990-2100 as a Function of Discount Rate[a]					
	0%	1%	3%	5%	10%
Percentage By Sector					
Sea level rise[b]	57.8	61.1	68.6	75.1	82.1
Agriculture	2.7	2.4	1.5	0.7	-0.6
Extreme weather[c]	33.5	30.1	22.7	16.3	9.5
Species	0.9	0.8	0.6	0.4	0.2
Malaria	5.2	5.6	6.7	7.6	8.7
Percentage By Region					
OECD-America	0.3	0.3	0.3	0.3	0.3
OECD-Europe	0.5	0.5	0.5	0.4	0.4
OECD-Pacific	0.1	0.1	0.1	0.1	0.1
C and E Europe and Former USSR	-0.1	-0.2	-0.2	-0.2	-0.2
Middle East	6.9	6.9	6.6	6.2	5.5
Latin America	12.3	12.7	13.6	14.5	15.8
South and SE Asia	42.0	42.5	44.2	46.4	50.3
Central planned Asia	6.4	5.6	3.7	2.1	0.3
Africa	31.7	31.7	31.3	30.2	27.5
Total (in billions of 1990 US dollars)					
Total	519 500	248 800	74 400	31 800	10 100

[a] Scenario: IS92a; equity weighted.
[b] Coastal protection, dryland loss, wetland loss and migration.
[c] Hurricanes, extra-tropical wind storms, river floods, hot spells, cold spells.

Species loss impacts estimated are relatively small. However, it should be noted that these are based on unreliable estimates of habitat and species value only (see Section 4.5), and therefore it cannot be assumed that all impacts on the natural world are insignificant.

Table 5.1.2 presents the results using FUND for the base case scenario adopted in this work - the IPCC IS92a scenario, with damages evaluated over the period 1900-2100 and using equity weighting. The net present value of the global damages (in 10^9 US dollars) over the period is shown, for a number of discount rates, along with a percentage breakdown both by sector/impact category and by region. The damages sum all impacts in the period 1990-2100 and are discounted back to 1990.

Damages due to sea level rise and extreme events are the dominant components of the damage.

Table 5.1.3 shows the marginal damages for each of the three principal greenhouse gases (emitted in each of the next two decades and at a range of discount rates) using the same base case assumptions.

Table 5.1.3
Marginal Damages for CO_2, CH_4 and N_2O Emissions

Greenhouse Gas	**Emission date**	**Damages (as a function of discount rate)**				
		0%	1%	3%	5%	10%
Carbon Dioxide ($/tC)	1995-2004	317	171	60	26	6
	2005-2014	311	157	48	18	3
Methane ($/t$CH_4$)	1995-2004	660	517	295	170	52
	2005-2014	831	556	252	120	24
Nitrous oxide ($/t$N_2O$)	1995-2004	32,735	16,862	5,459	2,217	434
	2005-2014	32,785	15,994	4,510	1,556	197

Source : FUND v1.6
Basis of calculations is our baseline assumptions, i.e.:
damages discounted to 1990;
time horizon: 2100;
scenario: IS92a;
equity-weighted;
no socially contingent effects.

Using the base case assumptions and emissions in the current decade, our baseline estimates of marginal damages using FUND are as follows:

Greenhouse gas	Discount rate		
	1%	3%	
carbon dioxide	170	60	$/tC,
methane	520	300	$/t$CH_4$
nitrous oxide	17 000	5 500	$/t$N_2O$

It is important to note, immediately, that although these are our baseline estimates for sensitivity analysis, the assumptions used are normative. The baseline estimate is not a 'best guess' as other assumptions may be equally valid. The results are presented to two significant figures, but that should not be interpreted as an indication of their reliability to this level of accuracy.

The results are clearly very sensitive to the assumptions about discount rate. At high discount rates the damages are reduced considerably because long term impacts are heavily discounted.

Another key sensitivity is the assumption made about aggregation of values across different regions. In Table 5.1.3 our baseline assumption of declining marginal utility of income is used. Whilst this is plausible it is not the commonest assumption in presenting aggregate damages. Simple summation of monetary damages is more common. Although this implies a welfare function which contravenes most ideas of equity, its results are presented in Table 5.1.4 for comparison.

Table 5.1.4
Marginal Damages for CO_2, CH_4 and N_2O Emissions without Equity Weighting

Greenhouse Gas	Emission date	Damages (as a function of discount rate)				
		0%	1%	3%	5%	10%
Carbon Dioxide (\$/tC)	1995-2004	142	73	23	9	2
	2005-2014	149	72	20	7	1
Methane (\$/tCH_4)	1995-2004	147	141	89	52	16
	2005-2014	264	186	87	41	8
Nitrous oxide (\$/tN_2O)	1995-2004	15,468	7,559	2,201	817	140
	2005-2014	16,313	7,632	1,975	631	71

Source : FUND v1.6
Basis of calculations is our baseline assumptions, i.e.:
damages discounted to 1990;
time horizon: 2100;
scenario: IS92a;
not equity-weighted;
no socially contingent effects.

Damages are decreased substantially by not using equity weighting, because the damages as a fraction of GDP are generally larger in poorer countries.

The effects of other sensitivities are shown in Table 5.1.5.

Table 5.1.5
FUND Sensitivity Analysis of Marginal Damages

Sensitivity	Damages in $/tC				
	0%	1%	3%	5%	10%
Base case	317	171	60	26	6
Emissions in 2005-2014	311	157	48	18	3
Time horizon of 2200	243	172	62	26	6
No equity weighting	142	73	23	9	2
Climate sensitivity of 1.5°C	186	101	35	15	3
Climate sensitivity of 4.5°C	590	318	112	49	11
IS92d scenario	288	156	56	25	6

Source: FUND v1.6
Basis of calculations is our baseline assumptions, i.e.:
damages discounted to 1990; time horizon: 2100;
no socially contingent effects.

Postponing emissions by 10 years, in general, slightly reduces the marginal costs, primarily because they are discounted for 10 more years. Extending the horizon to 2200 makes little difference, except for the zero discount rate. Damages become negative in the late 22nd century, because early incremental emissions lower the long term rate of temperature increase.

The treatment of equity, climate sensitivity and discount rate are critical to the marginal damage value estimate. It should be added that the inclusion of estimates of socially contingent damages might also be a key sensitivity.

Within FUND, uncertainties which are more amenable to statistical treatment have also been addressed. Probability distributions have been estimated for a large number of atmospheric, climatic and impact parameters. The details are presented in Appendix 1. Table 5.1.6 describes the outcomes of a Monte Carlo uncertainty analysis around the base case value for each discount rate assumption. The mean estimate is higher than the base case, because uncertainties are asymmetric and relationships non-linear. The uncertainty is also right-skewed so that median and mode values are smaller that the mean. Table 5.1.6 shows the standard deviation and various percentiles. The estimates of the geometric mean (μ) and geometric standard deviation (σ) are also given. μ and σ are parameters of the lognormal distribution.

It should be noted that the estimates of uncertainty in FUND are preliminary and therefore the uncertainties estimated are indicative of the form rather than a numerically precise probabilistic exercise.

Table 5.1.6
Uncertainty Analysis of Marginal Damages

Parameter	Damages of Carbon Dioxide Emissions (in $/tC)				
	Discount rate				
	0%	1%	3%	5%	10%
Base case	317	171	60	26	6
Mean	465	244	82	35	7
Standard Deviation	267	143	51	22	5
5%	158	81	26	11	2
95%	962	512	178	77	17
μ	400	200	67	30	6
σ	1.7	1.8	1.8	1.9	1.9

Source: FUND v1.6
Damage discounted to 1990
Emissions in 1995-2004
Scenario: IS92a
Time horizon: 2100
Equity weighted
No socially contingent effects.
μ = geometric mean, i.e. e^a, where a is the mean of the logarithm of damage distribution.
σ = geometric standard deviation, i.e. e^b, where b is the standard deviation of the logarithm of the damage distribution.

5.2 Results from the Open Framework

Table 5.2.1 presents the base case damages by sector and region from the Open Framework model, aggregated over the period 1990-2100using both 1% and 3% discount rates. The coastal resources (coastal protection, wetland loss, dryland loss and coastal migration) have been aggregated. Countries are grouped according to the regions defined in FUND. Natural hazard and 'other indirect' cost sectors are not included because the Open Framework calculates these damages on a global basis.

Comments about the spread of costs amongst the regions follow. The costs may actually vary quite significantly within a given region. The Open Framework is not intended to provide national estimates of damages. Countries mentioned below illustrate regional damages, and should not be taken as reliable estimates for individual countries. See Appendix 6 for further regional analysis.

Coastal and agricultural damages are mostly suffered in Africa and South and Southeast Asia. Together they make up for over 84% of the total coastal resource costs and over 95% of the agricultural damages. Many regions are projected to experience a benefit from the agricultural sector but they are relatively small compared to the costs borne in other regions or the costs in other sectors.

Table 5.2.1
Aggregate Damages (1990-2100) by Region and Impact Category

	Damages in 10^9 US$ (1990)					
Region	**Coastal**	**Agriculture**	**Water**	**Heating**	**Cooling**	**Biodiversity**
						1% Discount rate
Africa	1 783	760	1 152	-75	11 104	743
Centrally planned Asia	364	-1	-1 430	-7 986	6 321	889
Latin America	136	77	240	-948	695	264
Middle East	19	-60	196	-4 076	485	52
OECD-America	14	-1	608	-980	493	101
OECD-Europe	28	-2	240	-662	1 174	28
OECD-Pacific	9	-0	2	-290	44	3
S&E Asia	1 614	877	793	-4 139	5 159	2 002
C and E Europe and former USSR	66	-60	15 063	-3 758	1 717	29
Total	**5 483**	**1 590**	**16 864**	**-22 914**	**27 195**	**4 113**
3% Discount rate						
Africa	576	223	360	-17	2 135	190
Centrally planned Asia	155	-0	-576	-2 380	1 733	268
Latin America	52	28	87	-259	170	66
Middle East	7	-18	61	-960	108	12
OECD-America	4	-0	172	-239	118	23
OECD-Europe	8	-1	72	-179	276	7
OECD-Pacific	83	-0	0	-67	9	1
S&E Asia	510	305	279	-1 100	1 171	571
C and E Europe and former USSR	592	-21	4,295	-964	391	7
Total	**1 987**	**515**	**4 751**	**-6 165**	**6 110**	**1 146**

Source : Open Framework, v2.2
Natural hazard and other indirect damages not included

Basis of calculations is:
damages discounted at 1% and 3% to 1990;
time horizon: 2100;
scenario: IS92a;
equity-weighted;
no socially contingent effects.

Water resource damages are particularly large in the USSR and Eastern Europe which is surprising because the Russian Federation experiences a benefit in this sector indicating a huge burden on the other eastern European states (particularly Poland and Romania). A net benefit from this sector is experienced by the Centrally Planned Asia region (China in particular).

The energy sector for heating and cooling shows a very varied distribution of gains and losses. Africa, under this baseline warming scenario experiences the greatest cooling damages while saving least in their heating sector. The Middle East, on the other hand, has a large projected net gain. A good indication of the regional distribution of the damages and benefits is a comparison of the equity and non equity weighted results. Table 5.2.1 is equity weighted and shows that the cooling costs exceed the heating benefits by $4,000 billion. The equivalent non equity weighted results indicate a net benefit of $6,000 billion for the energy sector which indicates the tendency for costs to be incurred by low GNP per capita countries and benefits to be in the relatively wealthier countries.

Finally the biodiversity estimates show great losses to the South and Southeast Asian region. It should be noted though that these damages are not only an indication of the number of species that might become extinct in this region but is also related to the willingness to pay which is scaled to national GNP per capita. The high damages in this region are therefore a reflection of the high number of endangered species in countries like India and Indonesia but also of the relatively large GNP per capita of this region. However, for the reasons given above, damage estimates given for this sector should be treated with the greatest caution.

Other indirect sectors which are calculated by scaling from the direct damages are incorporated in Table 5.2.2. The results shown here cover all discount rates, but are restricted to a percentage breakdown by sector.

The table clearly shows that the indirect damages make up a substantial part of the total costs. In particular the 'other indirect' damages, which have been calculated by a scalar multiplication of the positive costs, contribute about two thirds of the total. Natural hazards (disasters) damages are also considerable.

The direct damages are largely attributable to the water resource sector. Heating benefits are quite substantial but are exceeded by the incremental cooling costs of this baseline warming scenario, leaving only a slight net cost for the energy sector globally. The differences in the regional distribution of these benefits and costs are however significant and will be discussed later. Coastal resources, agricultural and biodiversity damages contribute only small fractions of the total costs under these baseline assumptions.

Table 5.2.3 presents the marginal damages for each of the three principal greenhouse gases (emitted in each of the next two decades and at a range of discount rates) using the baseline assumptions we have chosen, i.e. a 'business as usual' type emission scenario, with equity weighting and no socially contingent effects. The damages sum all impacts in the period 1990-2100 and are discounted back to 1990.

The results from Table 5.2.3 indicate that, for the lower discount rates, delaying emissions has very little influence on the marginal damages. For the higher discount rates the difference increases between the marginal damages by a factor of about 2.

Table 5.2.2
Base Case Damages

Net Present Value of Total Damages 1990-2100 as a Function of Discount Rate				
	0%	1%	3%	10%
Percentage by Sector				
Coastal Protection	0.4	0.5	0.7	1.8
Wetlands	0.4	0.4	0.5	1.0
Drylands	1.3	1.4	1.7	3.3
Migration	0.3	0.3	0.4	0.5
Total Coastal	2.3	2.5	3.3	6.6
Agriculture	0.9	1.0	1.2	1.9
Water Resources	10.5	10.6	10.9	11.1%
Total Agriculture & Water	11.4	11.6	12.1	13.0
Heating Electric	-6.9	-7.0	-6.9	-2.8
Heating Fuel	-7.3	-7.4	-7.3	-4.4
Cooling	18.1	17.1	14.0	3.6
Total Heating & Cooling	3.9	2.7	-0.1	-3.6
Total Direct	17.6	16.8	15.2	16.0
Biodiversity	2.6	2.6	2.6	2.2
Disasters	14.6	15.3	16.9	20.6
Other Indirect	65.3	65.4	65.2	61.3
Total Indirect	82.4	83.2	84.8	84.0
Total in billions of 1990 US Dollars				
Total	338 460	159 306	43 529	3 477

Source: Open Framework, v2.2
Basis of calculations is our baseline assumptions, i.e.:
damages discounted at 0%, 1%, 3% and 10% to 1990;
time horizon: 2100;
scenario: IS92a;
equity-weighted;
no socially contingent effects.

Using the base case assumptions and emissions in the current decade, the estimates of marginal damages using the Open Framework are:

Greenhouse Gas	Discount rate		
	1%	3%	
carbon dioxide	160	64	\$/tC
methane	400	330	\$/tCH_4
nitrous oxide	26 000	9 300	\$/tN_2O

Table 5.2.3
Marginal Damages for CO_2, CH_4 and N_2O Emissions

Greenhouse Gas	Emission date	Damages (as a function of discount rate)				
		0%	1%	3%	5%	10%
Carbon Dioxide ($/tC)	1995-2004	325	164	64	36	14
	2005-2014	323	160	56	27	6
Methane ($/tCH$_4$)	1995-2004	504	405	325	267	146
	2005-2014	594	462	320	220	75
Nitrous oxide ($/tN$_2$O)	1995-2004	52,664	25,846	9,267	4,827	1,618
	2005-2014	52,900	25,549	8,358	3,761	821

Source : Open Framework, v2.2
Basis of calculations is our baseline assumptions

As with the FUND results, the baseline estimate is not a 'best guess' as other assumptions may be equally valid. Similarly, the results are again sensitive to the assumptions about the discount rate.

Results for a simple summation over regions of monetary damages (i.e. without equity weighting) are presented in Table 5.2.4 for comparison.

Table 5.2.4
Marginal Damages for CO_2, CH_4 and N_2O Emissions without Equity Weighting

Greenhouse Gas	Emission date	Damages (as a function of discount rate)				
		0%	1%	3%	5%	10%
Carbon Dioxide ($/tC)	1995-2004	147	74	29	17	7
	2005-2014	147	73	26	13	3
Methane ($/tCH$_4$)	1995-2004	182	160	145	125	73
	2005-2014	217	187	145	105	38
Nitrous oxide ($/tN$_2$O)	1995-2004	24,044	11,733	4,268	2,291	822
	2005-2014	24,248	11,677	3,871	1,787	412

Source : Open Framework, v2.2
Basis of calculations is our baseline assumptions,
except not equity-weighted;

As with FUND, damages are decreased substantially by not using equity weighting, because the damages as a fraction of GDP are generally larger in poorer countries. Generally the equity weighting increases the damages by more than a factor of two for this base case.

Sensitivity analysis undertaken with the Open Framework is less sophisticated than with FUND. Plausible values for low and high damages have been assessed along with the base case value. The results are indicative of the level of uncertainty that is plausible. Because high and low values for several independent parameters are used, the confidence interval represented is likely to be quite large. There is no attempt to characterise a probability distribution.

Table 5.2.5 presents the marginal damages found under the IS92a and IS92d scenarios at different discount levels and at the plausible uncertainty levels. The results are split into results with and without equity weighting. These results are discussed in the order of their significance to the uncertainty ranges:

- Climate and impact uncertainty. These are the source of the most extreme variations in the marginal damage estimates. Low, medium and high estimates are reported based on the combination of uncertainties at each stage of the calculation. Very large ranges of marginal damages result, leading to ratios of the high and low estimates exceeding a factor 2000 in some instances.
- Discount rates. The marginal damages are highly sensitive to the discount rate used. Comparison of 0% and 10% discount rate marginal damage estimates may lead to ratios of about 20 to 60.
- Equity weighting. The use of equity weighting increases the damage estimates by a factor of about 2 for the medium scenarios. This factor can however increase to about 10 (IS92a-Low at 3% discount rate).
- Socio-economic scenario. The marginal damage estimates for the two scenarios vary somewhat. The ratio of the IS92a and IS92d estimate varies between 0.4 and 2.5 over all the discount rates and plausible estimates.
- CO2 emission timing. The table only gives the marginal damages for CO2 emissions between 1995-2004. The estimates for a pulse between 2005-2014 are not included because the results are only marginally different (see Tables 5.2.2 and 5.2.3). The difference increases with the discount rate but even at 10% the effect of a 10 year delay is just a factor of two.

The range of estimates from low to high is as much as an order of magnitude for individual parameters and two orders of magnitude when all of the damages are added together. However, it is not clear what relationship exists between the presumed 80% confidence interval for each parameter and the calculated confidence interval for the aggregate estimate of damages. Most of the parameters represent consistent interpretations of the underlying scenario, to the extent that they are correlated with common driving forces or with each other rather than representing independent distributions. The present range of aggregate results probably represents a confidence interval somewhat greater than 80%, but perhaps not as great as 99%.

The uncertainty analysis is clearly subjective. The Open Framework reflects uncertainty at distinct domains of analysis to portray a sense of where the largest unknowns reside. The Open Framework clearly illustrates some of the potential risks of adverse climate change, while not ignoring the potential for fairly modest impacts.

Table 5.2.5
Uncertainty in Marginal Damages of CO_2

Sensitivity	Damages of Carbon Dioxide Emissions (in $/tC)				
	Discount rate				
	0%	1%	3%	5%	10%
EQUITY WEIGHTED					
IS92a-Low	14.76	7.38	2.63	1.37	0.52
IS92a-Med	325.28	164.45	64.02	36.00	13.62
IS92a-High	12,702.27	6,509.33	2,677.22	1,558.02	591.35
IS92d-Low	12.14	6.13	2.54	1.56	0.67
IS92d-Med	194.40	98.26	39.48	23.06	8.99
IS92d-High	7,032.98	3405.14	1,253.46	687.93	248.49
NON EQUITY WEIGHTED					
IS92a-Low	3.01	1.16	0.29	0.17	0.11
IS92a-Med	146.99	73.98	29.35	17.01	6.83
IS92a-High	6,829.32	3,516.82	1,456.35	853.87	336.06
IS92d-Low	4.28	1.95	0.73	0.46	0.22
IS92d-Med	93.22	46.28	17.90	10.17	3.97
IS92d-High	3,757.34	1,822.56	666.53	364.15	135.43

Source: Open Framework, v2.2
Damage discounted to 1990
Emissions in 1995-2004
Scenario: IS92a and IS92d
Time horizon: 2100
Equity weighted and non equity weighted
No socially contingent effects.

5.3 Comparison of FUND and Open Framework Results

FUND and the Open Framework have radically different structures and inputs (see Section 2.2.1). Comparison of the two is therefore difficult. Both can be used to make estimates of the marginal damages of greenhouse gas emissions, but, whilst the lists of sectors are not dissimilar, damages are calculated in very different ways. The most important differences are:

- Intangible costs in FUND are dominated by human mortality. All indirect (or intangible) costs in the Open Framework are in two sectors, biodiversity and "other",
- Mortality is calculated in four sectors in FUND, compared to only disasters in the Open Framework,

- The Open Framework uses more realistic climate change scenarios, including spatial patterns of temperature and precipitation, whereas FUND uses changes in precipitation and sensitivity tests of extreme events, and
- FUND draws upon published literature to provide benchmark climate change damages, whereas the Open Framework employs a number of parameters to relate physical impacts to damages.

5.3.1 Sectoral Comparison

Because of the different model structures and sectoral reporting definitions, comparison of sectoral damages is not straightforward. The two model results could, in principle, be manipulated in a variety of ways. Damages could be expressed as a percentage of world product (aggregate GDP). Alternatively, the models could be modified to report comparable damages, such as costs in a reference year corresponding to benchmark climate change ($2xCO_2$). The approach adopted here is to compare the sectoral percentages of the total damages (see Table 5.3.1). As marginal damages calculated by the two models are similar (at least in the base case), percentages of the total are similar to ratios of absolute values. Further and more complex model inter-comparison would be possible, but is not likely to reveal substantially different insights.

Table 5.3.1
Comparison of FUND and Open Framework Sectoral Results

Sector	**Percentage of Total Damages**			
	FUND	**FUND**	**OF**	**OF**
	1%	**3%**	**1%**	**3%**
Sea level rise	61.1	68.6	2.5	3.3
Species	4.4	4.1	2.6	2.6
Agriculture	2.4	1.5	1.0	1.2
Disasters			15.3	16.9
Extreme weather	30.1	22.7		
Malaria	5.6	6.7		
Water			10.6	10.9
Energy			2.7	-0.1
Other indirect			83.2	65.2
Total	**100**	**100**	**100**	**100**

Sources:
FUND v1.6 and Open Framework v2.2:
FUND results are equity weighted, IS92a, 1990-2100
Open Framework results are: equity weighted, medium estimates, IS92a, 1990-2100

The difference in structures of the two models makes a comprehensive comparison of sectoral damages impossible. Four sectors are common to the two models. The relative costs for biodiversity are comparable, reflecting common assumptions used to calibrate the models.

FUND and the Open Framework show a small net cost to agriculture in the equity weighted case. If equity weighting is not applied, the FUND results indicate a net global benefit. Some of this difference may be attributed to regional differences (discussed below), but it is not surprising given the different approaches to modelling agricultural effects.

There is a large difference between the estimates for sea level rise damages. Both models include similar estimates of protection, loss of wetlands and loss of drylands. However, FUND includes migration costs, and these can be quite large.

The estimates for disasters in the Open Framework are somewhat lower than that for extreme weather in FUND, because the later also includes the impacts of hot and cold spells on human health. See Appendix 4 for further details.

Damage categories which are not included (at least explicitly) in one model are significant in the other, notably malaria in FUND and the water sector in Open Framework. This illustrates the benefit of using the two approaches.

The major apparent difference is actually a similarity. Both models are dominated by a single sector. Sea level rise damages in FUND more than compensates for the benefits of climate change to agriculture. The Open Framework's "other" indirect sector accounts for almost three-quarters of the total damages. In the case of FUND, the mortality costs are calculated for specific threats. In contrast, the Open Framework's indirect sector is a collection of impacts that have not been quantitatively modelled (other than by a simple scalar based to some extent on published relationships between direct and indirect damages). These can be assumed to be very dependent on mortality damages.

The comparison of the two models shows that the simple, global approach to mortality assessment in the Open Framework is a short-coming. On the other hand, the exclusion of water and energy sectors from FUND is possibly problematic, given the damages values assessed for these sectors in the Open Framework. It is clear that the two analyses together are more valuable than either on its own.

5.3.2 Regional Comparison

Table 5.3.2 shows a comparison between the model results for the regional damages. Here the models have been developed to use the same regional aggregations. That is, the Open Framework reports regional totals from the country-level analysis using the FUND regions.

The two models agree in broad outline: developing countries suffer significantly higher costs than developed regions. For the OECD, costs are modest and in that sense similar. In both models S&SE Asia and Africa show large costs - the two regions giving more than half the total damages. But the balance between the regions is different in the two models - in FUND the damages in Asia are by far the largest, whereas in the Open Framework it is Africa which suffers bigger effects.

The difference in estimate for Latin America is significant. The Open Framework shows quite small costs as heating benefits compensate for costs in other direct sectors. The multiplier approach to assess indirect costs therefore produces only low overall damages. FUND, in contrast, shows high mortality in Latin America.

Table 5.3.2
Comparison of Regional Damages from FUND and Open Framework

Sector	Percent of Total Damages			
	FUND	FUND	OF	OF
	1%	3%	1%	3%
Africa	31.7	31.7	45	42
Centrally Planned Asia	6.4	5.6	-10	-10
Latin America	12.3	12.7	2	2
Middle East	6.9	6.9	-10	-10
OECD-America	0.3	0.3	1	1
OECD-Europe	0.5	0.5	2	2
OECD-Pacific	0.1	0.1	-1	0
S&SE Asia	42.0	42.5	23	21
Former USSR & E&C Europe	-0.1	-0.2	48	52
TOTAL	100	100	100	100

Sources:

FUND v1.6 and Open Framework v2.2:

FUND results are equity weighted, IS92abase case benchmark climate change damages 1990-2100

Open Framework results are equity weighted, medium estimates, IS92a, base case aggregate damages 1990-2100.

Open Framework regional totals do not include disasters or "other indirect" costs since these are calculated only at the global level.

The models disagree in sign and magnitude for three regions. In Centrally Planned Asia (largely China) and the Middle East, the Open Framework shows significant benefits in energy demand, leading to a net benefit from climate change. FUND shows high costs in Centrally Planned Asia, largely from mortality related to tropical cyclones, heat stress and malaria. FUND also estimates significant costs in the Middle East. The biggest difference between the models is for the region of the former USSR and East & Central Europe. Large damages to water resources dominate other impacts and offset benefits to heating and agriculture in the Open Framework. The explanation is not obvious, given the smaller damages in other regions for this sector. In FUND, which neglects water impacts, this region has a net benefit, driven by large gains in agriculture.

5.3.3 Comparison of Sensitivities and Uncertainty

We expect and observe differences between the results from the two models. They have different structures which limits their comparability, even with similar assumptions. Whilst the Open Framework has a much more geographically detailed representation of climatic impacts, FUND is stronger in its analysis of the dynamics of climate change and some sensitivities. The Open Framework therefore gives a better assessment of national vulnerability to climate change, but FUND a more thorough analysis of the economics of the climate problem. The differences are helpful in identifying key sensitivities and uncertainties.

The damages are more sensitive to the discount rate in FUND than in the Open Framework, implying that the damages are, in general, somewhat later in time. However, for discount rates of 3% or less this is a small effect. As most damages are driven by the level of climate change, similar sensitivity to discount rate is to be expected.

The use of different equity weightings also has similar results in the FUND and Open Framework models. The two models use the same exogenous socio-economic scenarios for regional incomes over time. And their calculations produce similar damage distributions between richer and poorer countries (although within each category there are major differences as described above). The result is that, in both cases, the estimates for the damage is reduced by a factor of about two or three if simple aggregation of regional totals is used instead of utility weighting based on marginal utility of income.

The two models produce varying results when the effects of using different socio-economic scenarios are considered. In both cases, the effect of moving towards a world with lower emissions, better environmental standards, lower population and higher per capita income is to reduce marginal damages as might be expected. However, with FUND, a change from the IS92a scenario to IS92d, produces a reduction in damages of less than 10%; with the Open Framework the change is more than 50%. The IPCC scenarios provide insufficient information to assess socio-economic sensitivity to climate change, and therefore require additional assumptions. We believe these, essentially *ad hoc*, assumptions are likely to be responsible for the different results.

The effect of the timing of emissions is small. A modest (10 year) delay in emissions reduces marginal damages, but largely because of the effect of discounting back to a common year. The sensitivity to a longer time horizon (2200 instead of 2100) has only been examined in the FUND model, but does not seem to be an important sensitivity.

The largest sensitivity found with the Open Framework is to different assumptions about the sensitivity of climate and impact levels to greenhouse concentrations. Differences of three orders of magnitude can be obtained by taking consistently high or low assumptions at each stage of the calculation. This is a powerful indication of the limitations in the state of the art of assessment of climate change impacts. These results cannot be compared directly with those of FUND, where climate sensitivity is treated separately from impact sensitivity - the latter being handled by Monte Carlo uncertainty analysis.

The structure and computational complexity of the Open Framework means that formal uncertainty analysis has only been undertaken in FUND. The results are consistent with the usual ExternE uncertainty assumption of a log normal (i.e. positively skewed) distribution. The mean is somewhat higher than the "best guess" value and the geometric standard deviation is about 1.8. This uncertainty is somewhat lower than some other assessment in ExternE for damage categories widely felt to be less uncertain than those of climate change. However, it should be noted that the uncertainty parameters used are based on expert judgement, and therefore the analysis is largely illustrative. Moreover, the formal uncertainty analysis excludes important issues handled separately by uncertainty analysis.

The uncertainty analyses of the two models are clearly very different and therefore not directly comparable, but both show large ranges of plausible estimates. FUND has sizeable uncertainty ranges: the 1-99 percentile range in the base case is $48-659/tC at a 1% discount rate and \$15-235/tC at a 35 discount rate. The equivalent low and high estimates for the Open Framework (although not formally identified as particular confidence limits) are even larger, \$7-6510/tC at a 1% discount rate and \$3-2670/tC at a 3% discount rate. This stresses the need for uncertainty analysis as opposed to a narrow focus on 'best guesses' in future climate change damage work.

It must also be recognised that neither model is designed to deal with the possibility that climate change impacts are qualitatively different from those identified as probable by the scientific community. Socially contingent health impacts under some conditions of socio-economic development and climate change could be as high as \$10,000 billion per year (see Section 4.1), with marginal damages of the order of \$10,000/tC. Alternatively, unidentified negative feedbacks in the climate system could make climate damages negligible. The probability of either of these is not easily quantified, so it would be unwise to assert they lie outside the 99% confidence limit.

5.3.4 Conclusions of the Comparison

At this stage in the evaluation of climate change damages, it is not realistic to expect models with substantially different structures to agree. Artificially forcing them to concur for specific sectors or regions would be unscientific and unhelpful. Rather, the diverse results should sound a strong note of caution, which should be made clear in any presentation of the costs of climate change. Large differences between estimates for specific sectors and regions are common. Disagreement between model estimates at this level is likely to increase in the near future.

The base case marginal damages assessed by FUND and the Open Framework are very similar for carbon dioxide (\$170/tC and \$160/tC respectively). The marginal damages of methane are somewhat higher in FUND (\$520/t as opposed to \$400/t). The Open Framework leads to higher estimates for the marginal damages of nitrous oxide (\$26,000/t versus \$17,000/t for FUND). Given the nature of the calculations these are all a remarkably good level of agreement. The close convergence of the two models on the marginal damages of all the greenhouse gases is rather surprising considering the different structures of the models. As the sectoral and regional differences are large, we judge that the very close agreement of the totals for marginal damages is fortuitous. It should not be used to imply certainty that this is a "correct value".

The uncertainty assessment and sensitivity analyses undertaken shows the range of damages which can be estimated with plausible assumptions about the impacts of climate change. The range is very large. It is found that the values are potentially very sensitive to assumptions about:

- climate sensitivity,
- the nature and level of impacts
- discount rate,
- the treatment of equity,
- the value of statistical life, and
- the magnitude of socially contingent effects.

6. CONCLUSIONS

The literature on climate change damages shows a very wide range estimates of the marginal costs of climate change. We have made a careful examination of the issues which reveals that there are a number of reasons for this. The impacts of climate change are far reaching in space and time, and their nature and level has not been accurately assessed in many cases. In valuing the impacts, difficult, and essentially normative, judgements are made about:

- discount rate
- the treatment of equity,
- the value of statistical life, and
- the magnitude of socially contingent effects.

Two models - FUND and the Open Framework - have been used to asses the damages of climate change. In so far as is possible, there has been an attempt to make the assumptions within the models consistent. However, they are very different in structure and purpose, so that convergence is neither possible nor desirable. The damages have been calculated for a range of different assumptions. For our base case results shown in Table 6.1, the marginal damages calculated by the two models are in good agreement.

Table 6.1
Marginal Damages ($) of Greenhouse Gas Emissions

Greenhouse Gas	Damage Unit	Marginal Damage from Model			
		FUND		Open Framework	
		1%	3%	1%	3%
Carbon Dioxide, CO_2	\$/tC	170	60	160	64
	\$/tCO_2	46	16	44	17
Methane, CH_4	\$/tCH_4	520	300	400	330
Nitrous Oxide, N_2O	\$/tN_2O	17 000	5 500	26 000	9 300

Source: FUND v1.6 and Open Framework v2.2
Basis: IPCC IS92a scenario
equity weighted
no socially contingent effects
emissions in 1995-2005
time horizon of damages 2100

The data in Table 6.1 are quoted in 1990 US dollars which is the norm for climate change damage work. For the purposes of ExternE, 1995 ECU is the standard currency. The relevant conversion factor is taken to be 0.96 (0.8 for 1990 ECU:1990 US\$; and 1.2 for 1995 ECU: 1990 ECU). In addition, the damages are restated for a 1995 start year, involving 5 years discounting (a factor of 1.05 for 1% discount rate and 1.16 for a 3% discount rate). The converted results are presented in Table 6.2.

Table 6.2
Marginal Damages (ECU) of Greenhouse Gas Emissions

Greenhouse Gas	Damage Unit	Marginal Damage from Model			
		FUND		Open Framework	
		1%	3%	1%	3%
Carbon Dioxide, CO_2	ECU/tC	170	70	160	74
	ECU/tCO_2	46	19	44	20
Methane, CH_4	ECU/tCH_4	530	350	400	380
Nitrous Oxide, N_2O	ECU/tN_2O	17 000	6 400	26 000	11 000

Source: FUND v1.6 and Open Framework v2.2
Basis: IPCC IS92a scenario
equity weighted
no socially contingent effects
emissions in 1995-2005
time horizon of damages 2100

In this assessment, we attempt to make clear the effects of different assumptions on the marginal damages of climate change. The base case values for carbon dioxide damages calculated from the two models should not therefore be quoted out of context or taken to be a 'correct' value. Uncertainty analysis in FUND indicates a geometric standard deviation of approximately 1.8, for uncertainties in climate and impacts which can be parameterised. But many important issues have not been quantified and create additional uncertainty. The treatment of equity, discount rate and possible socially contingent impacts in particular can have a large effect on damages. The effects of some of these sensitivities on the marginal damages of carbon dioxide (calculated in FUND) are shown in Table 6.3. Assumptions about socially contingent effects could affect the results even more.

Table 6.3
FUND Sensitivity Analysis of Marginal Damages for CO_2 Emissions

Sensitivity	**Damages in 1990$/tC (1995ECU/tC)**	
	1%	3%
Base case	170 (170)	60 (70)
No equity weighting	73 (74)	23 (27)
Low Climate sensitivity	100 (100)	35 (41)
High climate sensitivity	320 (320)	110 (130)
IS92d scenario	160 (160)	56 (65)

Source: FUND v1.6
Basis of calculations is our baseline assumptions, i.e.:
damages discounted to 1990;
emissions in 1995-2005:
time horizon: 2100;
no socially contingent effects.

The valuation of ecosystem and biodiversity impacts of climate change has proved difficult. Ecosystem valuation studies are qualitative or based on *ad hoc* assumptions. Thus, the estimates of values of marginal ecosystem effects which are available are very unreliable. In common with the rest of the ExternE Project no values for ecosystem damages are recommended.

An approach consistent with sustainability requires consideration of long term impacts, ecosystem stability and scale effects. This suggests the use of an assessment framework in which other approaches than the estimation of marginal damages are included. However, damage calculation will remain an important component of any integrated assessment.

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Appendix 1

The Climate Framework for Uncertainty, Negotiation and Distribution

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ANNEX 1. THE *CLIMATE FRAMEWORK FOR UNCERTAINTY, NEGOTIATION AND DISTRIBUTION*

This annex describes the *Climate Framework for Uncertainty, Negotiation and Distribution*, version 1.6, and presents the full set of results on which the main ExternE report is based, including those under uncertainty.

A1.1 The Model

FUND is an integrated assessment model of climate change. Figure 1 present its flow diagram. A description of an earlier version and its results can be found in Tol (1997a,b). Below, novelties of version 1.6 are treated. Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations, specified for nine major world-regions, defined in Table A1.1.

Figure 1. Flow diagram of the *Climate Framework for Uncertainty, Negotiation and Distribution*.

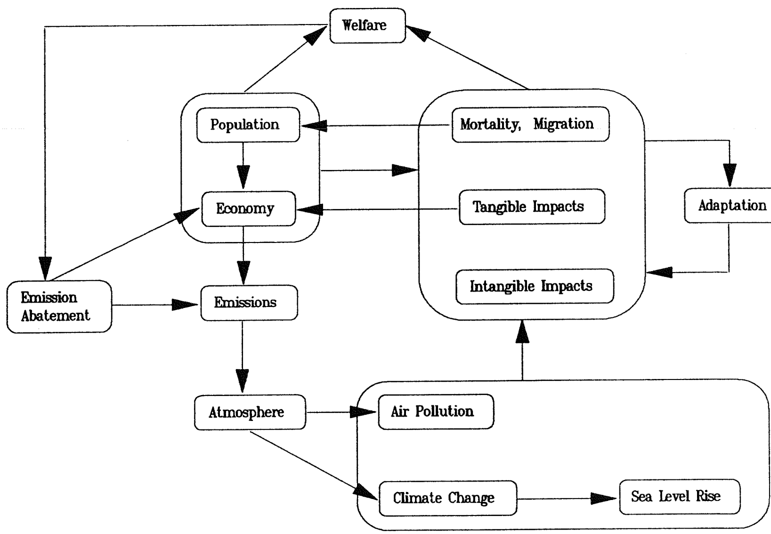

Table A1.1. Regions of the *Climate Framework for Uncertainty, Negotiation and Distribution.*

Region (acronym)	Description
OECD-America (OECD-A)	Canada, USA
OECD-Europe (OECD-E)	European Union, Norway, Iceland, Malta, Switzerland, Turkey, Israel
OECD-Pacific (OECD-P)	Japan, Australia, New Zealand
Central and Eastern Europe and the former USSR (CEE&fSU)	Poland, former Chzechoslovakia, Hungary, Bulgary, Romania, Albania, former Yugoslavia, former Soviet Union
Middle East (ME)	Asian-Arabic countries, Iran
Latin America (LA)	South and Middle America, Caribbean
South and Southeast Asia (S&SEA)	rest of Asia and Oceania, stretching from Afghanistan to Papua New Guinea, including archipalogo nations in Indian and Pacific oceans
Centrally Planned Asia (CPA)	China, Laos, Mongolia, Vietnam, North Korea
Africa (AFR)	Africa

The model runs from 1950 to 2200, in time steps of a year. The simulation period of earlier versions started in 1990. Some overlap with the observational record provides an opportunity for model validation; the prime reason for extending the simulation period into the past, however, is the necessity to initialize the climate change impact module. In *FUND*, climate impacts are assumed to depend on the impact of the year before, to reflect the process of adjustment to climate change. Without a proper initialization, climate impacts are misrepresented in the first decades.

The *IMAGE* 100-year database (Batjes and Goldewijk, 1994) is a valuable source for the scenarios for the period 1950-1990. *FUND*'s base scenarios for the period 2010-2100 are based on the EMF Standardised Scenario. The period 1990-2010 is a linear interpolation between observation and the EMF scenario. The period 2100-2200 is an extrapolation of the EMF scenario. In addition, a library of alternative scenarios is available, consisting of the EMF Standardised Scenario (proper), and the IPCC IS92a, IS92d and IS92f scenarios (Leggett *et al.*, 1992). IS92a is the base scenario used for EXTERNE. Note that the original EMF and IPCC scenarios had to be adjusted to fit *FUND*'s nine regions and yearly time-step.

The scenarios concern the rate of economic growth, the population growth, autonomous energy efficiency improvements, the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and methane and nitrous oxide emissions. The share of urban in total population is, up to 2025, based on the World Resources Databases (e.g., WRI, 1992); after 2025, urban population slowly converges to 95% of total population; this is not varied between the scenarios.

The scenarios of economic and population growth are perturbed by the impact of climate change. Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population; heat stress only affects urban population. Population also changes with climate-induced migration between the regions.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, and the impact of climate change on coastal zones, agriculture, extreme weather, natural ecosystems and malaria.

The physical parts of *FUND* differ considerably compared to previous versions. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

$$C_t = C_{t-1} + \alpha E_t - \beta(C_{t-1} - C_{pre}) \qquad (1)$$

where C denotes concentration, E emissions, t year, and *pre* pre-industrial. Table A1.2 displays the parameters for both gases.

Table A1.2. Parameters of equation (1).

gas	α^a	β^b	pre-industrial concentration
methane (CH_4)	0.3597	1/8.6	790 ppb
nitrous oxide (N_2O)	0.2079	1/120	285 ppb

[a] The parameter α translates emissions (in million metric tonnes of CH_4 or N_2O) into concentrations (in parts per billion by volume).
[b] The parameter β determines how fast concentrations return to their pre-industrial (and assumedly equilibrium) concentrations; $1/\beta$ is the atmospheric life-time (in years) of the gases.

The carbon cycle follows a five-box model:

$$Box_{i,t} = \rho_i Box_{i,t-1} + 0.000471\alpha_i E_t \qquad (2a)$$

with

$$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t} \qquad (2b)$$

where α_i denotes the fraction of emissions E (in million metric tonnes of carbon) that is allocated to box i (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and ρ the decay-rate of the boxes (ρ = exp(-1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). Thus, 13% of total emissions remains forever in the atmospheric, while 10% is -- on average -- removed in two years (after Hammitt *et al.*, 1992). Carbon dioxide concentrations are measured in parts per million by volume.

Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine *et al.* (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by radiative forcing RF), with a life-time of 50 years. In the base case, global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents, so:

$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \cdot \ln(2)} RF_t \tag{3}$$

Global mean sea level is also geometric, with its equilibrium determined by the temperature and a life-time of 50 years. These life-times result from a calibration to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996). *FUND* also calculates hurricane activity, winter precipitation, and winter storm activity because these feed into the damage module. However, these factors depend linearly on the global mean temperature. In the current model version, this is merely accounting; a future version of the model will improve on this. A future version will also investigate the influence of sulphate aerosols (a regional climate effect).

The climate impact module is largely the same as in Tol (1996, 1997a,b; cf. also Pearce *et al.*, 1996 and Watson *et al.*, 1997). Only a limited number of categories of the impact of climate change is considered. The damage module has two units of measurement: people and money. People can die (heat stress, malaria, tropical cyclones), not die (cold stress), or migrate. These effects, like all impacts, are monetized. Damage can be due to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 2.5°C). The benchmarks can be found in Table A1.3. Damage in the rate of temperature change slowly fades at a speed indicated in Table A1.4. Damage is calculated through a second-order polynomial in climatic change. Damage is distinguished between tangible (market) and intangible (non-market) effects. Tangible damages affect investment and consumption; through investment, economic growth is affected; through consumption, welfare is affected. Intangible damages affect welfare. Relative vulnerability to climate change changes with economic development in many ways. The importance of agriculture fall with per capita income growth, and so do malaria incidence and the inclination to migrate. Heat stress increases with urbanization. The valuation of impacts on non-marketed goods and services increases with per capita income.

The damage module of *FUND* is dynamic in the level of socio-economic development. Part of the dynamics hinges on the economic and demographic structure of the region, and part is directly indexed on per capita income. IC, the factor with which the intangible losses increase, follows

$$IC_{j,t} = \frac{Y^a_{j,t}/P^a_{j,t}}{1 + Y^a_{j,t}/P^a_{j,t}/20000} \frac{1 + Y^a_{j,0}/P^a_{j,0}/20000}{Y^a_{j,0}/P^a_{j,0}} \tag{4}$$

where *Y/P* denotes income per capita. *DC*, the factor with which damage largely related to poverty (such as malaria) decreases with economic growth, follows

$$DC_{j,t} = \frac{1 + Y^a_{j,0}/P^a_{j,0}/500}{1 + Y^a_{j,t}/P^a_{j,t}/500} \tag{5}$$

(4) and (5) are both logistic curves, the former increasing and the latter decreasing in per capita income. The scaling factors (20,000 and 500, respectively) are arbitrary — they approximately equal the 1990 per capita income in the richest and the poorest region.

The loss of species, ecosystems and the like C^S is modelled as

$$C^S_{j,t} = \frac{SL_j}{60} Y_{j,t} IC_{j,t} \frac{1}{2}\left(\frac{|\Delta T_t|}{0.04} + \left(\frac{\Delta T_t}{0.04}\right)^2\right) + \rho_S C^S_{j,t-1} \tag{6}$$

where *SL* is the species loss coefficient in fraction of GDP, divided by 60 to go from the level to the rate of change; 0.04 is the base line change of the global mean temperature (2.5°C in 60 years). Note that the dependency of valuation on per capita income is consistent between regions and over time. The foundation for the estimated welfare loss due to species, ecosystem and landscape loss is very weak.

The number of deaths D^H related to heat stress follows

$$D^H_{j,t} = D^{H,L}_{j,t} + D^{H,R}_{j,t} \tag{7a}$$

where

$$D^{H,L}_{j,t} = H^L_j \upsilon_{j,t} P_{j,t} \frac{T_t}{2.5} \tag{7b}$$

with *P* denoting population, υ the share that lives in the city; 2.5 is the base change in global mean temperature, and

$$D^{H,R}_{j,t} = \frac{H^R_j}{60} \upsilon_{j,t} P_{j,t} \frac{1}{2}\left(\frac{|\Delta T_t|}{0.04} + \left(\frac{\Delta T_0}{0.04}\right)^2\right) + \rho_D D^{H,R}_{j,t-1} \tag{7c}$$

The number of deaths related to cold stress D^C follows an identical scheme with different parameters; cold stress is assumed to affect the entire population, not just city dwellers.

(3)

The costs C^{HC} follow from

$$C_{j,t}^{HC} = VHL_{j,t}(D_{j,t}^{H} + D_{j,t}^{C}) \tag{8}$$

where

$$VHL_{j,t} = 250{,}000 + 175 Y_{j,t}^{a}/P_{j,t}^{a} \tag{9}$$

The number of additional malaria deaths D^M follows from

$$D_{j,t}^{M} = M_j DC_{j,t} P_{j,t}^{a} \frac{T_t}{2.5} \tag{10}$$

that is, malaria is assumed to be linear in the level of global mean temperature change, no adaptation takes places, and all damages are obtained at once. However, susceptibility to malaria is assumed to decrease with increases in per capita income. The loss in monetary terms follows from multiplication with (9).

Agricultural damage C^{Agr} is supposedly equal to

$$C_{j,t}^{Agr} = C_{j,t}^{Agr,L} + C_{j,t}^{Agr,R} \tag{11a}$$

where

$$C_{j,t}^{Agr,L} = Agr_j^{L} Y_{j,t}^{Agr} \frac{T_t}{2.5} \tag{11b}$$

and

$$C_{j,t}^{Agr,R} = Agr_j^{R} Y_{j,t}^{Agr} \frac{1}{2}\left(\frac{|\Delta T_t|}{0.04} + \left(\frac{\Delta T_t}{0.04}\right)^2\right) + \rho_{Agr} C_{j,t-1}^{Agr,R} \tag{11c}$$

Y^{Agr} is the agricultural product, the share of agriculture in total output. It changes with per capita income with an elasticity of -0.31, which corresponds to the per capita income elasticity across *FUND*'s 9 regions in 1990.

Hurricane damage C^{Hr} is

$$C_{j,t}^{Hr} = C_{j,t}^{Hr,L} + C_{j,t}^{Hr,R} \tag{12a}$$

where

$$C_{j,t}^{Hr,L} = \frac{1}{6} Hr_j Y_{j,t} \frac{HA_t}{0.25} \tag{12b}$$

with HA denoting hurricane activity; 0.25 is the base increase, and

$$C_{j,t}^{Hr,R} = \rho_{Hr} C_{j,t-1}^{Hr,R} + \begin{cases} \frac{5}{6} \frac{Hr_j}{60} Y_{j,t}^a \frac{1}{2} \left(\frac{|\Delta HA_T|}{0.004} + \left(\frac{\Delta HA_t}{0.004} \right)^2 \right) & if \quad \Delta HA_t > 0 \\ \frac{1}{5} \frac{1}{6} \frac{Hr_j}{60} Y_{j,t}^a \frac{1}{2} \left(\frac{|\Delta HA_t|}{0.004} + \left(\frac{\Delta HA_t}{0.004} \right)^2 \right) & if \quad \Delta HA_t < 0 \end{cases} \tag{12c}$$

where 0.004 is the base increase in hurricane activity per year (0.25/60). The number of additional deaths due to hurricane activity exactly mirrors (12); the costs follow from multiplication by (9).

Damage due to river floods C^{RF} is modelled as

$$C_{j,t}^{RF} = RF_j Y_{j,t}^a \frac{P_t}{0.1} \tag{13}$$

with P denoting winter precipitation; 0.1 is the base increase.

Damage due to winter storms C^{WS} is modelled as

$$C_{j,t}^{WS} = WS_{j,t} Y_{j,t}^a \left(\frac{SA_t}{0.06} \right)^2 \tag{14}$$

with SA denoting winter storm activity; 0.06 is the base increase.

The number of people forced to migrate is

$$PL_{j,t} = \frac{L_j}{60} DC_{j,t} P_{j,t}^a \frac{|\Delta SL_t|}{0.008} \tag{15}$$

where SL denotes sea level; 0.008 is the base increase (0.50 meter in 60 years). Migration is assumed to decline with decreasing poverty. The costs of people leaving C^L is then

$$C_{j,t}^L = PL_{j,t} 3 Y_{j,t}^a / P_{j,t}^a + \rho_L C_{j,t-1}^L \tag{16}$$

and the costs of people entering C^E

$$C_{j,t}^{E} = 0.4Y_{j,t}^{a}/P_{j,t}^{a}\sum_{i}\mu_{ij}PL_{i,t} + \rho_{E}C_{j,t-1}^{E} \tag{17}$$

where μ_{ij} is the fraction of people (in region i) that leaves region i and enters region j. The foundations of the estimates of the number of migrants and the resulting economic and welfare losses are very weak. Including migration influences the structure of the model, however, by establishing a link between the regional populations. The numbers are too low to have a substantial impact on population growth rates.

The costs of coastal protection C^{CP} are

$$C_{j,t}^{CP} = C_{j,t}^{CP,L} + C_{j,t}^{CP,R} \tag{18a}$$

where

$$C_{j,t}^{CP,L} = \frac{3}{4}CP_{j}Y_{j,t}^{a}\frac{SL_{t}}{0.50} \tag{18b}$$

0.50 is the base increase, and

$$C_{j,t}^{CP,R} = \rho_{CP}C_{j,t-1}^{CP,R} + \begin{cases} \frac{1}{4}\frac{CP_{j}}{60}Y_{j,t}^{a}\frac{1}{2}\left(\frac{|\Delta S_{T}|}{0.008} + \left(\frac{\Delta S_{t}}{0.008}\right)^{2}\right) & if \ \ \Delta S_{t}>0 \\ \frac{1}{5}\frac{1}{4}\frac{CP_{j}}{60}Y_{j,t}^{a}\frac{1}{2}\left(\frac{|\Delta S_{t}|}{0.008} + \left(\frac{\Delta S_{t}}{0.008}\right)^{2}\right) & if \ \ \Delta S_{t}<0 \end{cases} \tag{18c}$$

The costs of dryland loss C^{DL} follow

$$C_{j,t}^{DL} = C_{j,t}^{DL,L} + C_{j,t}^{DL,R} \tag{19a}$$

where

$$C_{j,t}^{DL,L} = \frac{3}{4}DL_{j}Y_{j,t}^{a}\frac{SL_{t}}{0.50} \tag{19b}$$

0.50 is the base increase, and

$$C_{j,t}^{DL,R} = \rho_{DL} C_{j,t-1}^{DL,R} + \begin{cases} \frac{1}{4}\frac{DL_j}{60} Y_{j,t}^a \frac{1}{2}\left(\frac{|\Delta S_T|}{0.008} + \left(\frac{\Delta S_t}{0.008}\right)^2\right) & \text{if } \Delta S_t > 0 \\ \frac{1}{5}\frac{1}{4}\frac{DL_j}{60} Y_{j,t}^a \frac{1}{2}\left(\frac{|\Delta S_t|}{0.008} + \left(\frac{\Delta S_t}{0.008}\right)^2\right) & \text{if } \Delta S_t < 0 \end{cases} \quad (19c)$$

The tangible costs of wetland loss $C^{WL,\,T}$ are

$$C_{j,t}^{WL,T} = \rho_{WL,T} C_{j,t-1}^{WL,T} + \begin{cases} \frac{1}{2}\frac{WL_j}{60} Y_{j,t}^a \frac{1}{2}\left(\frac{|\Delta S_T|}{0.008} + \left(\frac{\Delta S_t}{0.008}\right)^2\right) & \text{if } \Delta S_t > 0 \\ \frac{1}{5}\frac{1}{2}\frac{WL_j}{60} Y_{j,t}^a \frac{1}{2}\left(\frac{|\Delta S_t|}{0.008} + \left(\frac{\Delta S_t}{0.008}\right)^2\right) & \text{if } \Delta S_t < 0 \end{cases} \quad (20a)$$

and the intangible costs of wetland loss $C^{WL,\,I}$ are

$$C_{j,t}^{WL,I} = \rho_{WL,I} C_{j,t-1}^{WL,I} + \begin{cases} \frac{1}{2}\frac{WL_j}{60} Y_{j,t}^a IC_{j,t} \frac{1}{2}\left(\frac{|\Delta S_T|}{0.008} + \left(\frac{\Delta S_t}{0.008}\right)^2\right) & \text{if } \Delta S_t > 0 \\ \frac{1}{5}\frac{1}{2}\frac{WL_j}{60} Y_{j,t}^a IC_{j,t} \frac{1}{2}\left(\frac{|\Delta S_t|}{0.008} + \left(\frac{\Delta S_t}{0.008}\right)^2\right) & \text{if } \Delta S_t < 0 \end{cases} \quad (20b)$$

The parameters of the equations above can be derived from Table A1.3 -- which gives the benchmark impacts for the level and rate of change per impact category -- and Table A1.4 -- which gives the life-times (in years) of the impacts, with $\rho=1-1/\text{life-time}$.

Other novelties in *FUND*1.6 are the reparameterization of the emission reduction module, and changes in the decision optimization structure. These aspects of *FUND* are not relevant for EXTERNE.

Table A1.5 presents the net present value of total damages over the period 1990-2100, and its breakdown over the regions, for discount rates of 0, 1, 3, 5 and 10%. Total damages range between 238.3 and 2.7 trillion dollar, depending on the discount rate chosen. Independent of that, South and Southeast Asia contribute most to world damage, followed by Latin America and Africa. China's contribution does depend on the discount rate (it starts a net winner and ends a net loser, because of its declining importance of agriculture and increasing urbanization). The OECD is relatively little vulnerable to climate change. Central and Eastern Europe and the former Soviet Union are net benefitters of climate change.

Table A1.3. Monetized estimates of the impact of global warming (in 10^9 US$).

region	species	life	agric.	sea	extreme	total
level	(global mean temperature: +2.5°C; sea level: +50 cm; hurricane activity: +25%; winter precipitation: +10%; extratropical storm intensity: +10%)					
OECD-A	0.0	-1.0	-5.3	0.9	2.5	-2.9
OECD-E	0.0	-1.1	-6.0	0.3	0.3	-6.5
OECD-P	0.0	-0.5	-6.1	1.5	5.5	0.3
CEE&fSU	0.0	3.7	-23.2	0.1	0.2	-19.1
ME	0.0	3.5	3.1	0.1	0.0	6.6
LA	0.0	67.0	7.3	0.2	0.0	74.5
S&SEA	0.0	81.4	15.8	0.2	0.6	98.8
CPA	0.0	58.4	-22.2	0.0	0.1	36.3
AFR	0.0	22.5	5.4	0.1	0.0	28.0
rate	(global mean temperature: 0.04°C/year; other variables follow)					
OECD-A	0.3	0.2	0.3	0.2	0.2	1.2
OECD-E	0.3	0.2	0.0	0.2	0.0	0.7
OECD-P	0.2	0.1	0.0	0.3	0.4	1.0
CEE&fSU	0.1	0.1	0.0	0.0	0.0	0.2
ME	0.0	0.0	0.1	0.0	0.0	0.2
LA	0.0	0.4	0.1	0.1	0.0	0.6
S&SEA	0.0	0.3	0.1	0.1	0.0	0.6
CPA	0.0	0.2	0.3	0.0	0.0	0.5
AFR	0.0	0.0	0.1	0.0	0.0	0.2

Table A1.4. Duration of damage memory per category.[a]

category	years	category	years
species loss	100	immigration	5
agriculture	10	emigration	5
coastal protection	50	wetland (tangible)	10
life loss	15	wetland (intangible)	50
tropical cyclones	5	dryland	50

[a] Damage is assumed to decline geometrically at a rate of 1-1/lifetime.

Source: After Tol (1996).

Table A1.5. Regional damages of climate change; percentage of the net present value of total damage over the period 1990-2100.[a]

Region	0%	1%	3%	5%	10%
OECD-A	3.1	3.4	4.1	4.9	5.7
OECD-E	4.4	4.6	5.1	5.4	5.3
OECD-P	2.5	2.6	3.1	3.5	3.8
CEE&fSU	-0.9	-1.0	-1.2	-1.4	-1.8
ME	10.1	10.5	11.4	12.1	12.8
LA	17.9	18.7	20.9	23.5	27.7
S&SEA	35.3	34.8	33.6	32.5	31.0
CPA	12.5	11.0	7.4	4.1	0.6
AFR	15.2	15.4	15.6	15.6	14.9
World[b]	238.3	107.4	27.7	10.2	2.7

[a] Damages discounted to 1990; time horizon: 2100; model: *FUND*1.6; scenario: IS92a; simple sum; no higher order effects.
[b] Trillion US dollars (1990 values).

Table A1.6 repeats Table A1.5, this time aggregating regional impacts equity-weighted. Equity-weights basically equalize impact unit values at their global average (at least, to a linear approximation). The pattern of Table A1.5 is accentuated. China's contribution falls because of its assumed rapid growth (and, hence, rapidly declining equity weight).

Table A1.7 presents the net present value of total damages, and its breakdown over its impact categories. Sea level rise is the most important category, particularly at the shorter term. Extreme weather, particularly the balance of heat and cold stress, comes second, and increases in importance over time. Agriculture is a net benefitter of climate change.

Table A1.8 repeats Table A1.7, this time equity-weighted. The importance of species loss falls, as this is mostly valued in the richer regions. Agriculture switches sign, indicating that poorer regions are losers here, and rich regions winners.

Table A1.6. Regional damages of climate change; percentage of the net present value of total damage over the period 1990-2100.[a]

Region	0%	1%	3%	5%	10%
OECD-A	0.3	0.3	0.3	0.3	0.3
OECD-E	0.5	0.5	0.5	0.4	0.4
OECD-P	0.1	0.1	0.1	0.1	0.1
CEE&fSU	-0.1	-0.2	-0.2	-0.2	-0.2
ME	6.9	6.9	6.6	6.2	5.5
LA	12.3	12.7	13.6	14.5	15.8
S&SEA	42.0	42.5	44.2	46.4	50.3
CPA	6.4	5.6	3.7	2.1	0.3
AFR	31.7	31.7	31.3	30.2	27.5
World[b]	519.5	248.8	74.4	31.8	10.1

[a] Damages discounted to 1990; time horizon: 2100; model: *FUND*1.6; scenario: IS92a; equity-weighted; no higher order effects.
[b] Trillion US dollars (1990 values).

Table A1.7. Sectoral damages of climate change; percentage of the net present value of total damage over the period 1990-2100.[a]

Sector	0%	1%	3%	5%	10%
Sea level rise[b]	52.5	55.9	64.4	73.1	83.9
Agriculture	-3.3	-3.3	-3.3	-3.2	-3.1
Extreme weather[c]	42.2	38.8	29.9	21.0	10.3
Species	4.5	4.4	4.1	3.6	2.8
Malaria	4.0	4.3	4.9	5.5	6.1
Total[d]	238.3	107.4	27.7	10.2	2.7

[a] Damages discounted to 1990; time horizon: 2100; model: *FUND*1.6; scenario: IS92a; simple sum; no higher order effects.
[b] Coastal protection, dryland loss, wetland loss and migration.
[c] Hurricanes, extratropical wind storms, river floods, hot spells, cold spells.
[d] Trillion US dollars (1990 values).

Table A1.8. Sectoral damages of climate change; percentage of the net present value of total damage over the period 1990-2100.[a]

Sector	0%	1%	3%	5%	10%
Sea level rise[b]	57.8	61.1	68.6	75.1	82.1
Agriculture	2.7	2.4	1.5	0.7	-0.6
Extreme weather[c]	33.5	30.1	22.7	16.3	9.5
Species	0.9	0.8	0.6	0.4	0.2
Malaria	5.2	5.6	6.7	7.6	8.7
Total[d]	519.5	248.8	74.4	31.8	10.1

[a] Damages discounted to 1990; time horizon: 2100; model: *FUND*1.6; scenario: IS92a; equity-weighted; no higher order effects.
[b] Coastal protection, dryland loss, wetland loss and migration.
[c] Hurricanes, extratropical wind storms, river floods, hot spells, cold spells.
[d] Trillion US dollars (1990 values).

A1.2 The Marginal Costs of Greenhouse Gas Emission According to *FUND*1.6

A limited number of estimates of the marginal costs of CO_2 emissions float around in the literature. They have been assembled in the Second Assessment Report of Working Group III of the Intergovernmental Panel on Climate Change (Pearce *et al.*, 1996). This assessment is reproduced in Table A1.9. Two types of marginal cost estimation methods are distinguished. One is based on the average additional cost of a small perturbation of an exogenous scenario (commonly IPCC's IS92a or something very similar, denoted as business as usual). The other is based on the shadow value of carbon dioxide emissions along an optimal path. The latter method is theoretically preferred (because it avoids approximation) but cannot be applied without going into the contentious issue of defining optimality. For practical purposes, as in EXTERNE, it is better to use tables of marginal costs per unit of emission, so that tedious model calculations are avoided.

The estimates of Table A1.9 show a wide range. The upper bound of Cline can be explained by (1) high benchmark estimates of climate change; (2) a long time horizon combined with a low discount rate; and (3) constant vulnerability to climate change. Ayres and Walter's estimate is on the high side because they use a low discount rate and OECD values for the whole world. Nordhaus shows that the expected value of marginal costs is higher than the best guess value, because uncertainties are asymmetric and relationships non-linear (cf. Tol, 1995). Fankhauser's estimates are expected values, centered around a discount rate of 3%.

Table A1.10 presents the marginal costs of climate change according to *FUND*, using a simple summation of the impact across its nine regions. For a discount rate of 3-5%, the marginal costs of carbon dioxide emissions are comparable to those that can be found in the literature. Table A1.10 also presents marginal damage estimates for methane and nitrous oxide. Usually, greenhouse gases are converted from one to another using their global warming potentials. The global warming potential of a gas is defined as the time integral of radiative forcing per unit emission divided by the same integral for carbon dioxide. Schmalensee (1993) and Richards and Reilly (1993) criticized the concept because the relationship between radiative forcing and impact may well be highly non-linear and because time discounting is ignored. The global damage potential is defined as global warming potential, with radiative forcing replaced by impact and discounting introduced. In fact, the global damage potential is the ratio of the marginal damages. Table A1.11 displays global damage potentials as estimated with *FUND* and as reported in the literature. Results are very similar, despite the fact that *FUND*'s impact module depends also on the rate of climate change and vulnerability is a function of socio-economic development.

Table A1.9. The marginal costs of CO_2 emissions.[a]

Study	Type[b]	1991-2000	2001-2010	2011-2020	2021-2030
Nordhaus[c]	MC		7.3 (0.3-65.9)		
Ayres and Walter[c]	MC		30-35		
Nordhaus	CBA				
- best guess		5.3	6.8	8.6	10.0
- expected value		12.0	18.0	26.5	n.a.
Cline	CBA	5.8-124	7.6-154	9.8-186	11.8-221
Peck and Teisberg	CBA	10-12	12-14	14-18	18-22
Fankhauser	MC	20.3 (6.2-45.2)	22.8 (7.4-52.9)	25.3 (8.3-58.4)	27.8 (9.2-64.2)
Maddison	CBA	5.9	8.1	11.1	14.7
	MC	6.1	8.4	11.5	15.2
This study[d]	MC	11	13	15	18

[a] current (1990) value $\$^{1990}$/tC; figures in brackets denote 90% confidence intervals.
[b] MC = marginal social cost study, CBA = shadow value in a cost-benefit study.
[c] Time of emission not explicitly considered.
[d] Time horizon 2100; discounted to start of decade; discount rate: 5%; model: *FUND*1.6; scenario: IS92a; simple sum; no higher order effects.

Sources: Pearce *et al.* (1996); see also Ayres and Walter (1991), Nordhaus (1994b), Cline (1992, 1993), Peck and Teisberg (1991), Fankhauser (1995) and Maddison (1995).

Table A1.10. Marginal damages for CO_2, CH_4 and N_2O emissions; damages discounted to 1990; time horizon: 2100; model: *FUND*1.6; scenario: IS92a; simple sum; no higher order effects.

Discount rate	0%	1%	3%	5%	10%
Carbon dioxide ($/tC)					
1995-2004	142	73	23	9	2
2005-2014	149	72	20	7	1
Methane ($/t$CH_4$)					
1995-2004	147	141	89	52	16
2005-2014	264	186	87	41	8
Nitrous oxide ($/t$N_2O$)					
1995-2004	15,468	7,559	2,201	817	140
2005-2014	16,313	7,632	1,975	631	71

Table A1.11. Global damage potential, impact per tonne of CH_4 and N_2O relative to impact per tonne of CO_2.

	FUND[a]	*OF*[b]	Kandlikar[c]	Fankhauser[d]	Hammitt[e]	GWP[f]
CH_4	14	18	12	20	11	25
N_2O	348	342	282	333	355	320

[a] Emissions between 1995 and 2004; time horizon: 2100; discount rate: 3%; model: *FUND*1.6; scenario: IS92a; simple sum; no higher order effects.
[b] Emissions between 1995 and 2004; time horizon: 2100; discount rate: 3% model: *Open Framework*; scenario: IS92a; simple sum; no higher order effects.
[c] Time horizon: 100 years; discount rate: 2%; scenario: IS92a; quadratic damages.
[d] Emissions between 1991 and 2000; time horizon: 2100; GDP is calculated as ratio of mean marginal damages.
[e] Emissions in 1995; time horizon: 2100; discount rate: 3%; scenario: IS92a; middle case
[f] Time horizon: 100 years.

Sources: Own calculations; Kandlikar (1995, 1996), Fankhauser (1995), Hammitt *et al.* (1996), Schimel *et al.* (1996).

The estimates of Table A1.10 are based on different values (e.g., for human mortality risks) for different regions. This is inconsistent with the common approach of EXTERNE. Instead of adjusting regional values (which would lead to inconsistencies in the valuation of local and global environmental issues, and inconsistencies over time), it has been decided to use income-dependent weights in aggregating regional impact (as proposed by Fankhauser *et al.*, 1997). The weights are the inverse of per capita income (relative to its global average) so that equity-weighted per-unit values are approximately the same for all regions. Table A1.12 shows the result of this for marginal damage of greenhouse gas emissions.

Table A1.12. Marginal damages for CO_2, CH_4 and N_2O emissions; damages discounted to 1990; time horizon: 2100; model: *FUND*1.6; scenario: IS92a; equity-weighted; no higher order effects.

Discount rate	0%	1%	3%	5%	10%
Carbon dioxide ($/tC)					
1995-2004	317	171	60	26	6
2005-2014	311	157	48	18	3
Methane ($/t$CH_4$)					
1995-2004	660	517	295	170	52
2005-2014	831	556	252	120	24
Nitrous oxide ($/t$N_2O$)					
1995-2004	32,735	16,862	5,459	2,217	434
2005-2014	32,785	15,994	4,510	1,556	197

Table A1.13 presents the results of a sensitivity analysis around the base estimates, i.e., the equity-weigthed marginal costs of emissions in the decade 1995-2004. Postponing emissions by 10 years slightly reduces the marginal costs, primarily because they are discounted for 10 more years. However, the estimate for the zero per cent discount rate reveals that undiscounted marginal costs are also somewhat lower, because of a slower rate of climate change in the future and reduced vulnerability. Extending the horizon to 2200 makes little difference, except for the zero discount rate. Yearly marginal damages become negative in the second half of the 22nd century, because early additional emissions lower the rate with which temperature increases on the long term. Equity weights do matter a lot as damage on poorer countries counts much more in the global total. Including the effect of climate change on economic growth adds a little to the marginal estimates, but not sufficiently so to justify an in-depth analysis right now; lacking much insight, higher-order effects have been included in a very *ad hoc* way. Perturbing the climate sensitivity has an obvious and substantive influence on the marginal damages. If *FUND* runs with a higher (IS92f) or lower (IS92d) emission scenario, marginal costs are higher or lower. The effect is not large, partly because the difference in climate change only becomes substantial in the long run, and partly because IS92d leads to a more equitable income distribution than IS92a (so impact in developing countries is and counts less) while IS92f has overall higher economic growth rates.

Table A1.13. Sensitivity analysis marginal damage of carbon dioxide emissions (in $/tC); damage discounted to 1990; emissions in 1995-2004; model: *FUND*1.6; scenario: IS92a; time horizon: 2100; equity weighted; no higher order effects.

case discount rate	0%	1%	3%	5%	10%
base (Table A1.12)	317	171	60	26	6
emissions in 2005-2014	311	157	48	18	3
horizon: 2200	243	172	62	26	6
simple sum (Table A1.10)	142	73	23	9	2
higher order impacts	360	192	66	28	6
climate sensitivity: 1.5°C	186	101	35	15	3
climate sensitivity: 4.5°C	590	318	112	49	11
IS92f	348	187	65	28	6
IS92d	288	156	56	25	6

Table A1.14 presents the marginal damages over the period 1990-2100, and their breakdown over the regions, for discount rates of 0, 1, 3, 5 and 10%. South and Southeast Asia contribute most to world damage, followed by Latin America and Africa. The OECD is relatively little vulnerable to climate change, particularly if the difference in income levels are taken into account. Central and Eastern Europe and the former Soviet Union are net benefitters of climate change.

Table A1.14. Regional marginal damages over the period 1990-2100.[a]

Region	0%	1%	3%	5%	10%
OECD-A	5	3	1	1	0
OECD-E	7	4	1	1	0
OECD-P	4	2	1	0	0
CEE&fSU	-2	-1	0	0	0
ME	15	8	3	1	0
LA	28	15	5	2	0
S&SEA	54	26	8	3	1
CPA	8	3	1	0	0
AFR	23	12	4	1	0
World	142	73	23	9	2

[a] Damages discounted to 1990; time horizon: 2100; model: *FUND*1.6; scenario: IS92a; simple sum; no higher order effects.

Table A1.15 presents the marginal damages, and their breakdown over the impact categories. Sea level rise is the most important category. Extreme weather, particularly the balance of heat and cold stress, comes second, and increases in importance over time. Agriculture is a net benefitter of climate change. Table A1.16 repeats Table A1.15, this time equity-weighted. The importance of species loss falls, as this is mostly valued in the richer regions. Agriculture switches sign, indicating that poorer regions are losers here, and rich regions winners.

Table A1.15. Sectoral marginal damages.[a]

Sector	0%	1%	3%	5%	10%
Sea level rise[b]	89	48	16	7	1
Agriculture	-4	-2	0	0	0
Extreme weather[c]	46	21	5	2	0
Species	5	3	1	1	0
Malaria	7	3	1	0	0
Total	142	73	23	9	2

[a] Damages discounted to 1990; time horizon: 2100; model: *FUND*1.6; scenario: IS92a; simple sum; no higher order effects.
[b] Coastal protection, dryland loss, wetland loss and migration.
[c] Hurricanes, extratropical wind storms, river floods, hot spells, cold spells.

Table A1.16. Sectoral marginal damages.[a]

Sector	0%	1%	3%	5%	10%
Sea level rise[b]	204	115	43	19	4
Agriculture	6	3	1	0	0
Extreme weather[c]	88	42	12	5	1
Species	1	1	0	0	0
Malaria	19	10	4	2	0
Total	316	171	60	26	6

[a] Damages discounted to 1990; time horizon: 2100; model: *FUND*1.6; scenario: IS92a; equity-weighted; no higher order effects.
[b] Coastal protection, dryland loss, wetland loss and migration.
[c] Hurricanes, extratropical wind storms, river floods, hot spells, cold spells.

A1.3 Results under Uncertainty

Uncertainty prevails in all aspects of climate change. The chemistry of radiative active gases in the atmosphere is known only to a certain extent, and much less can be said with a degree of certainty about its interaction with the biosphere. The influence of changes in radiative forcing on climate is only known in broad lines. For important details such as regional and seasonal patterns of precipitation or tropical cyclones, even the sign of change is in dispute. Note that climate change also influences atmospheric chemistry and stocks and flows of greenhouse gases. Knowledge on the impacts of a change in climate is equally scant, particularly if valued in monetary terms, and heavily influenced by many other processes, such as economic development over the next century.

In theory, it is possible to incorporate all these uncertainties into an estimate of the marginal impact of emissions of carbon dioxide, methane or any other greenhouse gas. One should have a model of atmosphere, climate, economy, population and impacts available, for example, FUND or the Open Framework. Then, one should quantify the uncertainties about the model's main parameters in probability distribution functions. Finally, one should randomly vary the parameters according to their distributions a substantial number of times, calculate the marginal impact for each run, and then calculate the mean and variance of the marginal impacts.

Although straigthforward, the above procedure may be computationally demanding. This problem forestalled uncertainty to be thoroughly analyzed with the Open Framework. Another problem is the quantification of the uncertainties. The larger part of the literature attempt to quantify the best estimates of impacts, without, as noted, overwhelming success. Little attention has been paid sofar to quantification of the uncertainties about the best guesses. Notable exceptions are the studies by Morgan and Keith (1996), Nordhaus (1994a) and Titus and Narayanan (1996), on climate change, aggregate climate impacts and sea level rise, respectively. The first study is based on in-depth interviews with a limited number of climatologists. The second study is based on a questionnaire. The third study combines a literature survey with interviews and questionnaires and a process model. This limited basis for quantification of uncertainties is of limited use, since the variables reported not necessarily correspond to the variables in the model used to estimate marginal impacts.

Therefore, the quantification of the uncertainties about the parameters of *FUND* is largely based on expert knowledge, that is, Richard Tol's qualitative interpretation of an informal selection of the literature and informal talks with topical experts. Table A1.17 provides an overview of the assumptions made for the analysis of parameter uncertainty. The modal values equal the best guesses. Distribution and spread are based on the knowledge of the present author, which is informally informed by the literature.

Table A1.17. Description of parameter uncertainty.

parameter	distribution	characteristics		parameters	
climate sensitivity	gamma	mode	2.50	α	8.1270
(per doubling CO_2)		mean	2.85	β	0.3508
		std.dev.	1.00		
sea level sensitivity	gamma	mode	0.31	α	5.9957
(per °C)		mean	0.36	β	0.0613
		std.dev.	0.15		
hurricane sensitivity	normal	mean	0.00	μ	0.00
(per °C)		std.dev.	0.10	σ	0.10
flood sensitivity	normal	mean	0.04	μ	0.04
(per °C)		std.dev.	0.04	σ	0.04
storm sensitivity	normal	mean	0.02	μ	0.02
(per °C)		std.dev.	0.02	σ	0.02
atm. life-time CH_4	triangular	mode	8.6	a	8.0
		mean	10.2	b	16.0
		std.dev.	1.3	c	8.6
atm. life-time N_2O	triangular	mode	120	a	100
		mean	130	b	170
		std.dev.	15	c	120
life-time temperature	triangular	mode	50	a	25
life-time sea level		mean	58	b	100
		std.dev.	16	c	50
atm. life-times CO_2	normal[a]	mean	363; 74; 17; 2	μ	mean
		std.dev.	half mean	σ	std.dev.
driving scenarios[b]	normal	mean	1.0	μ	1.0
		std.dev.	0.1	σ	0.1
impacts[c]	normal	mean	1.0	μ	1.0
		std.dev.	0.5	σ	0.5
VOSL[d]	gamma	mean	1.0	α	2.6180
		std.dev.	1.0	β	0.6180
life-time impacts	normal[a]	mean	Table A1.4	μ	mean
		std.dev.	quarter mean	σ	std.dev.

[a] Knotted at zero.
[b] Multiplier of economic growth, population growth, AEEI, ACEI and exogenous emissions land-use change.
[c] Multiplier of impact due to/on species, heat, cold, malaria, agriculture, hurricane (life and property), floods, winter storms, migration, coastal protection, dry land, wet land.
[d] Value of a statistical life; multiplier of VOSL, which is time and region-dependent, equalling 240 times the per capita income.

Table A1.18 presents the results of a Monte Carlo analysis with 2500 runs applying the uncertainty assumptions described in Table A1.17 to marginal impact estimates of *FUND*. For comparison, the best guess estimate (i.e., the marginal costs with all parameters set at their central estimate) is also given. The best guess is a conservative estimate of the marginal costs of CO_2. The mean estimate is higher than the best guess, because uncertainties are asymmetric and relationships non-linear (cf. Tol, 1995). The uncertainty about the marginal costs is also asymmetric (right-skewed) so that median and modal[1] marginal costs are smaller that the mean. For small discount rates, the mode also lies above the best guess. Mode (the most likely value of the marginal costs) and best guess (the marginal costs if all parameters are set to their most likely value) deviate in a non-linear system. The uncertainty is large, as is revealed by the standard deviation and the confidence intervals. The coefficient of variation varies around 2/3. The upper bound of the 95% interval lies at more than 2.5 times the best guess, more than two times the mean. The uncertainty is so large mainly because of the non-linearities in the system and the convolution of uncertainties. The many impact categories and regions, varied independently of one another, dampen the overall uncertainty. Interestingly, even the one-percentile marginal costs is positive, although the distributions of Table A1.17 do allow for the enhanced greenhouse effect to have a positive effect. Figure 1 display the frequency distribution of the marginal costs for a 3% discount rate, along with a fitted Lognormal distribution. The estimates of the location (μ) and scale (σ) parameters of the lognormal distribution are also given in Table A1.18.

Table A1.19 presents a limited sensitivity analysis on the results in Table A1.18. In the top rows, a selection of the results of Table A1.18 is reproduced for 1,000 runs. Convergence seems reasonable. Then, also for 1,000 runs to save computational time, the value of a statistical life (an 'ethical' choice, to some at least) is assumed to be known with certainty. Both mean and variance fall considerably, stressing once more the importance of human health issues in the context of global warming. In the lowest rows, the Normal distributions for the impact uncertainties are replaced with Gamma distributions, assuming the same mean and variance. The difference between Normal and Gamma is that the former (latter) is symmetric (right-skewed) and assumes both positive and negative (only positive) values. Not surprisingly, mean, standard deviation and 95% confidence interval shift upwards. The extent is remarkable.

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[1] Note that the mode (the most probable outcome) and the best guess differ in a non-linear system.

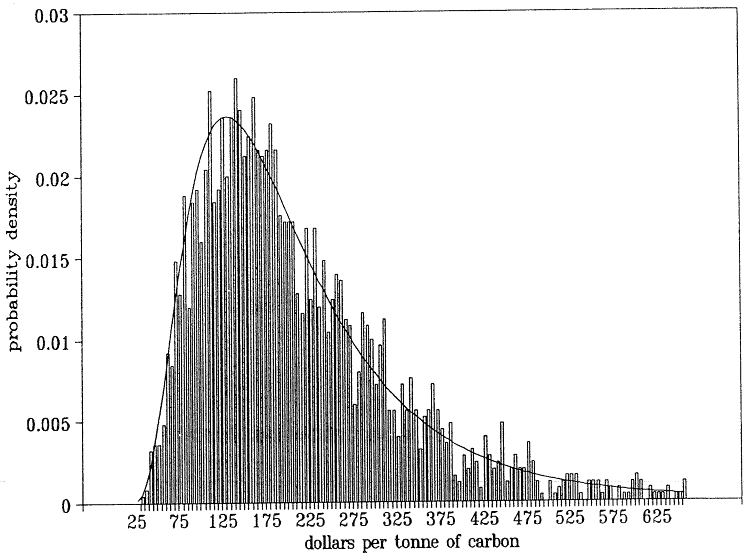
Table A1.18. Characteristics of the uncertainty about the marginal costs of carbon dioxide emissions (in $/tC).

discount rate	0%	1%	3%	5%	10%
Best guess	317	171	60	26	6
Mean	465	244	82	35	7
Median	405	210	70	29	6
Mode	340	190	54	22	5
Standard deviation	267	143	51	22	5
1-percentile	106	54	17	7	1
5-percentile	158	81	26	11	2
95-percentile	962	512	178	77	17
99-percentile	1390	744	259	114	26
Geometric mean	6.0	5.3	4.2	3.4	1.8
Geometric std.dev.	1.7	1.8	1.8	1.8	1.9

Table A1.19. Sensitivity analysis uncertainties.

Discount rate	0%	1%	3%	5%	10%
Base case (as in Table A1.18)					
Mean	475	250	84	36	8
Standard deviation	267	143	50	22	5
5-percentile	168	86	28	11	2
95-percentile	976	521	183	79	17
Value of a statistical life assumed certain					
Mean	399	212	73	31	7
Std.deviation	233	126	45	20	4
5-percentile	141	71	23	10	2
95-percentile	867	458	161	69	15
Gamma instead of Normal distributions for impacts					
Mean	745	391	132	56	12
Standard deviation	441	237	84	37	8
5-percentile	243	127	40	16	3
95-percentile	1575	839	290	120	26

Figure 2. Uncertainty about the marginal costs of carbon dioxide emissions. Damages discounted to 1990 at 3%; emissions in 1995-2004; model: *FUND*1.6; scenario: IS92a; time horizon: 2100; equity-weighted; no higher order effects.



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Appendix 2
The Open Framework Model

Evaluation of Climate Damages: Sensitivity of the Open Framework to Emissions of Carbon Dioxide, Methane and Nitrous Oxide

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The Open Framework provides a consistent platform for spatial analysis of climate change scenarios and their impacts. The global version links first-order impact indicators and economic valuation of the cost of climate change. The model is essentially a research tool. However, special attention has been given to providing users access to the data and results in the form of tables (dBase format) and maps (Idrisi GIS format).

The sequence of steps in the OF are:

1. Specify a reference scenario without climate change. This reference scenario includes global GHG emissions based on the IPCC 1992 a and d scenarios, projections of economic conditions and identification of impact sectors and their sensitivity to climatic variations. The reference scenario is the baseline against which aggregate climate change impacts are gauged.
2. Calculate global-average temperature change and sea level rise. Transient projections are provided by the 1994 version of MAGICC (Osborn and Wigley, 1994; Raper, Wigley and Warrick, 1995; Wigley and Raper, 1992, 1993, 1995; Wigley, 1993, 1994) (). MAGICC is a relatively simple upwelling-diffusion, energy balance climate model that distinguishes between land and ocean and between hemispheres. In all cases, the default model parameters are used. In the 1994 version this includes the effects of sulphur dioxide, which leads to less global warming than earlier climate change projections.
3. Add pulses of GHG emissions to the global GHG emissions. The reference emissions (the IS92a and IS92d scenarios) are from the MAGICC input library. In the ExternE project, the pulses of CO_2, NOx and CH_4 were added to the reference scenario. Combinations of the pulses were also created.
4. Calculate the incremental effect of the pulses on global-average temperature and sea level. MAGICC reports values every five-years from 1990 to 2100 for realised global-average temperature change and mean sea level rise, with reference to 1990. The incremental effect is the difference between the reference emissions and the pulse emissions (e.g., the IS92a + a 10% pulse of CO_2).
5. Create spatial scenarios of climate change. The general circulation model experiment from the Goddard Institute of Space Sciences (GISS) equilibrium run tracks the differences between the present and a scenario of climate change. The GCM scenario was scaled to the global-average temperature projection from MAGICC. This results in a time-dependent climate change scenario consistent with the assumptions of the global emissions. The spatial pattern of anomalies from the GISS scenario is retained, however.

For this project, a single year, 2100, was used, assuming a linear projection from the present climate (i.e. 1990).

6. Calculate first-order impact models for the current climate and for the scenario of climate change. The baseline climate is based on the 0.5 degree latitude by longitude climatology of Cramer and Leemans (1994). Climate parameters for the baseline are mean monthly temperature and precipitation for the period of record. These methods of creating scenarios are common in climate change impact assessment (see Viner and Hulme 1993, Carter *et al.* 1994).
7. Summarise the impacts by country. The first-order impact variables were extracted to provide country-average values, in most cases area-weighted sums (e.g. water deficit)or averages (e.g. heating degree days).
8. Calculate country-level economic impacts. The reference projections, climate sensitivity-cost equations and first-order impacts are used to derive country-level estimates of impacts from 1990 to 2100. This is done for the direct-cost sectors where country-level estimates of use value can be reasonably calculated.
9. Sum the country-level direct costs to a global total and add global contingent value sectors. For sectors such as disasters and health, a global estimate of damage costs has been calculated based on methods of contingent valuation, willingness to pay and the statistical value of life.
10. Calculate proportion of costs attributable to the added pulses of GHGs. The time dependent projections of costs were attributed to the pulses by multiply the costs by the proportion of global warming (or sea level rise for coastal sectors) caused by each pulse.
11. Calculate net present values. NPVs are calculated for both the total cost of climate change and the proportion attributed to each GHG. The range of discount rates used was 0%, 1.5%, 3%, 5% and 10%.

The relationships between changes in temperature, precipitation and sea level rise and the selected impact sectors are shown in Figure 1. Low, medium and high estimates of the impacts and costs of climate change are reported, based partly on subjective estimates of the range of likely effects.

The OF itself is relatively flexible and modest in size. However, all of the supporting and intermediate data files comprise almost 1Gb of disk space. A selection of the output data, viewing software in the OF, and help files are available on CD-ROM.

Climate Change:	Temperature	Precipitation	
Resource Model:	Degree Days	Water Balance	Sea Level Rise

Valuation of Impacts :			
Energy	Heating & Cooling		
Agriculture	Change in area suitable for cultivation		
Water Resources		Surplus/deficit	
Coastal Protection			For valuable coast
Loss of Wetland			Where protected
Loss of Dryland			Where not protected
Biodiversity	Changed habitat		Related to wetland lost
Human Migration	Change land use	Water scarcity	Loss of coastal land
Natural Hazards	Heat waves	Drought	Storms/surge
Health/Welfare	Heat stress	Water scarcity	Displacement
Other Sectors	Regional multipliers, resource conflicts		

Figure 1. Impact Models and Sectors. Light shade indicates small impacts not directly evaluated; medium shade indicates impacts and sectors that are modelled in a qualitative way due to the limitations of data and methods of economic valuation; heavy shade indicates combinations of causes and impacts that are not relevant.

Table 1. Pulses of greenhouse gases evaluated in the OF

Title	Description	Code	Total pulse, 1990-2100		
			CO2	CH4	N20
IS92a+CO2 (95)	IS92a + CO2*5% (Pg C), 1995-2004	a	150	80463	1751
IS92+CO2 (05)	IS92a + CO2*5% (Pg C), 2005-2014	b	1505	80463	1751
IS92a+CH4 (95)	IS92a + CH4*5% (Tg CH4), 1995-2004	c	1501	80731	1751
IS92a+CH4 (05)	IS92a + CH4*5% (Tg CH4), 2005-2014	d	1501	80752	1751
IS92a+N2O (95)	IS92a + N2O*5% (Tg N), 1995-2004	e	1501	80463	1758
IS92a+N2O (05)	IS92a + N2O*5% (Tg N), 2005-2014	f	1501	80463	1758
IS92a+3GHG (95)	IS92a + 3GHG*5% (CO2, CH4, N2O), 1995-2004	g	1504	80731	1758
IS92a+3GHG (05)	IS92a + 3GHG*5% (CO2, CH4, N2O), 2005-2014	h	1505	80752	1758
IS92d+CO2 (95)	IS92d + CO2*5% (Pg C), 1995-2004	i	991	63983	1625
IS92d+CO2 (05)	IS92d + CO2*5% (Pg C), 2005-2014	j	992	63983	1625
IS92d+CH4 (95)	IS92d + CH4*5% (Tg), 1995-2004	k	988	64242	1625
IS92d+CH4 (05)	IS92d + CH4*5% (Tg), 2005-2014	l	988	64254	1625
IS92d+N20 (95)	IS92d + N20*5% (Tg N), 1995-2004	m	988	63983	1632
IS92d+N20 (05)	IS92d + N20*5% (Tg N), 2005-2014	n	988	63983	1632
IS92d+3GHG (95)	IS92d + 3GHG*5% (CO2, CH4, N2O), 1995-2004	o	991	64242	1632
IS92d+3GHG (05)	IS92d + 3GHG*5% (CO2, CH4, N2O), 2005-2014	p	992	64254	1632

Notes: Based on results from MAGICC.

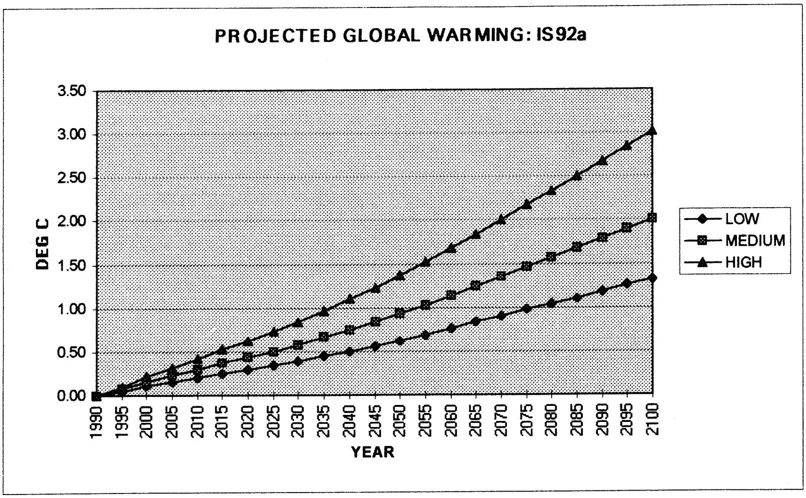

Figure 3a. Projected Global Warming from the IPCC 1992a Scenario. Source: MAGICC 1994 version.

General Assumptions

The principal results presented here are for a "non-interventionist" scenario. However, two reference scenarios from the IPCC suite of scenarios developed in 1992 were incorporated into the OF. This sections presents the critical assumptions for the two scenarios (). Two major differences between the two scenarios are explicit: population growth in the IS92a world reaches 11.3 billion by 2100, compared to 6.4 billion in the IS92d scenario, and world GNP is larger, although per capita GNP is less ($21,500). In addition, it is possible to infer differences in the scenarios regarding: technology and the rate of adaptation to resource scarcity and 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-interventionist" scenario and a vision of higher income and environmental values.

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 also imply higher usage and demand for resources, resulting in higher prices.

Economic Growth

Economic growth in the IS92a scenario – 2.9% to 2025 and 2.0% thereafter – is significantly higher than in the IS92d scenario – 3.7% to 2025 then falling to 1.7%. 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.

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 2. Quantified Assumptions for Two Reference Scenarios

Sector	**Assumptions**	**Unit**	**1990**	**Projection: 2100**	
				IS92d	**IS92a**
Population	No.	b	5.3	6.4	11.3
Economy	World GNP	$b	19,958	180,480	242,950
	GNP per capita	$	3,800	28,200	21,500
	Growth rate	%/yr	1.3	2.0	1.7
	Agricultural GNP	%	6.2	2.6	+
Energy prices	Fuel	$/GJ	6	18	24
	Electricity	$/GJ	21	34	39
Energy demand	Heating	EJ/yr	67	64	198
	Cooling	EJ/yr	692	1,658	11,492
Water	Global price	$/m^3	0.55	4.08	3.11

Uncertainty in the Open Framework

The Open Framework links together models from diverse sources and at varying spatial and temporal resolutions to estimate total and marginal costs of climate change. Because of this structure and the volume of data generated, it is not feasible to undertake a formal, quantitative analysis of uncertainty or parameter sensitivity. On the other hand, the Open Framework is built upon the premise that uncertainty in estimating climate change damages is important, and varies at different levels of analysis:

This section describes some of those uncertainties and the range of results presented in the Open Framework. In comparison to the formal testing in FUND, the emphasis here is on the domain of uncertainty and reasonable estimates of the range of potential damages.

Domain of uncertainty
Throughout the Open Framework, low, medium and high estimates of climate change damages are reported. These are mostly subjective estimates, with different interpretations for different domains of analysis.

Climate sensitivity: the low, medium and high values are MAGICC's estimates of climate sensitivity (1.5 ° C, 2.5 ° C and 4.5 ° C). While the IPCC is not explicit about the probability of climate change, this range is generally taken to represent the 10%, 50% and 90% points in a cumulative probability distribution. These probability estimates are used as subjective benchmarks in the subsequent analysis.

Pattern of climate change: At present only on GCM scenario has been tested in the Open Framework. A different spatial pattern of climate change would certainly alter the outcomes, especially if large economies such as the US, China, India and Brazil suffer substantially different impacts. In the present suite of impacts, this is only likely for agriculture (relatively minor costs) and water resources (potentially greater damages).

First-order impact models: The present Open Framework includes relatively simple impact models. These could be compared against other constructions of the relationship between climate and its impacts. For example, the sensitivity of cooling demand to different base temperatures and relative humidity might be interesting. The choice of impact model is probably most significant for water resources (reflecting assumptions of evapotranspiration and water use efficiency) and sea level rise (where decision agent approaches can lead to higher costs).

Sensitivity to climate change as reflected in economic and social reference scenarios: The Open Framework compares two scenarios, the IS92a and IS92d. In formal terms, the scenarios are driven by different levels of population and GDP, which are used to scale impacts. However, they are also taken as different qualitative worlds. This leads to somewhat different assumptions of sensitivity to climate change – the link between the first-order model and economic valuation. The range of values used is discussed below.

Assumptions regarding economic valuation of damages: As for sensitivity, a range is used to reflect economic values, such as the value of statistical life and the value of wetlands lost. Together with the estimates of sensitivity, these assumptions have the largest effect on the resulting damage estimates.

Range of parameter estimates
If all of the parameters in the Open Framework are independent, and the low, medium and high estimates are independent samples of each distribution, then the outcome would be a confidence interval that is much larger than the nominal 80% indicated above. Table 3 suggests that the parameters are largely driven by either the climate or the economy. That is they are not independent. For example, the amount of wetlands lost, area of drylands lost and incidence of disasters due to climate change are primarily related to climate change rather than

economic or technological driving forces. Similarly, 17 of the 26 variables are linked to assumptions of economic growth, per capita wealth, etc. Indices such as the value of wetlands, value of drylands and price elasticity of water supply are logically linked – increases in wealth imply increases in each of these values.

Only a few of the variables are directly correlated with each other in the sense that one variable drives or is strongly related to the value of a different variable. The closest linkage are the value of land (wetland and dryland), endangered species (related to loss of land) and the incidence of disasters in the reference case (especially for drought, which depends on changes in water supply and demand).

The only potential anomaly is the value of statistical life. A high value of life should imply a low number of lives lost in the reference case as society should be willing to spend more on disaster preparedness, early warning and mitigation. This is more likely for some disasters (drought, cyclones) than others (lightning, tornadoes).

Table 3. Relationship between parameters

No.		Driving force			Correlation
		Climate	Economy	Technology	
	Coastal resources	√			
1	Wetlands lost, %		√		
2	Cost of wetlands lost		√		5
3	Underdeveloped low lying coast, %	√			4
4	Area of drylands lost per 1m sea rise	√			3
5	Cost of dryland lost		√		2
6	Migrant population, %		√		
7	Cost per migrant		√		
	Agriculture				
8	Sensitivity of agricultural GDP to area suitability			√	9
	Water				
9	Water deficit elasticity of supply		√		8
10	Water deficit elasticity of demand			√	
11	Price elasticity of supply		√		
12	Price elasticity of demand		√		
13	Water deficit elasticity		√	√	
	Biodiversity				
14	Endangered species made extinct, %	√			1,4
15	Existence value of species		√		
16	Use and option value, % of EV		√		15
	Heating and Cooling				
17	Price of fuel		√	√	
18	Reference demand for energy		√	√	
	Natural Hazards				
19	Incidence of disasters, reference		√		9,10
20	Incidence of disasters, climate change	√			
21	Cost of disaster, reference		√		
22	Cost of disaster, climate change	√			
23	Lives lost, reference		√	√	
24	Lives lost, climate change	√			
25	Value of statistical life		√		23
	Other Sectors				
26	Scalar multiplier		√	√	

Annex: Equations for Estimating the Costs of Climate Change

The Open Framework estimates the costs of climate change for the IPCC's IS92a and IS92d scenarios using the output from the MAGICC and GISS models as well as economic inputs. Country level cumulative costs for all sectors (except the heating and cooling sectors which report annual costs) are calculated for the years 1990, 2000, 2010, 2025, 2050, 2075 and 2100. The net present value is found by interpolating (using a polynomial equation) between these points and discounting them at 0, 1, 3, 5 and 10%.

Coastal Impacts

Protection cost

To calculate the cumulative protection costs, the country level cost estimates for a 1m sea level rise have been scaled using a polynomial constant (1.28):

$$PC_x(t) = pc_x \times \left(\frac{\Delta s(t)}{100}\right)^c$$

$PC_x(t)$ = Cumulative protection costs for a given sea level rise in country x in year t (M$)

pc_x= Protection Costs for 1 meter sea level rise in country x (M$) (Delft, 1993)

Δs = Sea level rise in year t (cm)

c = Polynomial constant (implied by Titus *et al,* 1991, see also Fankhauser, 1992)

Wetlands costs:

It is assumed that wetlands will be lost if coasts are protected or if coasts are left unprotected. The area of wetland lost is calculated from country level estimates of wetlands in danger given a 1m sea level rise. For the IS92a scenario it is assumed that protective measures will be taken while no measures are assumed for the IS92d scenario. This theoretical area lost is multiplied by a low, medium and high estimate of the actual percentage that can realistically be expected to be lost:

$$LWL_x(t) = aWL_x \times \left(\frac{\Delta s(t)}{100}\right) \times \left(\frac{pWL}{100}\right)$$

$LWL_x(t)$ = Loss of wetlands in country x due to the Δs sea level rise in year t (km^2)

aWL_x = Potential amount of wetlands in country x in danger due to a 1m sea level rise (km^2) (IPCC, 1990)

$\Delta s(t)$ = Sea level rise in year t (cm)

pWL = Estimation of actual percentage of potential wetlands that would be lost (%)

The cumulative costs then follow from the area of wetland lost multiplied by the value of the wetlands lost, which is scaled into the future using the growth in agricultural GDP:

$$WLC_x(t) = LWL_x(t) \times cWL \times \left(\frac{aGDP(t)}{aGDP(1990)}\right)$$

$WLC_x(t)$ = Cumulative costs of wetland loss in country x in year t (M$)

$LWL_x(t)$ = Loss of wetlands in country x due to the Δs sea level rise in year t (km^2)

cWL = Cost of wetlands lost i.e. capital value, 1990 (M$/km^2) (based on Fankhauser (1992) and other valuation studies)

aGDP(t) = Global Agricultural GDP in year t (M$)

Drylands costs:
Drylands are lost if underdeveloped coastlines recede. Similar to the wetland costs, the area of drylands lost is calculated first. Country level data and uncertainty ranges are used:

$$LDL_x(t) = (lLLC_x \times aLLC) \times \left(\frac{\Delta s(t)}{100}\right) \times \left(\frac{pLLC}{100}\right)$$

$LDL_x(t)$ = Loss of dryland in country x due to the Δs sea level rise in year t (km^2)

$lLLC_x$ = Length of low lying coast in country x (km) (IPCC, 1990)

aLLC = Area of underdeveloped coast lost per kilometre of coast for a 1 m rise in sea level in the USA (km^2/km) (based on Fankhauser, 1992)

pLLC = Percentage of the low lying coast which is underdeveloped i.e. which would suffer loss of dryland, 1990 (%) (based on Fankhauser, 1992)

Δs(t) = Sea level rise in year t (cm)

The cumulative costs are then estimated by multiplying the area lost to the value of the land, which is scaled upwards using the global agricultural GDP:

$$DLC_x(t) = LDL_x(t) \times cDL \times \left(\frac{aGDP(t)}{aGDP(1990)}\right)$$

$DLC_x(t)$ = Cumulative costs of dryland loss in country x in year t (M$)

$LDL_x(t)$ = Loss of dryland in country x due to the Δs sea level rise in year t (km^2)

cDL = Cost of dryland lost i.e. capital value (M$/km^2)

aGDP(t) = Global agricultural GDP in year t (M$)

Coastal migration:
It is assumed that people living in the dryland areas lost to sea level rise will be forced to migrate. The cumulative costs of migration are found by multiplying the number of people forced to migrate by the cost per migrant (which is scaled into the future using the development of per capita GNP):

$$MGC_x(t) = \frac{CPD_x(1990) \times \left(\frac{pPD}{100}\right) \times \left(\frac{P_x(t)}{P_x(1990)}\right) \times LDL_x(t) \times cMG \times \left(\frac{GNPpc(t)}{GNPpc(1990)}\right)}{1{,}000{,}000}$$

$MGC_x(t)$ = Cumulative costs of migration from country x in year t (M$)

$CPD_x(t)$ = Coastal population density in country x in year t (People/km^2) (IPCC, 1990)

pPD = Proportion of population density in areas of the coast at risk , as a % of coastal population density, 1990 (%)

$P_x(t)$ = Population in country x in year t (Persons)

$LDL_x(t)$= Loss of dryland in country x due to the Δs sea level rise in year t (km^2)

(4)

cMG = Annual cost of climate migrants, 1990 ($/person/year) (Ayers and Walters (1991) and Cline(1992))

GNPpc(t) = Global GNP per capita in year t ($/Person)

$\Delta s(t)$ = Sea level rise in year t (cm)

Heating and Cooling Demand

Unlike the other sector costs, the benefits to the heating sector as well as the costs to the cooling sector are annual costs. Cumulative costs are calculated in compiling output reports from the OF. Both models use spatial data (the number of heating and cooling degree days) from the GISS model scaled to the MAGICC output.

Heating benefits:

It is assumed that reduction of heating degree days will lead to benefits in heating systems fuelled by either electricity or fuel (e.g., gas). An index is used which indicates the annual change in the number of heating degree days:

$$Rh_x = \frac{\left(\frac{hDD_x(2100) - hDD_x(1990)}{hDD_x(1990)}\right)}{2100 - 1990}$$

Rh_x = Index indicating the change in the number of heating degree days per year in country x

$hDD_x(t)$= Number of heating degree days (base 15 °C) in country x in year t

A Stockholm Environment Institute model (SEI, 1993) produced baseline estimates of regional electricity and fuel used in domestic heating. The heating degree day index is used to find the incremental use attributable to climate change. Regional annual costs are found using projected electricity and fuel prices and are divided amongst the countries in the region according to their share of the heating degree days in 1990:

$$HC_{x:f,e} = Rh_x \times (t - 1990) \times p_{f,e}(t) \times E_{r:f,e}(t) \times \left(\frac{hDD_x(1990)}{hDD_r(1990)}\right) \times 1000$$

$HC_{x:f,e}(t)$ = Annual fuel and electricity costs of heating in country x in year t (M$)

Rh_x = Ratio indicating the change in the number of heating degree days per year in country x

t = year

$p_{f,e}(t)$ = World price of fuel or electricity in year t (M$/GJ)

$E_{f,e}(t)$ = Base projection of fuel and electricity use in region r in period t (EJ/yr)

$hDD_x(t)$ = Number of heating degree days (base 15 °C) in country x in year t

$hDD_r(t)$ = Number of heating degree days (base 15 °C) in region r in year t

Cooling costs:

The electrical cooling costs are calculated in the same fashion as the electrical and fuel heating costs. An index to measure the change in the number of cooling degree days per year is calculated first:

$$Rc_x = \frac{\left(\frac{cDD_x(2100) - cDD_x(1990)}{cDD_x(1990)}\right)}{2100 - 1990}$$

Rc_x = Ratio indicating the change in the number of cooling degree days per year in country x

$cDD_x(t)$= Number of cooling degree days (base 20 °C) in country x in year t

The annual costs of cooling are found using the same method for the heating sector. Due to the conversion from Watt-hours to joules however the equation is multiplied by a factor 3.6:

$$CC_{x\cdot e} = Rc_x \times (t - 1990) \times p_e(t) \times E_{r\cdot e}(t) \times \left(\frac{cDD_x(1990)}{cDD_r(1990)}\right) \times 3.6$$

$CC_x(t)$ = Annual cooling costs in country x in year t (M$)

Rc_x = Ratio indicating the change in the number of cooling degree days per year in country x

t = Year t

$p_e(t)$ = World price of electricity in year t (M$/GJ)

$E_e(t)$ = Base projection electricity use in region r in period t (TWh/yr)

$cDD_x(t)$ = Number of cooling degree days (base 20 °C) in country x in year t

$cDD_r(t)$ = Number of cooling degree days (base 20 °C) in region r in year t

Agriculture and Water Resource

Both these sectors use spatial data from the GISS model that is scaled to the MAGICC output.

Agriculture costs

These costs are calculated using an index of the change in the area suitable for rain-fed agriculture (regions with biotemperatures between 5 ° C and 25 ° C and precipitation between 500mm and 2500mm per year):

$$A_x = \frac{a_x(2100) - a_x(1990)}{a_x(1990)}$$

A_x = Agricultural index of the change in land suitable for rain-fed agriculture in country x

a_x = Weighted sum of the area in country x suitable for rain-fed agriculture

The cumulative agricultural costs are found by multiplying the index by projected agricultural GNP (estimated based on the present relationship between agricultural GNP and per capita GNP) and a measure of the sensitivity to the index:

$$AGC_x(t) = A_x \times \left(\frac{S}{100}\right) \times aGDP_x(t) \times \frac{\Delta t(t)}{\Delta t(2100)}$$

$AGC_x(t)$ = Cumulative agricultural costs in country x in year t (M$)

A_x = Agricultural index of the change in land suitable for agriculture in country x

S = Sensitivity of Agricultural GNP to first-order agricultural index (%)

$aGDP_x(t)$ = Agricultural GDP in country x year t (M$)

$\Delta t(t)$ = Temperature change in year t (°C)

Water resources

The costs to water resources are derived from an economic model of supply and demand. The changes in supply and quantity demand are dependent on the spatial model of water deficits, income and price. The change in the total value demanded is equal to the change in price and quantity:

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

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

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

$\Delta Q/Q$ = Proportional change in quantity of water demanded or supplied

$\Delta W/W$ = Proportional change in water deficit

$\Delta P/P$ = Proportional change in the price

$\Delta(P.Q)/P.Q$ = Proportional change in value water demanded or supplied

α_s = Water deficit elasticity of supply

β_s = Income elasticity of supply

ε_s = Price elasticity of supply

α_d = Water deficit elasticity of demand

β_d = Income elasticity of demand

ε_d = Price elasticity of demand

From this the change in the value demanded can be derived:

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

The income effect, however, is not attributable to climate change and is therefore not used in the equation. First an index is calculated which is equal to $\Delta W/W$ in the year 2100:

$$W_x = \frac{(Wd_x(2100) - Ws_x(2100)) - (Wd_x(1990) - Ws_x(1900))}{|Wd_x(1990) - Ws_x(1900)|}$$

W_x = Water deficit index for country x

$Wd_x(t)$ = Water deficit in country x in year t (sum of all the months which experience a water deficit)

$Ws_x(t)$ = Water surplus in country x in year t (sum of all the months which experience a water surplus)

Using this index the cumulative costs may be calculated. The water deficit elasticity is a function of the price and water deficit elasticities of demand and supply. The ((t-1990)/2) factor is used to calculate cumulative costs:

$$WRC_x(t) = c_x(1990) \times w_x(1990) \times \alpha_{wd} \times W_x \times \frac{\Delta t(t)}{\Delta t(2100)} \times \frac{(t-1990)}{2} \times 1000$$

$WRC_x(t)$ = Cumulative water resource costs in country x at time t

$c_x(t)$ = Water withdrawal costs in country x in year t ($\$/m^3$)

$w_x(t)$ = Water withdrawal in country x in year t (km^3/yr)

$GNP_x(t)$ = GNP of country x in year t (M$)

α_{wd} = Water deficit elasticity

W_x = Water deficit index for country x

$\Delta t(t)$ = Temperature change in year t (°C)

Biodiversity, Natural Hazards and Other Sectors

Biodiversity

The cumulative costs of biodiversity loss are simply found by estimating the number of species that would be lost per country and multiplying it by the value per species. The existence values are scaled to the GNP per capita in United States in 1990 since the existence values are based on contingent valuation studies there. The use and option values are assumed to be a fixed percentage of the existence value:

$$BDC_x(t) = N_x \times \left(\frac{pN}{100}\right) \times \left(EV \times \left(\frac{GNPpc_x(t)}{GNPpc_{USA}(1990)} + \frac{pUOV}{100}\right)\right) \times P_x(t) \times \left(\frac{\Delta t(t)}{\Delta t(2100)}\right) \times \left(\frac{t-1990}{2}\right)$$

$BDC_x(t)$ = Cumulative costs of loss of biodiversity in country x and for year t (M$)

N_x = Number of threatened species in country x (UNEP, 1995)

pN = Proportion of endangered species made extinct by climate change (%) (Fankhauser, 1992)

EV = Existence Value of endangered species in the USA, 1990 ($/person/year/species) (Fankhauser, 1992)

$GNPpc_x(t)$ = GNP per capita in country x in year t ($/person)

$GNPpc_{USA}(1990)$ = GNP per capita in the USA in 1990 ($/person)

pUOV = Use and option value as a proportion of existence value (%) (Fankhauser, 1992)

$P_x(t)$ = Population in country x in year t (people)

$\Delta t(t)$ = Temperature change in year t (°C)

Natural Hazards

The cumulative costs of natural hazards is found by using historic data (1967-1992) to give a low, medium and high estimate of the cost and number of lives lost per disaster per year. 17 different types of hazards are considered. A low, medium and high scalar is then used to project the change in the incidence, number of lives lost and the economic impact per disaster in the reference scenario and with climate change. The lives lost are valued by means of the value of a statistical life, which is scaled up by per capita GNP. First the costs per year (in 2100) for the reference and climate change scenario are:

$$NH_{rs} = \sum_{1}^{h}\left[\left(I_h \times i_{h:rs}\right)\left(\left(D_h \times d_{h:rs}\right) + \left(L_h \times l_{h:rs} \times VSL \times \frac{GNPpc(2100)}{GNPpc(1990)}\right)\right)\right]$$

$$NH_{cc} = \sum_{1}^{h}\left[\left(I_h \times i_{h:rs} \times i_{h:cc}\right)\left(\left(D_h \times d_{h:cc}\right) + \left(L_h \times l_{h:cc} \times VSL \times \frac{GNPpc(2100)}{GNPpc(1990)}\right)\right)\right]$$

NH_{rs} = The annual damages of natural hazards in the reference scenario in 2100

NH_{cc} = The annual damages of natural hazards due to climate change in 2100

I_h = Incidence of hazard h per year (based on the historical data from 1967-1992)

$i_{h:rs}$ = Scalar for projecting the change in the incidence of hazard h in the reference scenario

$i_{h:cc}$ = Scalar for projecting the change in the incidence of hazard h due to climate change

D_h = Damage per hazard h (based on the historical data from 1967-1992) (M$)

$d_{h:rs}$ = Scalar for projecting the change in the costs of hazard h in the reference scenario

$d_{h:cc}$ = Scalar for projecting the change in the costs of hazard h due to climate change

L_h = Average number of lives lost per occurrence of hazard h (based on the historical data from 1967-1992)

$l_{h:rs}$ = Scalar for projecting the change in the number of lives lost due to hazard h in the reference scenario

$l_{h:cc}$ = Scalar for projecting the change in the number of lives lost due to hazard h with climate change

VSL = Value of a statistical life in 1990 (M$/person)

GNPpc(t) = Global GNP per capita in year t ($/person)

From these costs per year the cumulative cost can be found:

$$NHC(t) = \left(\frac{NH_{cc} - NH_{rs}}{2100-1990}\right) \times (t-1990) \times \left(\frac{t-1989}{2}\right)$$

NHC(t) = Cumulative costs of natural hazard in year t

NH_{rs} = The annual damages of natural hazards in the reference scenario in 2100

NH_{cc} = The annual damages of natural hazards due to climate change in 2100

t = Year t

Health, Welfare and Other Sectors

These costs are calculated at the global level. The net present value of the positive costs from other sectors is simply multiplied by a scalar to find the net present value for 'other sectors':

$$OSC_{NPV} = s \times PC_{NPV}$$

OSC_{NPV} = Global net present value for 'other sectors' (M$)

s = Scalar multiplier

PC_{NPV} = Net present value of all positive costs (coastal resources, agriculture and water resources, cooling costs, disasters and biodiversity) (M$)

Annex: Values of variables used in the Open Framework

The following table lists all of the parameters used in the OF to estimate the range of impacts. The parameters for disasters have been summarised. The averages of the scalars for the economic losses, lives lost and incidence of natural hazards are included as well as the minimum and maximum. There are 17 natural hazards considered which are all given subjective projections into the future under the reference and climate change scenarios using these scalars. Similar treatment is given to the energy reference projections, which cover the major world regions (disaggregated by country).

Parameters used in the OF

No.			*IS92a*			*IS92d*			*Range*
			low	**med**	**high**	**low**	**med**	**high**	
	Wetlands								
1	pWL	%	50	75	100	50	75	100	2
2	cWL	M$/km^2	0.50	1.25	5.00	0.50	1.25	5.00	10
	Drylands								
3	pLLC	%	50	80	100	50	80	100	2
4	aLLC	km^2/km	0.60	0.90	1.20	0.60	0.90	1.20	2
5	cDL	$M/km^2	0.5	2.0	5.0	0.5	2.0	5.0	10
	Migration								
6	pPD	%	50	75	100	50	75	100	2
7	cMG	$/year	75	1,000	4,500	75	1,000	4,500	60
	Agriculture								
8	S	%	10	50	100	10	50	100	10
	Water resources								
9	α_s		-0.05	-0.15	-0.25	-0.05	-0.15	-0.25	5
10	α_d		0.05	0.15	0.25	0.05	0.15	0.25	5
11	ε_s		0.65	0.33	0.00	0.60	0.30	0.00	--
12	ε_d		-0.70	-0.50	-0.30	-0.65	-0.45	-0.25	3
13	α_{wd}		0.07	0.33	1.42	0.08	0.37	1.75	25
	Biodiversity								
14	pN	%	0.2	2.0	7.5	0.1	1.5	5	75
15	EV	$/pers/yr /species	0.1	3.0	10	0.1	3.0	10	100
16	pOUV	%	10	33	67	10	33	67	7
	Heating and Cooling								
17	Price	$/GJ							
-a	Electricity		20	39	39	17	34	34	2
-b	Fuel		12	25	25	9	18	18	3
18	Demand								
-a	Heating	EJ/yr	50	198	794	17	67	269	16
-b	Cooling	TWh/yr	2873	11492	45966	414	1658	6632	111
	Natural Hazards								
19	i_{rs} average (min or max)		0.81 (0.25)	1.01	1.12 (1.50)	0.71 (0.00)	0.87	0.93 (1.25)	1.5
20	i_{cc} average (min or max)		1.04 (0.75)	1.20	1.47 (2.00)	0.91 (0.50)	1.05	1.21 (1.35)	1.5
21	d_{rs}		2.25	5	10	3	5	10	4
22	d_{cc} average (min or max)		1.00 (0.80)	1.17	1.43 (1.75)	0.97 (0.90)	1.06	1.21 (1.50)	1.5
23	l_{rs} average (min or max)		0.61 (0.10)	0.85	1.21 (1.50)	0.41 (0.00)	0.64	0.96 (1.25)	3
24	l_{cc} average (min or max)		1.00 (0.80)	1.17	1.43 (1.75)	0.97 (0.90)	1.06	1.21 (1.50)	1.5
25	VSL	M$/pers.	1.0	3.0	10.0	1.0	3.0	10.0	3
	Other sector costs								
26	s		0.67	1.00	1.33	2.00	2.67	4.00	4

Symbols (in the order that they appear in the table):

pWL = Estimation of actual percentage of potential wetlands that would be lost (%)
cWL = Cost of wetlands lost i.e. capital value, 1990 (M$/km^2) (based on Fankhauser (1992) and other valuation studies)
aLLC = Area of underdeveloped coast lost per kilometre of coast for a 1 m rise in sea level in the USA (km^2/km) (based on Fankhauser, 1992)
pLLC = Percentage of the low lying coast which is underdeveloped i.e. which would suffer loss of
dryland, 1990 (%) (based on Fankhauser, 1992)
cDL = Cost of dryland lost i.e. capital value (M$/km^2)
$CPD_x(t)$ = Coastal population density in country x in year t (People/km^2) (IPCC, 1990)
pPD = Percentage of population in dryland area lost to sea level rise that migrate (%)
cMG = Annual cost of climate migrants, 1990 ($/person/year) (Ayers and Walters (1991) and Cline(1992))
S = Sensitivity of Agricultural GNP to first-order agricultural index (%)
α_s = Water deficit elasticity of supply
ε_s = Price elasticity of supply
α_d = Water deficit elasticity of demand
ε_d = Price elasticity of demand
α_{wd} =[E1] Water deficit elasticity
pN = Proportion of endangered species made extinct by climate change (%) (Fankhauser, 1992)
EV = Existence Value of endangered species in the USA, 1990 ($/person/year/species) (Fankhauser, 1992)
pUOV = Use and option value as a proportion of existence value (%) (Fankhauser, 1992)
$i_{h:rs}$ = Scalar for projecting the change in the incidence of hazard h in the reference scenario
$i_{h:cc}$ = Scalar for projecting the change in the incidence of hazard h due to climate change
$d_{h:rs}$ = Scalar for projecting the change in the costs of hazard h in the reference scenario
$d_{h:cc}$ = Scalar for projecting the change in the costs of hazard h due to climate change
$l_{h:rs}$ = Scalar for projecting the change in the number of lives lost due to hazard h in the reference scenario
$l_{h:cc}$ = Scalar for projecting the change in the number of lives lost due to hazard h with climate change
VSL = Value of a statistical life in 1990 (M$/person)
s = Scalar multiplier

Appendix 3

Linking Weak and Strong Sustainability Indicators: The Case of Global Warming

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1. INTRODUCTION

The philosophy of a sustainable management of natural resources has been derived from the theory of environmental and resource economics. Originally the concept was developed for renewable resources, especially forests, for which maximum sustainable yields have been calculated. Hartwick (1978) has widened the sustainability principle to applications for exhaustible resources. The concept of a circular economy, as developed by Pearce and Turner (1990, p. 35), has established a broader concept which includes the function of the natural environment as a sink for emissions and waste.[1]

With regard to the assimilative capacity of the environment, ecosystem health is threatened by the greenhouse effect. The Conference of the Parties to the Framework Convention on Climate Change in Berlin 1995 has shown once more the need for a protocol in which the parties commit themselves to reduction targets for the different greenhouse gases (or for many developing countries: targets to limit increases). With regard to Article 3.1 of the Convention, targets for individual states should be defined "in accordance with their common but differentiated responsibilities and respective capabilities".

The role of scientific research in this process is helping decision makers to derive reasonable reduction targets. However, the appropriate decision rule depends on the underlying interpretation of the sustainability paradigm which can follow an ecological or an economic approach.

- From an ecological perspective, the "strong" sustainability rule requires that the total sum of greenhouse gas emissions should not exceed the assimilative capacity of the atmosphere and that, at least, irreversible and catastrophic effects on the global ecosystem should be avoided.
- From a welfare theoretic perspective, a "weak" sustainability approach is based on the principle that social welfare should be maximised and the total costs of climate change (abatement, adaptation and damage costs) should be minimised.

In order to bring ecological and economic requirements together, it is necessary to enhance integrated scientific assessments of climate change. During the past years, several approaches for integrating ecological aspects into economic theory have been conducted by models of integrated assessment of climate change. However, these models can still be divided into two groups: economic approaches based on cost-benefit analysis, and ecological approaches based on environmental targets (Weyant et al. 1996).[2]

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[1] Beyond that some additional issues are discussed within the sustainability paradigm. For example, Daly emphasizes the role of eco-efficiency as a basic management rule: "Improving end use efficiency of resources is desirable regardless whether the resource is renewable or non-renewable" (Daly, 1990, p. 5). Additionaly, the German Council of Environmental Advisors (SRU, 1994, p. 48) stresses that the aspect of protecting human health is neglected by many proponents of sustainability, and introduces health as a further important goal.

[22] Some contributions towards a more ecological-oriented target-setting have been made by advocates of ecological economics, e.g. general contributions to integrated ecological and economic models like the one of Common and Perrings, 1992, and special contributions to the consideration of sustainability aspects of climate change into economic analysis, like the ones of Spash, 1994, and Hohmeyer, 1996.

Against this background, the aim of this paper is to explain the weak and strong sustainability approach of climate protection and to show reasonable applications, weaknesses, possible improvements and linkages of both approaches. In a first step, main features of "weak" and „strong" sustainability approaches towards climate stability will be characterised. Then damage cost studies of global warming will be discussed which represent indicators of the weak sustainability approach.[3] Further, the examples of the "inverse scenario" approach of the German Advisory Council on Global Change (WBGU) and the environmental space concept of the Dutch Advisory Council for Research on Nature and Environment (RMNO) will be described and discussed for illustrating operational indicators of strong sustainability. Finally, the integration of damage cost modules into a broader methodological framework of strong sustainability is recommended.

2. WEAK AND STRONG SUSTAINABILITY APPROACHES FOR ASSESSING CLIMATE CHANGE

2.1 Definition of Weak and Strong Sustainability

In several contributions, damage cost calculations of climate change like that of Nordhaus (1991), Cline (1991) and Fankhauser (1995) were criticised especially from an ecological perspective. It had been argued that mere neo-classical optimisation concepts tend to ignore the ecological, ethical and social dimension of the greenhouse effect, especially issues of an equitable distribution and a sustainable use of non-substitutable, essential functions of ecosystems.[4]

The ecological argument addresses the use of damage cost values for computing optimal levels of emission abatement neglecting the special function of the atmosphere as a sink for greenhouse gases. This function is absolutely scarce and essential for the global ecosystem. It is feared that, by putting certain monetary values on this essential natural function, politicians may be encouraged to "sell" it in exchange for goods being possibly of higher value in a short time horizon (e.g. income).

[3] Since a detailled description of the contents and results of existing studies has already been done in the IPCC Second Assessment Report (Pearce et al., 1996), this paper focuses on the critical issues of the studies and the further development of their methodological framework.

[4] Most of the critical arguments pointing out the limits of traditional cost-benefit-analysis can be found in the IPCC Second Assessment Report (IPCC 1995, WG III).

An early proposal for considering sustainability constraints in cost-benefit analysis has been made by Barbier, Markandya and Pearce (1990, pp. 1260 - 1261). They formulate a sustainability criterion requesting that the sum of damages done by a certain amount of projects should be zero. If E_i is the damage done by the i-th project, the criterion is

$$\sum_i E_i \leq 0 \qquad (1)$$

The idea of the criterion is that any environmental damage should "be compensated by projects specifically designed to improve the environment" (Markandya and Pearce, 1991, p. 150). In terms of welfare economics, the compensation criterion is shifted from hypothetical to actual compensation.
However, the sustainability criterion of Barbier, Markandya and Pearce is "weak" because it allows for unconstrained elasticities of substitution between different types of natural capital. For example, a further depletion of the ozone layer can be compensated by projects supporting the protection of panda bears. Such a weak sustainability criterion should be supplemented by "strong" sustainability criteria which stress more the limitations of substitutability. In this sense, "strong sustainability regards natural capital as providing some functions that are not substitutable by man-made capital. These functions, labelled 'critical natural capital', are stressed by defining sustainability as leaving the future generations a stock of natural capital not smaller than the one enjoyed by the present generation" (Cabeza Gutés 1996, p. 147).[5]

2.2 Elements of a Theoretical Foundation of Weak and Strong Sustainability

2.2.1 Sustainable Preferences and Adjusted Discount Rates

Strong sustainability, as defined above, is defined in physical terms. This definition is hardly compatible with neo-classical economics having pushed physical factors into the background. What counts in neo-classical welfare theory are subjective perceptions and preferences of people. This preferences of individuals give a certain value to man-made or natural capital. Following this logic, climate stability is a limiting factor of human development if and only if some individuals have an aversion against observed climate risks. As long as individuals do not care about climate change, climate protection does not produce any benefit for them and has, therefore, no economic value. In other words: strong sustainable development can only be translated into neo-classical economics by introducing individual preferences for the long-term protection of life-support functions of ecosystems. Thus, the protection of critical natural capital can be achieved if revealed preferences for intact ecosystems exist.

Such a translation of sustainable development into terms of welfare economics has been suggested by Chichilnisky (1996a). Chichilnisky introduces "sustainable preferences" which are defined by two axioms to rule out "dictatorial" solutions. In her approach, neither the present nor future generations should be dictatorial.

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[5]Similar definitions can be found in Pearce and Atkinson (1993) and Pearce, Hamilton and Atkinson (1996), pp. 85 - 87. It should be added that critical elements of natural capital can neither be subsituted by man-made capital nor by other elements of natural capital, as the example of the ozone layer and the panda bear may illustrate.

The axioms are:

- no dictatorship of the present (no finite set of generations should be dictatorial), and
- no dictatorship of the future („the very long run" should not be dictatorial).

The axioms can easily be related to the strong and weak sustainability paradigms. While the weak sustainability approach of discounted utilitarianism can be characterised as a dictatorship of the present, the strong sustainability approach can be regarded as dictatorship of the future.[6] The non-dictatorial solution are the so called "sustainable preferences" or the "Chichilnisky criterion". Sustainable preferences are sensitive to the welfare of all generations. This means that:

- the conventional way of discounting future preferences may lead to unsustainable development paths and catastrophic outcomes for future generations, so special weight has to be given to future generations.
- On the other hand, zero discounting may discriminate against the present generation. If consumption in all periods would be weighted equally on an endless time scale, weights would sum to infinity.

Chichilnisky (1996b, p. 2) sees empirical evidence that sustainable preferences exist already within the present generation. If such empirical evidence can be found, the conventional way of measuring and discounting peoples values for the future have to be adjusted. Such adjustments will be described more detailed in chapter 3 of this paper.

2.2.2 Uncertainty and Multi Criteria Analysis

Even if sustainable preferences are assumed, the question is whether the costs and benefits of climate change are quantifiable. In a complex and uncertain situation where irreversible damages can occur, Faucheux and Froger (1994) argue that the conventional Bayesian approach of assuming known risk probabilities is not appropriate. According to Faucheux and Froger, the assumption of bounded rationality[7] is more adequate to the problem. Bounded rationality means limited ability of the human mind to collect, remember and evaluate information. Assuming uncertainty and bounded rationality supports the strong sustainability paradigm, since the optimisation of outcomes can be judged as over-ambitious in situations where even valid estimates of rough future trends are hard to find. Faucheux and Froger refer to Simon (1972, p. 410) who explains the consequences of assuming bounded rationality as follows: „The decision question has been switched to the question of how much of the actor's resources should be allocated to search". Initiating such a process of search is called procedural rationality. The methodological consequence is that satisfactory choices may become more relevant than optimal choices, and safe minimum standards may function as rules of thumb during the process of search. It is nevertheless necessary to classify and evaluate

[6] In the terminology of Beltratti, Chichilnisky and Heal (1994), the strong sustainability criterion is called the "green golden rule". They define it as the configuration of the economy which gives the highest indefinitely maintainable level of long run utilities. In principle, the green golden rule requires a zero functional consumption of exhaustible resources.

[7] Bounded rationality is an established assumption among new institutional economists, see e.g. Simon (1972) and Rennings (1992), p. 16.

alternative outcomes in a weighting scheme. Faucheux and Froger (1994, p. 62) suggest the multicriteria analysis as an analytical tool for decision making based on procedural rationality.

2.2.3 Scale Issues and Ecological Carrying Capacity

Daly (1992) has addressed the categories of weak and strong sustainability by separating the policy goals of sustainable scale, just distribution and efficient allocation. Scale refers to the ecological carrying capacity requiring that economic activities should not jeopardise the stability of ecosystems. According to Daly, processes which are relevant to the level of entropy, as e.g. resource use or flows of matter-energy, should be restricted according to a sustainable scale. Scale has to be measured in absolute physical units. A good scale is one that is at least sustainable, that does not erode environmental carrying capacity over time. In other words, future environmental carrying capacity should not be discounted in present value calculations. An optimal scale is at least sustainable, but beyond that it is a scale at which we have not yet sacrificed ecosystem services that are at present worth more at the margin than the production benefits derived from further growth in the scale of resource use" (Daly 1992, pp. 186 - 187). Hence, economic growth should be adjusted to the absolute carrying capacity of ecological systems. This is seen as a prerequisite for dealing with questions of distribution and allocation of natural resources.

Using Daly's categories, the valuation of external costs seems to be useful to gather indicators of efficient allocation. However, correcting market failure by estimating the "right" social costs is only the third and last step within the sequential process of addressing policy issues of sustainability, equity and efficiency. Obviously, additional ecological and social indicators are needed for the first two steps. Pursuing this, pressures endangering the long-term stability of ecosystems have to be identified and transformed into critical thresholds. Such thresholds function as "safe minimum standards" (Hampicke, 1993, p. 149; Bishop, 1978, pp. 10 - 18) for essential parts of ecosystems. Daly has used the metaphor of „plimsoll lines" to describe this function of scale limits (Daly, 1992, p. 192).[8]

2.3 Indicators of Weak and Strong Sustainability

The weak sustainability approach is represented by external cost estimates of climate change being closely related to the economic rule of maximising welfare. Thus, external costs can be interpreted as indicators of weak sustainability. They indicate the amount of money that has to be spent for the compensation of the estimated welfare losses. The question discussed in this paper is whether these indicators are useful and which role external costs may play in a broader concept of strong sustainability.

In comparison with that, indicators of strong sustainability should offer information about critical elements of the natural capital. Firstly, they should inform about changes in quantity

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[8] While the concept of Daly is strictly based on the law of entropy, the relevance of entropy processes to explain interactions in open economic and ecological systems seems to be vague and is still disputed (Rennings 1994, pp. 106 - 110; Binswanger 1993, pp. 220 - 229). Alternative approaches are more oriented on ecological criteria like the "resilience and stability of ecosystems" (Common and Perrings, 1992, pp. 15 - 21).

and quality of essential natural resources and functions. Secondly, they should reflect how far the actual use of natural resources is away from a sustainable scale.

Although the process of specifying and quantifying critical elements and thresholds evokes several problems, some progress has been made in developing physical sustainability indicators during the last years (Billharz/Moldan 1995). Rennings and Wiggering (1997) have focused on the assimilative capacity concerning acidification and eutrophication. While critical thresholds can be observed and measured for these problems, the issue becomes more difficult for linear or uncertain risks where no safe levels are obvious. With regard to climate change, the question has to be answered if and how acceptable levels of greenhouse gas emissions can be quantified.

3. ASSESSMENT OF WEAK SUSTAINABILITY INDICATORS OF CLIMATE CHANGE

3.1 Handling of Global Warming in External Cost of Energy Studies

Due to methodological and empirical problems, the major valuation studies estimating external costs in the energy sector refused to integrate damage costs of climate change into their results. Two different options have been used alternatively:

- The first alternative is the calculation of abatement costs (for specified CO2-reduction targets) instead of damage costs. Most advocates of an ecological paradigm of sustainable development prefer the use of abatement costs because they are normally related to CO2-reduction targets leading to sustainable future emission paths. The abatement cost option has been chosen e.g. by studies from de Boer/Bosch (1995), Bernow et al. (1996) and Ott (1996).
- Other research teams, being more obliged to a neo-classical paradigm of external costs, decided to renounce the use of damage cost values until more comprehensive studies and methodologies are available. Amongst this groups are the research teams of the valuation studies of the European Commission (ExternE) and of the U.S. Department of Energy (DOE-Study). As Lee (1996, p. 16), one of the authors of the DOE-Study, states: „The earlier studies include estimates of damages from climate change; the more recent studies do not include them in their summary tabulations.“ And in a footnote he remarks that „this conclusion does not say that damages from climate change are zero, but that precise estimates of these damages do not have a sound scientific basis because of great uncertainty“.

3.2 Problems of Valuing Global Warming Damages

The report of phase II of the ExternE project (EC 1994, pp. 159 - 162) does not recommend the use of any monetary value for global warming, but describes the state of the art concerning the valuation of damages. The main results have been that:

- greenhouse gas emissions from each fuel cycle are known accurately,
- the impacts of global warming are complex, scenario dependant, very uncertain, long term and potentially very large,
- the regional variation of climatic change is poorly understood,
- the most comprehensive impact assessments (IPCC) are largely qualitative,
- the results are very sensitive to scenarios considering secondary effects, especially starvation in developing countries,

- serious ethical questions are touched which go beyond mere allocation questions of welfare theory and
- there is no consensus about these fundamental ethical questions.

Similar conclusions have been drawn by the Intergovernmental Panel of Climate Change (IPCC) in it's Second Assessment Report being finished in the end of 1995.[9] The report cites the range of estimates of marginal damage at 5 - 125 $ per ton of carbon emitted now (Pearce et al., 1996, p. 218). The Working Group III of the IPCC has given special attention to the assessment of cost-benefit analysis and the incorporation of intra- and intergenerational equity aspects. It has identified some key problems being not adequately addressed by applying traditional cost-benefit-analysis to climate change (IPCC 1995, WG III, pp. 7 - 16; Arrow/Parikh/Pillet et al. 1996, p. 59):

- large uncertainties,
- long time horizons,
- global, regional and intergenerational nature of the problem,
- wide variations of the cost estimates of potential physical damages due to climate change,
- wide variations of the cost estimates of mitigation options,
- low confidence in monetary estimates for important consequences (especially non-market impacts),
- possible catastrophes with very small probabilities and issues of intragenerational equity (especially lower values for statistical lives of people in developing countries than those in developed countries).

Besides these weaknesses, some additional methodological problems are still unsolved. While normally marginal impacts of single power plants are calculated in recent damage cost studies, marginal impacts of one power plant on the global climate seem to be insignificant (Plambeck/Hope, 1996, p. 784). Also Hohmeyer (1996) points out that valid cost-benefit optimisation is impossible because future marginal costs are impossible to derive for long term climate change. For that reason, average values have to be used. Thus, the "bottom up" approach and the estimation of marginal, site-specific effects has to be modified for the global warming issue.

The issue of serious ethical questions refers to normative assumptions of external cost studies which are not transparent for the user of the results. One assumption is that economic welfare is measured by people's willingness to pay or willingness to accept compensation. Thus, the welfare of rich people and nations has a greater weight in the results than the welfare of poor ones. Especially the common way of valuing human lives in developing countries lower than those in developed countries is highly disputed. Another implicit, but central judgement concerns the possibility of compensating future individuals for climate damages. Such

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[9] The structure of the IPCC includes three Working Groups: Working Group I (WGI) assessed the science of climate change, Working Group II (WGII) focused on the analysis of impacts and response strategies, and Working Group III (WG III) studied the socio-economic implications of impacts, adaptation, and mitigation and prepared future emissions scenarios (Arris 1996, p. 1). Each Working Group prepared a final report and a summary for policymakers (SPM) (IPCC 1995, WG I - III). The summaries are supplemented by a synthesis report covering the issues of all the three Working Groups (IPCC 1995).

assumptions have to be made transparent, and a representative range of assumptions should be used in the form of an ethical sensitivity analysis.

3.3 Improvements of Damage Cost Valuation

3.3.1 Intragenerational Equity

Responding to the IPCC criticism, Fankhauser and Tol (1995) and Tol (1996b) have derived a research agenda for the economic assessment of climate change impacts including:

- improved damage estimates for less developed countries;
- improved estimates for non-market losses, especially morbidity and ecosystem effects;
- assessment of the importance of variability and extreme events;
- models of the process of adaptation and the dynamics of vulnerability;
- formal uncertainty assessments and analyses of the outcomes;
- improved comparison and aggregation of estimates between countries;
- improved comparison and aggregation of estimates between generations;

ensuring consistency between economic and non-economic impact assessment.

Following this research agenda, first progress can be observed, especially concerning the handling of intra- and intertemporal equity questions.[10] Intragenerational equity questions have been addressed by contributions from Fankhauser, Tol and Pearce (1996) and Azar and Sterner (1996). Both use an approach of equity weighting: on the basis of the existing estimates of global warming damages, willingness to pay values are adjusted in the aggregation process. While aggregating estimates for single countries or world regions to a global value, the damages are weighted by the inverse of income. Damages of rich countries are weighted down and damages of poor countries are weighted up by adjusting these damages to the average annual per capita world income. The reason for the adjustment is „decreasing marginal utility of money and for the same reason we can argue that a given (say one dollar) cost which affects a poor person (in a poor country) should be valued as a higher welfare cost than an equivalent cost affecting an average OECD citizen" (Azar and Sterner, 1996, p. 178). Thus, equity weighting leads to the result that damages and deaths in developed countries do not count more than in developing countries. Due to the fact that the annual world income does not rise is constant, it has to be used as a budget restriction.

Beyond issues on intragenerational distribution, improvements concerning intergenerational equity have been made by several authors and will be described more detailed in the next section.

3.3.2 Intergenerational Equity

The results of monetary values of climate change damages depend substantially upon the choice of the discount rate. The higher the discount rate, the lower the present value of future damages. Thus, discounting is often criticised because it produces incentives to shift environmental risks from the present to the future. However, the relationship between

[10] Additionally, some efforts have been made towards a more dynamic modelling of climate change damages which will de not discussed within this paper. See for details Tol (1996a; 1996c).

discount rate and climate change is very ambiguous. Lowering the discount rate induces an increasing level of economic activity and investment. This would probably lead to further emissions of greenhouse gases (CEC/US Joint Study, 1993, S. 2-19). The relationship between the discount rate and environmental deterioration is known as the "conservationist's dilemma", since both, high and low discount rates, can favour environmental conservation (Norgaard/Howarth, 1991, p. 90).

Commonly, a range of discount rates is used in cost-benefit-analyses. Following Markandya, discount rates of 0, 3 and 10 percent represent an adequate range of parameters for the European Union (CEC/US Joint study, 1993, p. 2-22). 3 percent are taken as a rate for social time preference, 0 percent and 10 percent as extreme parameters for sensitivity analysis.[11] With regard to climate change, none of the three rates is satisfying: while rates of 3 to 10 percent lead to nearly zero costs for long term damages, a rate of 0 percent may evoke infinite costs.

3.3.3 Time-variant discount rates

The rate of 3 percent can be derived from the concept of social time preference (STP), a measure of the decline of social welfare or utility of consumption over time (Markandya/Pearce, 1991, p. 142). The social time preference depends on the rate of pure individual time preference (ITP) or impatience, on the growth rate of real consumption per capita (W), and on the elasticity of the marginal utility of consumption (U). The equation is:

$$STP = ITP + W \times U \qquad (2)$$

An important argument against the STP concept is that ecological "limits to (economic) growth" will set biophysical constraints on W in the long run. When choosing the rate of W, such constraints should be taken into consideration. For the EU, Markandya recommends a rate for W of around 1 or 2 percent as a low sustainable rate (CEC/US Joint study, 1993, p. 2-20).

It is argued from an environmental perspective that ITP should be refused in social investment decisions. This position takes the perspective of society as a whole and criticises impatience for being irrational. For a society - contrary to the individual view - it seems to be unreasonable to privilege present preferences above future preferences. However, a collective view conflicts with methodological individualism being a fundamental element of welfare economics.

Rabl (1993) argues that a discount rate for intergenerational effects should be defined by taking the perspective of future generations. From Rabl's point of view, market interest rates can only be taken to the extent that a market exists. Following Rabl, the longest time horizon of market transactions is 30 to 40 years. Thus, there is no inconsistency in lowering the interest rate for damages beyond that time horizon. In consequence, Rabl recommends to split STP in an

[11] Relative high (market) discount rates of 6 or more percent normally represent the concept of opportunity costs of capital.

STP = ITP + W x U for short term effects (< 30 to 40 years) (3)

and an

STP = W x U for long term effects (> 30 to 40 years) (4)

At first glance, the splitting concept and the time horizon for market transactions chosen by Rabl seem to be very arbitrary. At second glance, a special treatment of long term effects seems to be reasonable, because otherwise damages occurring a hundred or more years in the future will be totally ignored in monetary valuation studies. Understood as a first rule of thumb, Rabl's concept of time-variant discount rates helps to improve the treatment of long term effects in external cost studies.

More accurate values can be estimated by using models of overlapping generations (OLG-models). For example, Bayer and Cansier (1996) have developed a simple OLG-model including four generations with a life expectancy of 4 periods for each generation. A more realistic, but complex model should include about 40 generations. The aim of OLG-models for calculating costs of climate damages is to estimate the discounted value of investments into climate protection when benefits go beyond the life expectancy of the current generation. The calculation is done year by year considering the demographic structure of the current generation. While all effects of climate protection on consumption within the life expectancy of the current generation are discounted by using STP including ITP, all effects beyond the current generation are discounted by using STP without ITP.

Following the idea of the Chichilnsky's criterion (see section 2.2.1), Heal (1996, pp. 6 - 7) has introduced the concept of logarithmic discounting with a similar consequence, namely a decreasing discount rate in time. In his approach, the discount rate is inversely proportional to distance into the future. This formalisation has been derived from the Weber-Fechner law stating that „human response to a change in a stimulus is inversely proportional to the pre-existing stimulus“ (Heal, 1996, p. 6). Heal argues that a decreasing discount rate is a natural phenomenon: „postponement by one year from the next year to the year after, is clearly quite a different phenomenon from postponement from fifty to fifty one years hence. The former represents a major change: the latter a small one“. Compared with the approach of Rabl, the concept of logarithmic discounting is more elaborated and sophisticated. The main advantage is that discontinuous damage functions can be avoided.

It can be summarised that the introduction of time-variant discount rates is reasonable with regard to long-term environmental damages. To express it in the words of Sterner and Azar (1996, p. 174), „a constant discount rate should only be seen as a special case of the more general case where the discount rate is allowed to vary“.

Markandya's estimate for ITP is around 1 or 2 percent. Added with W, the result is a STP of 2 to 4 percent (CEC/US Joint study, 1993, p. 2-20). Rabl's estimates of W are quite similar to Markandya's values (Rabl, 1993, p. 2 - 4).

3.3.4 Zero discount rate

A more radical position is to set the discount rate equal to zero (Pearce, 1993, pp. 57 - 61). A zero discount rate follows the rule that consumption at one point of time does not count more than welfare at another point of time. However, it is feared that a zero discount rate would imply infinite social costs and total current sacrifice (Pearce, 1993, p. 58).

Nevertheless, there is some reason to use zero discount rates for certain natural resources (W_{NR}) whose market value are expected to rise proportionally to the Gross Global Product (GGP). One important example is the demand for safety, expressed in terms of an statistical value of life (VSL). It can be assumed that the growth rate of the WTP for reducing health risks will be at least as high as the growth rate of GGP. All things considered, 0 percent seems to be an appropriate discount rate only if

$$W = 0 \quad (5)$$

or if

$$W > 0, \text{ and } W_{NR} \approx W \quad (6)$$

A prerequisite for (6) is that W_{NR} is not already included in calculations of the underlying cost and benefit streams. Studies expressing the cost of global warming as a percentage of GGP (Mayerhofer, 1994, pp. 2 - 5) already include W_{NR}, whereas WTP for reducing health risks can be assumed to be at least proportional to GGP but is commonly calculated with a constant statistical value of life (Rabl, 1994, pp. 1 - 2).

3.3.5 Discounting, equity and distribution

The main controversial issue among the different discounting concepts is the question of compensation among generations. While the use of market interest rates assumes compensation from one generation to another for losses of natural capital, the use of lower discount rates assumes more or less that environmental protection is the only way to make these transfers (Arrow/Cline/Mäler et al. 1996, p. 133). Following this argument, intergenerational fairness can be characterised as a matter of distribution across generations. It seems to be reasonable to separate these issues of distribution from issues of efficiency. According to Daly, "the policy instrument for bringing about a more just distribution is transfers - taxes and welfare payments" (Daly, 1992, p. 186). Norgaard and Howarth argue in the same direction by pointing out that "if we are concerned about the distribution of welfare across generations, then we should transfer wealth, not engage in inefficient investments. Transfer mechanisms might include setting aside natural resources, and protecting environments, educating the young, and developing technologies for the sustainable management of renewable resources. Some of these might be viewed as worthwhile investments on the part of this generation, but if their intent is to function as transfers, then they should not be evaluated as investments. The benefits from transfers, in short, should not be discounted" (Norgaard/Howarth 1991, p. 98).

From this point of view, the discount rate should only function as a mechanism of efficient allocation of resources. Distributional aspects are separated from allocation, although they are not independent. It is plausible that transfers to future generations change relative prices. As

Norgaard and Howarth remark: "With different distributions and efficient allocations, new prices arise. One can no more speak of 'the' rate of interest when societies are giving major consideration to the sustainability of development than one can speak of 'the' price of timber when deciding whether to conserve forests. Redistributions change equilibrium prices" (Norgaard/Howarth, 1991, p. 97).

3.4 Conclusions

It can be summarised that the approach of deriving weak sustainability indicators of global warming by estimating damage costs requires strong normative choices about inter- and intragenerational fairness and the handling of uncertainty. This normative choices are made in most cases implicitly, i.e. they are hidden under a veil of aggregation and discounting rules. These problems have been especially emphasised by the Second IPCC Assessment Report. However, important responses to the IPCC criticism have now been made. While the long term dynamic effects of global warming and the resulting social and economic impacts are still not well understood, at least some important contributions have been made with regard to an improved handling of intra- and intergenerational equity issues. As far as allocation is concerned, an appropriate range of discount rates should integrate

- 0 percent as a rate for long term effects which are expected to rise with GDP,
- 1 percent as rate for STP ignoring ITP,
- 3 percent as a rate for STP including ITP and
- higher discount rates representing market interest rates (concept of opportunity costs of capital).

The concept of time-variant discount rates seems to be consistent within the principles of welfare theory. While 3 percent can be used as a standard discount rate, lower rates can be applied for the long-term global warming effects.

It is obvious that equity weighting and time-variant discounting will have a substantial influence on the fact which amount of investments for stabilising the global temperature can be justified by mere economic reasons. In the IPCC report with a cited range of 5 - 125 $ marginal per ton of carbon, the lower bound of the range is derived from the Nordhaus study. Using mainly the Nordhaus parameters and a model considering the retention of carbon in the atmosphere, Azar and Sterner (1996, p. 182) introduce time-variant discount rates and equity weighting as described above. Doing this, they calculate marginal damages in the range of 260 - 590 $ per ton of carbon. This is roughly 50 to 100 times higher than the Nordhaus value.

Nevertheless, large uncertainties concerning future climate scenarios and damage paths remain. A reasonable solution may be to link monetary indicators with more ecologically oriented approaches which will be presented in the next chapter.

4. ASSESSMENT OF STRONG SUSTAINABILITY INDICATORS OF CLIMATE CHANGE

4.1 Indicators of environmental space

Important early contributions to the discussion of acceptable levels of greenhouse gas emissions have been made by the Dutch Advisory Council for Research on Nature and Environment (RMNO) (Weterings/Opschoor 1994) and by the German Enquete Commission „Preventive Measures to Protect the Earth's Atmosphere". The Enquete-Commission has derived specific national reduction targets and general targets for developed and developing countries (German Bundestag 1991, Vol. 1; pp. 70-75) from the recommendations of the World Conference on Atmospheric Change in Toronto 1988. The recommendation of the conference had been (German Bundestag, 1991,Vol 2, 796 -840):

- to reduce global emissions of CO2 and other trace gases by over 50 percent by the year 2050 and
- to reduce global CO2 emissions by about 20 percent by the year 2005, relative to 1988 emission levels.

Furthermore, the recommendations of the RMNO and the Enquete Commission are based on a study of Krause, Bach and Koomey (1990) estimating tolerable CO_2-emissions. The authors calculate a tolerable relative deviation of 0,1°C per decade (data on the ability of trees to migrate suggest this as a maximum rate of temperature-rise) and an absolute warming limit of 2,0-2,5°C above pre-industrial level for the next 100 years (which would lead to a maximum acceptable sea level rise of 1 meter in the forthcoming centuries). Within this temperature change the most important ecological functions are supposed to be sustained. These thresholds have been transferred into critical concentrations and critical emission paths.

In a report to the RMNO, Weterings and Opschoor have used the concept of environmental space to share the global budget for CO_2-emissions among nations. They describe the concept of environmental space as follows:
"Environmental utilization space (or: environmental space) is a concept which reflects that at any given point in time, there are limits to the amount of environmental pressures that the earth's ecosystem can handle without irreversible damage to these systems or to the life support processes that they enable. This suggests to search for the threshold levels beyond which actual environmental systems might become damaged in the sense indicated above, and to regard this set of deductively determined critical values as the operational boundaries of the environmental space" (Weterings/Opschoor 1994, p. 3).

Five different criteria have been used for the distribution of the carbon-budget over regions and nations:

- GNP,
- land area,

- current energy consumption (status quo criterion),
- current population (equity current criterion; equal emission per capita),
- current and future population (equity cumulative criterion; equal emission per capita).

Following each of the five criteria, the global carbon-budget was distributed among nations and regions. The different sustainability indicators (according to different distribution criteria) were compared to the actual and forecast performance of the OECD countries (see table 1). The report comes to the conclusion that "the OECD does not meet the various sustainability criteria currently and is not forecast to do so in the forthcoming decades. Nor any of the individual member-states does. Even if we forget about a more equal distribution in respect of the developing countries, the OECD emission exceeds sustainability (status quo) by more than a factor 2. From the equity perspective the OECD performance is unsustainable by a factor of 7 to 10" (van der Loo 1993, p. 65).

Obviously, the definition of strong sustainability standards requires some normative choices. Compared with "weak" optimisation concepts, the advantage is that these choices are made explicitly and are not hidden under a veil of aggregation and discounting rules.

Table 1

Sustainability Criteria for OECD-carbon release

Criterion	OECD Budget 1985- 2100 (% global budget)	(GtC)	OECD Annual average (GtC)	% current emission
GNP	63 %	189	1.64	57 %
Land area	24 %	72	0.63	22 %
Status Quo	47 %	140	1.17	42 %
Equity current	16 %	48	0.42	15 %
Equity cumulative	11 %	33	0.29	10 %

(Assumption: Sustainable world carbon budget 300 GtC as estimated by Krause et al. 1990; OECD current annual release 2.8 GtC)

Source: van der Loo (1993), p. 65.

4.2 The "Inverse Scenario" or "Tolerable Window Approach"

Another example of making such choices explicitly and describe them transparently is the "inverse scenario" of the German Advisory Council on Global Change (WBGU). Based on the scenario assumptions, the WBGU draws the conclusion that the acceptable absolute positive deviation from the present mean temperature on earth is 1.3 °C and a temperature change of 0.2 °C per decade is the tolerable upper limit.

The new "scenario for the derivation of global CO_2-reduction targets and implementation strategies" was published on the occasion of the Climate Conference in Berlin (WBGU, 1995a, pp. 111-128). The scenario specifies firstly tolerable stresses for humans and nature, “and then, by proceeding backwards, the long-term global reduction target is derived which would ensure that these maximum stress levels are complied with” (WBGU, 1995b, pp. 3 - 4). Thus, the “backwards mode” of the scenario follows a strong sustainability approach being based on acceptable impacts or minimum standards of climate stability. Standard scenarios are carried out in a “forwards mode” estimating future, possibly non-sustainable emission and damage paths.[12]

The “backwards scenario“ or “inverse scenario“ contains six steps (see figure 1):

1. In step one, a range of tolerable stresses caused by climate change is defined. Identifying tolerable impacts and damages, the „inverse scenario“ starts explicitly with a *normative judgement*.
2. In step two, temperature changes are derived which assure that the tolerable stresses are not exceeded.
3. In step three and four, admissible concentrations and
4. emissions of greenhouse gases (here: only CO_2) are quantified by using models of climate dynamics and the carbon cycle.
5. In step five, the total emission reduction has to be broken down to individual states or groups of countries.
6. In a final step, a mix of efficient instruments for mitigating climate change has to be derived.

The basic normative principles of the council are the preservation of Creation and the prevention of excessive costs. The principle of preservation of Creation is formalised in the form of a tolerable “temperature window” (WBGU 1995b, p. 7) being derived from the natural temperature fluctuation during the geological period having shaped our present environment (late Quaternary period). The minimum and maximum values of this temperature window are the last ice age (10.4 °C) and the last interglacial period (16.01 °C). With an extension of this temperature range by 0.5 °C at either end, the window extends from 9.9 °C to 16.6 °C. Using these thresholds, the acceptable absolute positive deviation from the present mean temperature on earth (15.3 °C) is only 1.3 °C.

The principle of the prevention of excessive costs is defined very crudely in losses of GGP. On the assumption that a disruption of economic systems will take place if losses of GGP exceed 5 percent, this value is taken as a threshold for economic impacts. The possible unequal spatial distribution of damages across nations (e.g. for island states) and non-monetary burdens are not yet considered in this minimum-standard. Most monetary estimates of doubling CO_2-concentrations until 2100 (mean temperature increase of roughly 0.2 °C per decade) have calculated GGP-losses of around 1-2 percent. Considering that these calculations did not include several damage categories (e.g. extreme events) and may have underestimated the total costs, the WBGU sees “good reason to assume that with a temperature change of 0.2 °C per decade the upper limit for adaptation costs of 5 percent of GGP would be reached” (WBGU 1995b, p. 8).

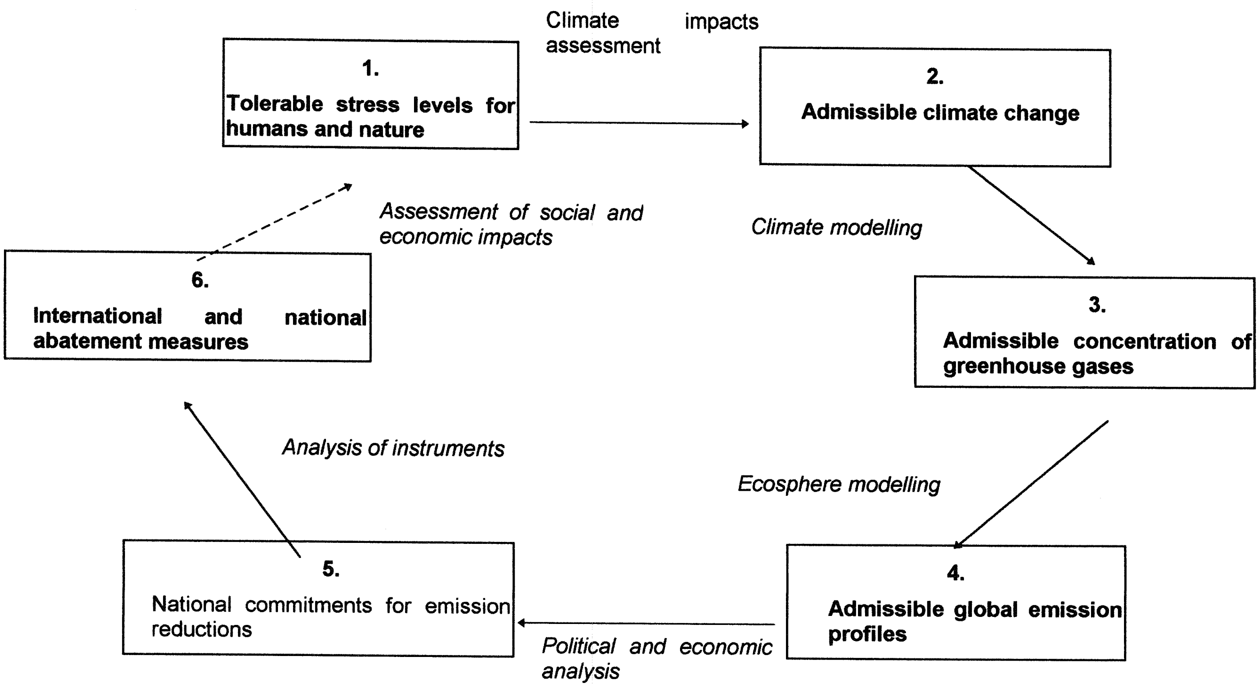
The thresholds of the temperature window have been formulated as minimum standards for political reasons because the results should not be assessed too pessimistically. With the help

[12] For example, the impact pathway methodolody of the ExternE-project belongs obviously to these “forwards mode” scenarios (EC 1995, pp. 7 - 30).

of these operational criteria, a two-dimensional climate window is defined that should not be exceeded.

It is important to mention that the missing link of "backwards" and "forwards" scenarios is the assessment of social and economic impacts. This assessment is located here between step 6 and 1. Pursuing a closed circle of integrated assessment, an economic analysis of different abatement and adaptation strategies would be desirable, including a valuation of remaining damages with monetary or non-monetary values.

The Council's „inverse scenario"



5. DISCUSSION AND CONCLUSIONS

It has been shown that the outcomes of studies estimating economic and social impacts in monetary units are very uncertain. However, as the alternative approaches of strong sustainability have illustrated, uncertainties do not disappear when norms are used instead. Schellnhuber (1995, p. 58), one of the developers of the "inverse scenario", states that norms can only induce maximums or minimums (e.g. a safe minimum standard) and not optimums. If the identification of optimal emission paths among minimum and maximum standards would be pursued, the strong sustainability approach should be supplemented by an economic impact assessment of damages, adaptation and abatement strategies. This would close the circle of integrated assessment of climate change.

Given perfect information about damage paths and present as well as future preferences, impact assessment would be able to replace the normative judgements in step 1 of the „inverse scenario". However, in the light of the discussion about decision-making under uncertainty, it becomes clear that a complete substitution of normative judgement by cost-benefit-analysis or integrated assessment models will hardly be possible. Damage cost valuation techniques themselves contain central normative assumptions.

On the other hand, even normative target approaches often depend on monetary values for defining tolerable stress levels. The "inverse scenario" documents this close link between acceptable emission paths and economic damages. Thus, it becomes evident that further information about the global distribution of costs and benefits of climate change is desirable for the political negotiation process. For example, what is to do when global average damages do not exceed 5 percent of GGP, but reach 100 percent of the national income for certain island states and coastal zones? And how to handle high disparities of damages between economic sectors, social groups or species? Which damages can be compensated, which can not?

Many of these questions can only be answered by following a broader approach of strong sustainability including damage figures as far as valid estimates are available. Within the negotiation process, tolerable stress levels depend on specific burdens and economic costs of world regions and losses of certain economic sectors or societal groups. Thus, the relevance of imperatives like preservation of creation and prevention of excessive costs for political negotiations can be improved by more disaggregated sectoral and regional information about climate change impacts.

So, it seems reasonable to improve economic impact assessment and to include it into integrated models for assessing climate change policy (WBGU1995b, p. 7). Weak and strong sustainability indicators can be used complementarily in the assessment of climate change. Both can be understood as parts of broader approaches of integrated assessment models.

The critical IPCC review of social cost studies seems to have influence on research and has enhanced methodological progress, especially the handling of intra- and intergenerational equity issues. Further progress may lead towards more dynamic models and a multidimensional valuation of impacts. It should be noted that damage cost valuation is only one aspect in a modern interpretation of cost benefit analysis as it has been described in the

IPCC report (Munasinghe et al., 1996, p. 170). According to the IPCC report, cost benefit analysis encompasses a family of decision-analysis techniques like multicriteria analysis or decision analysis. Using such a broad interpretation, social and economic impacts do not necessarily have to be described in monetary units. A main disadvantage of cost benefit analysis is that in complex decision situations relevant multiple criteria (e.g. efficiency, equity, uniqueness of resources or health and safety) are mixed and reduced to one single criterion. Multicriteria analysis may be a better way to show trade-offs between these different policy goals (Munasinghe et al., 1996, p. 168).

It can be summarized that monetary indicators within a weak sustainability approach dominate the economic literature because cost benefit analysis has commonly been interpreted in a narrow sense. Broadly speaking, the narrow approach can be charaterized by assuming perfect markets (e.g. rationality and flexibility) with the exception that the existence of external costs is admitted. Global environmental problems and especially global warming require a broader approach considering inter alia uncertainty, bounded rationality, equity and scale effects. Obvious deficits of economic approaches with regard to these issues have promoted the search of more adequate alternatives. Ecological economics, one of the relevant scientific streams for searching new ideas, is driven by the underlying paradigm of strong sustainability. It is concluded here that, even within a strong sustainability paradigm, estimates of costs and benefits of climate protection remain to be a valuable and important tool for decision making. The prerequesite for an appropriate use of cost benefit analysis is a move towards a more frequent use of multiple, monetary and non-monetary valuation schemes.

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Appendix 4

Climate Change and Disasters: Economic Valuation of Altered Risk

Thomas E. Downing
Richard Tol

1. Introduction

A major source of climate change impacts is the potential toll of weather-related disasters[1]. However, scientific estimates of the impact of climate change on natural hazards is fraught with difficulty. This appendix draws upon a recent European Union research project, *Climate change and extreme events, altered risk and socio-economic consequences* and economic assessments of climate change to review the prospects for climatic hazards (see Downing, and Olsthoorn, and Tol 1996, 1998).

2. Climate Change and Climatic Hazards

The usual climate change impact assessment approach is to link scenarios of climate change with impact models and then to evaluate the potential costs. However, this is not readily accomplished for climatic disasters. Calculating the future costs of climatic hazards is constrained by the lack of knowledge in three essential spheres:

1. Scenarios of climate change do not yet present a consensus of the likely effects on many climatic hazards.
2. The present distribution of extreme events in uncertain, and may not be stationary on the time scale of decades to centuries.
3. Exposure and vulnerability to climatic hazards are changing, rapidly in many parts of the world. The maximum potential loss is unknown except for a few developed regions.

In addition, the imposition of incremental trends in climate (e.g., global warming and sea level rise) upon distributions of extreme events requires downscaling from the global to the local and from long-term trends to specific events. This problem may be best illustrated by an example. The impact of a major flood depends on the confluence of when the flood occurs (day or night, holiday season or winter, etc.) and where it occurs (e.g., major metropolitan or rural area), in addition to discharge stage, velocity and duration. The impacts will be largely influenced by the state of preparedness (including warning), exposure to losses (e.g., insurance cover, private and public assistance), and recovery (e.g., replacement of infrastructure). All of these factors vary over time and space. Local government may be unable to respond to emerging threats just as a failure of land use controls to protect vulnerable areas increases the

[1] A sense of some definitions may be helpful. A disaster is the realisation of a hazard (geophysical event) and societal vulnerability. The risk of a disaster is usually taken as product of hazardness and vulnerability. Disaster events related to atmospheric anomalies can be termed weather-related disasters, that is they stem from actual weather systems and episodes. More generally, the range of potential disasters related to the atmosphere can be called climatic hazards, that is they are inherent in the climate system and its exploitation by societies.

hazard. A shift in location and a change in land use policy could affect flood damages to a greater degree than climate change *per se*.

The differences between countries and regions and over time are remarkable. Cyclones and storm surges in Bangladesh in the 1970s killed hundreds of thousands. A recent storm killed thousands, following improvements in early warning and cyclone-proof shelters. Hurricanes in North America rarely kill more than a hundred.

Table 1. Changes in climatic hazards and impacts

	Climate change			**Direct impacts**			**Contingent effects**
Hazard	↑Temp.	↑Precip	↑Wind	Lives lost	Insured property	Economic losses	
Frost	- -		-	-	-	-	
Heat waves	++	-	-	+		+	?
Drought	+	- - -	+			+++	++
Flood		+++		+		++	+
Mid-latitude windstorms		+	+++		++	+	+
Severe weather		+++	+	++	+	+	
Tropical cyclones	+	++	++	+++	+++	+++	++

Notes: - and + indicate a decrease or increase in impacts. The sign of the impact is relative to the direction of climatic changes. The strength of the increase in hazard is indicated by ++ or +++. A ? indicates an uncertain relationship. Severe weather includes lightning, hail and tornadoes. Tropical cyclones includes storm surge related to sea level rise.

Where mortality varies significantly by region and is related to economic development, economic valuation of disaster effects is sensitive to the baseline scenario of economic development, assumptions about valuations methods, and choice of discount rate.

In contrast to mortality rates, however, property losses due to natural hazards are increasing. As per capita income increases, the value of possessions exposed to losses increases. Development in hazardous locations has been common in many areas, for example, the south-east coast of the US.

To forecast local damages from future disasters would require solving the time-place-risk conundrum. To what extent would intensity and duration be altered? When would events occur, compared to changes in vulnerability? What areas would be affected (either more or less than at present)?

The objective of most economic assessments of climate change is to derive an annual average cost. The above methodological problems make this problematic for many climatic hazards. Nevertheless, some insight into the range of potential impacts and their determinants can be gained through an examination of potential changes in climatic hazards.

Table 1 evaluates seven natural hazards that are likely to be affected by climate change (increased temperature, precipitation or wind). Direct impacts are commonly grouped as lives lost, insured property losses and economic losses (including uninsured losses, damage to infrastructure, and disruption of economic activity). Socially contingent effects could include changes in investment, retreat from hazardous zones, and social and psychological effects.

Frost and cold spells are likely to decrease throughout the world. Even a small increase in temperature can dramatically reduce frost risk. Winter cold stress is linked to increased mortality in many temperate countries. Reduced cold stress would have a measurable benefit on lives lost, and some economic benefit through, for example, reductions in frozen pipes (generally insured), reduced need for road de-icing agents, reduced frost damage to roads and infrastructure, and fewer agricultural losses (not insured).

The converse is true for heat stress, strongly related to temperature in addition to precipitation, wind and humidity. The acute mortality effects of heat stress may compensate for the benefits from reduced cold stress – with distinct regional differences. However, the economic losses of heat stress (on its own) are relatively small. There may be some loss of quality in agriculture, damage to road surfaces and disruption of economic activity (such as sporting events). Most of the serious economic losses during heat waves are due to drought in addition to higher temperatures (discussed below). Few of the effects of heat waves are insured, other than through routine health services. Appendix 7 reports in more detail on health impacts.

Drought is essentially a prolonged lack of rainfall, although higher temperatures and wind can be major factors. For instance, the 1995 hot summer and drought in the UK was driven to a significant extent by increased demand for garden watering. Similarly dry, but cooler weather in 1997 did not result in as much pressure on water delivery systems. Very few people die of dehydration. However, a large number of people are affected by drought and can be threatened with famine if the higher order impacts are not mitigated through appropriate disaster planning, mitigation and emergency responses. Although some agricultural produce is insured against drought (or income is maintained through subsidies), little direct insurance is available to mitigate drought impacts. The impacts, however, can be enormous – up to 10% of GDP for prolonged episodes in especially vulnerable countries, as in the 1991/92 drought in Zimbabwe (Benson and Clay 1994).

Riverine floods are related to precipitation – both prolonged abundance and increases in intensity in smaller catchments. It may be possible to have both increased drought and increased flood in future climates. Seasonal differences may be accentuated by climate change, resulting in wetter winters and drier summers. Less rainfall and prolonged dry spells could be punctuated by more intense showers and higher runoff. However, regional projections have not been widely available. The loss of life due to floods is significant, but not very large except for coastal storm surges in developing countries (discussed below). Economic losses can be large, and insurance is variable. Many European and North American countries offer government-supported insurance. The UK is unique in having private flood insurance on a commercial basis. The socially-contingent effects can be significant — disruption to infrastructure (e.g., bridges) and changes in land use.

Mid-latitude windstorms can be exacerbated by driving rain. Insured and economic damages can be huge, over US$1 billion per storm in developed economies, but few lives are lost. The socially contingent effects are likely to be small, although loss of mature vegetation is a major concern. If windstorms became sufficiently frequent, building standards and insurance coverage would be altered to reduce exposure.

The most contentious estimates of the damages of climatic hazards concerns tropical cyclones and related storm surges. The synoptic causes of tropical storms are complex, not readily related to changes in single climatic elements such as sea surface temperatures. The present and potential consequences of cyclones are larger than all of the other climatic hazards – thousands of lives lost in developing countries, billions of dollars of insured and economic losses in developed countries. The higher order effects on GDP, investment, and even human habitability are significant. For example, the 1995 storms in the Caribbean led to a significant reduction in tourism and GDP (estimated at 18% in Antigua and Barbuda).

Severe weather – lightning, hail, and tornadoes – receive less attention. A shift from cyclonic to convective precipitation could result in these hazards becoming common in areas that rarely experience them at present. If so, the number of lives lost and insured property losses could be significant. For example, lighting probably causes the most deaths in the US among natural hazards (twice the mortality rate of hurricanes) and accounts more than $40million in insured losses due to fires (Alexander 1993). Yet, lightning deaths receive little media or public attention.

The likelihood of regional changes in each climatic hazard is difficult to judge. Increased temperatures are most likely, leading to reduced hazards associated with cold spells and increased heat-related hazards. Hazards related to precipitation – drought and floods – are likely to increase in some regions and decrease in others. Some estimates suggest that summer droughts could increase dramatically, but much depends on precipitation and the effect of carbon dioxide enrichment on evapotranspiration. There is little consensus at present on future distributions of windstorms and tropical cyclones. Some studies have used increases in mean wind speed as a surrogate for indices of storminess, which are less readily available from climate change models. The incidence of severe weather may increase in temperate regions where cyclonic storms are replaced by convective summer rainfall. However, the future global incidence of severe weather remains uncertain.

The impacts of climate change must be related to projections of exposure and vulnerability. Some aspects of exposure are readily projected at a macro scale, for instance population growth and per capita GDP. However, the critical determinants are more difficult: the population-at-risk is related to locale (occupancy of flood plains), while building construction and design (vulnerability to wind vortices, elevation above the flood height) determine much of the economic losses. The interactions between vulnerability and hazard are even more difficult: state of preparedness that saves lives, early warning and preparedness that reduce event damages, adoption of insurance to spread losses, state policies and enforcement of building standards and land use. Or more speculatively, modification of weather to reduce the hazard itself.

3. Global Damage Estimates

The Open Framework (OF) includes a global assessment of the impacts of natural disasters. This is a singular attempt to capture the range of potential changes due to climate change. The steps are:

1. Global data on the incidence and number of people affected by disasters.
2. Estimation of the present economic impacts of disasters and the statistical value of life.
3. Reference scenarios of the incidence and impacts of disasters in 2100, based on trends and assumptions regarding exposure and sensitivity.
4. Scenarios of the global-average effect of climate change (in 2100) on the incidence (frequency) and impact (intensity) of natural disasters.
5. Comparison of the reference and climate change scenarios.
6. Interpolation of the impacts from 1990 to 2100 and calculation of net present values of the impacts.

Each of these steps is subject to considerable uncertainty. To capture some of this uncertainty, the OF convention of maintaining a low, medium and high estimate of each variable is followed. This results in a wide spread of potential impacts. Perhaps the best interpretation of the assessment in the OF is as a sensitivity test of the range and characteristics of disaster impacts in the context of climate change.

Details of the sequence of steps and assumptions follow.

3.1 Present distribution of disasters

Data from the Red Cross (IFRCRCS, 1993) provides the baseline for the present distribution of natural disasters. Table 2 shows data for 1967-1992. The definition of disaster is somewhat variable, but generally includes significant mortality or a large population affected. Thus, the global assessment only captures "disasters" in the conventional sense of large-scale events that require external resources. Many more small disasters, causing loss of life, injury and economic impacts at the individual scale, are not included. This is particularly notable for severe storms such as lightning.

The most deadly hazards are related to food crises (drought, famine, food shortage) and complex emergencies (civil strife, displaced), with an annual average mortality of somewhat less than half a million people. Cold related (avalanche, cold wave) and heat related (fire, heat wave) disasters are less common with relatively minor impacts, but note that the definition of disasters excludes many local events of this nature. Storms (cyclone, hurricane, mid-latitude storm, typhoon) and floods are the most common disasters, with significant impacts. Epidemics (including insect infestations) have a high rate of mortality. Landslides are less frequent, but also have a high mortality rate.

Table 2. Global incidence and impacts of natural disasters, 1967-1992

	Number	Killed	Injured	Affected
Avalanche	29	1,237	146	500,000
Civil strife	207	3,007,154	92,481	135,653,524
Cold wave	92	4,926	10	71,000
Cyclone	394	846,240	181,171	80,485,116
Displaced persons	97	68,741	6,979	25,611,475
Drought	430	1,333,728	18	1,426,239,250
Epidemic	291	124,338	267	5,791,234
Famine	15	605,832	0	12,950,000
Fire	729	81,970	16,626	814,341
Flood	1,358	304,870	266,336	1,057,193,110
Food shortage	22	252	0	28,320,267
Hurricane	120	15,139	15,798	6,028,833
Heat wave	25	7,470		
Insect	66	0	0	446,000
Landslide	236	41,992	3,435	3,603,580
Storm	819	54,500	96,031	68,122,580
Typhoon	380	34,684	45,134	63,321,930

3.2 Present economic impacts

The economic cost per event is based on generalised values, largely from Munich Re (1993) for windstorm, flood, drought, fire and hail. Costs of other hazards are estimated, with very little data, in an attempt to be comparable across hazard types. The low and high estimates are subjective, comprised of ratios of the medium estimate. Figure 1 shows the relative spread of costs for each hazard type, in terms of lives lost and economic damages (not just the insured losses).

The statistical values of life used in the assessment are ($M):

- Low: $0.50M, somewhat higher than Fankhauser's (1995) estimate for developing countries
- Medium: $1.50M, equivalent to Fankhauser's average for developed countries
- High: $7.50M, somewhat higher than values used by previous ExternE projects

The medium estimate, as a global average, is comparable to the ExternE project's assumption of 3.1 MECU (1995) in Europe and weighted according to average per capita income in other regions (see Appendix 5). The assessment does not value the effects of disasters on morbidity (the population affected) or indirect losses. The global impacts presented here are not subject to equity weighting. And, the assessment does not include any positive impacts of disasters.

The cost for the medium estimate for each type ranges from $3 to 500 billion (Table 3). The total cost is $775 billion, but with a range from a third less to five times greater.

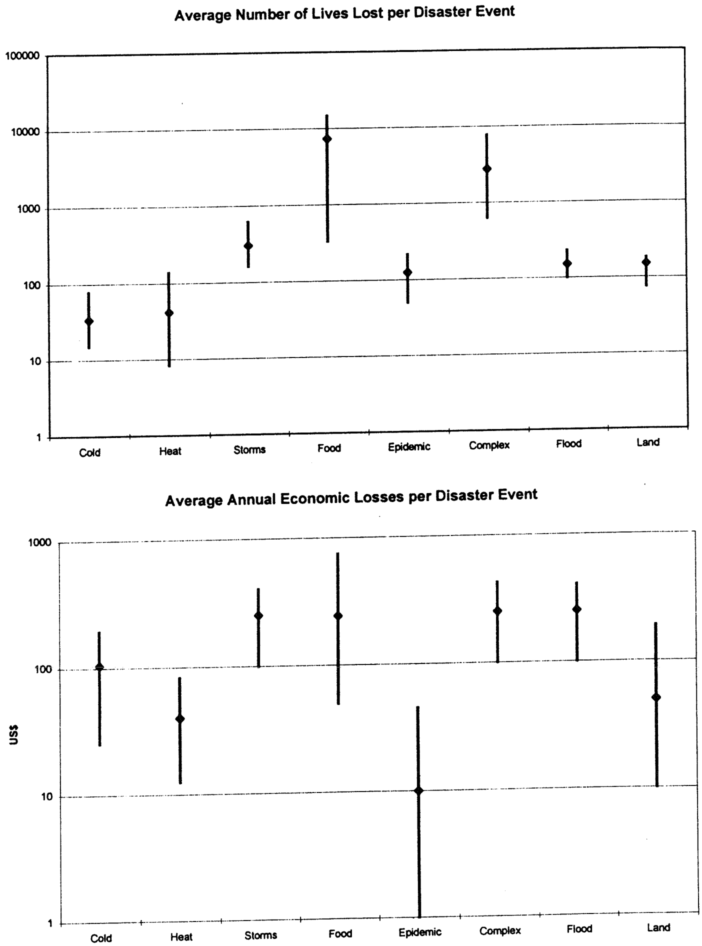

Figure 1. Annual average impacts of disasters: lives lost (top) and economic losses (bottom).

Table 3. Baseline (1990) estimates of impacts of natural disasters, US$M

	Value of lives lost			Total cost of disasters		
	Low	Medium	High	Low	Medium	High
Cold	573	2,292	14,325	815	2,695	15,051
Heat	1,334	5,338	33,362	2,842	7,851	37,886
Storms	6,243	24,971	156,069	19,947	47,811	197,181
Food	46,730	186,920	1,168,249	53,735	198,595	1,189,264
Epidemic	3,918	15,673	97,955	4,632	16,863	100,097
Complex	113,828	455,313	2,845,709	119,908	465,447	2,863,949
Flood	2,526	10,102	63,140	13,390	28,209	95,732
Land	2,002	8,007	50,043	2,238	8,400	50,751
Total	177,154	708,616	4,428,853	217,507	775,871	4,549,912

Note: Hazards are grouped, see Table 4.

3.3 Reference scenarios for 2100

The baseline (1990) estimates are projected to 2100, without the influence of climate change. The basis for the projections is a set of multipliers that represent the range of likely trends in disasters. The trends are subjective evaluations of a reference world-view consistent with the IS92a scenario. This includes increasing per capita income, relatively high population growth, and little concern for environment.

The projected trends are related to:

- Incidence: In most cases, the central estimate of the number of events does not change much. The exception is where there is a strong dependence on income. For example, the incidence of food shortage is likely to decrease as per capita incomes increase. Conversely, some increase in the incidence of other hazards is projected as people occupy more hazardous areas, consistent with the assumption of higher populations and little land use regulation.
- Exposure of lives: The historical trend of decreasing mortality due to hazards is continued, even though populations continue to grow. The statistical value of life increases over time, in line with global-average increase in per capita GDP.
- Exposure of property: Again, the historical trend of increasing property losses, partly related to higher incomes, is continued.

In each case, the low and high estimates are more extreme views: either pessimistic or optimistic. Table 4 shows the assumptions for each hazard.

Table 4. Factors applied to estimate the reference number and impact of disasters in 2100

	Number of Events			Lives Lost			Economic Losses		
	Low	Med	High	Low	Med	High	Low	Med	High
Avalanche	1.00	1.10	1.20	0.90	1.10	1.45	2.25	5.00	10.00
Civil strife	0.90	1.25	1.50	0.90	1.25	1.50	2.25	5.00	10.00
Cold wave	0.90	1.00	1.10	0.50	0.75	1.10	2.25	5.00	10.00
Cyclone	0.75	1.00	1.00	0.75	1.00	1.50	2.25	5.00	10.00
Displaced persons	0.90	1.25	1.50	0.90	1.25	1.50	2.25	5.00	10.00
Drought	0.90	1.10	1.20	0.10	0.25	0.50	2.25	5.00	12.00
Epidemic	0.90	1.10	1.20	0.50	0.75	1.25	2.25	5.00	10.00
Famine	0.25	0.50	0.75	0.10	0.25	0.50	2.25	5.00	10.00
Fire	1.00	1.10	1.20	0.90	1.25	1.50	2.25	5.00	10.00
Flood	0.90	1.10	1.20	0.50	0.75	1.10	2.25	5.00	12.00
Food shortage	0.25	0.50	0.75	0.10	0.25	0.50	2.25	5.00	10.00
Hurricane	0.75	1.00	1.00	0.75	1.00	1.50	2.25	5.00	10.00
Heat wave	0.90	1.00	1.10	0.50	0.75	1.10	2.25	5.00	10.00
Insect	0.90	1.10	1.20	0.50	0.75	1.10	2.25	5.00	10.00
Landslide	1.00	1.10	1.20	0.90	1.10	1.45	2.25	5.00	10.00
Storm	0.75	1.00	1.00	0.75	1.00	1.50	2.25	5.00	10.00
Typhoon	0.75	1.00	1.00	0.75	1.00	1.50	2.25	5.00	10.00

Note: For IS92a reference scenario

3.4 Scenarios of climate change impacts

The same process as above is used to project the incidence and impacts of disasters in 2100, this time including a set of factors that reflect the changing risk due to climate change (Table 4). IN the absence of robust scenarios from global climate models, this approach provides a realistic sensitivity test. The argument follows:

- Incidence: Cold-related events decrease, while heat related events increase sharply. The central estimate for wind-related disasters is a modest increase (10%). Water-related hazards, such as drought, increase (30%) due to the increases in potential evapotranspiration.
- Lives lost: In most cases only modest changes in intensity are anticipated, leading to relatively modest increases in lives lost. The exceptions are drought, fire, heat waves and insect infestations, where climate change could lead to large changes in intensity.
- Economic damages: As above, the changes in intensity do not lead to large increases in economic losses. The exceptions are the same as for lives lost.

Table 5 shows the factors that are used to alter the reference projection of annual average disaster costs in 2100.

Table 5. Factors applied to estimate the number and impact of disasters in 2100 due to climate change

	Number of Events			Lives Lost			Economic Losses		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Avalanche	0.75	0.90	1.00	0.80	0.90	1.00	0.80	0.90	1.00
Civil strife	1.10	1.25	1.50	1.00	1.10	1.25	1.00	1.10	1.25
Cold wave	0.75	0.90	1.00	0.80	0.90	1.00	0.80	0.90	1.00
Cyclone	1.00	1.10	1.50	1.00	1.10	1.50	1.00	1.10	1.50
Displaced	1.10	1.25	1.50	1.00	1.10	1.25	1.00	1.10	1.25
Drought	1.10	1.30	1.50	1.10	1.50	1.75	1.10	1.50	1.75
Epidemic	1.10	1.30	1.50	1.00	1.10	1.25	1.00	1.10	1.25
Famine	1.10	1.30	1.50	1.00	1.10	1.25	1.00	1.10	1.25
Fire	1.25	1.50	2.00	1.10	1.50	1.75	1.10	1.50	1.75
Flood	1.00	1.10	1.25	1.00	1.10	1.50	1.00	1.10	1.50
Food shortage	1.10	1.30	1.50	1.00	1.10	1.25	1.00	1.10	1.25
Hurricane	1.00	1.10	1.50	1.00	1.10	1.50	1.00	1.10	1.50
Heat wave	1.25	1.50	2.00	1.10	1.50	1.75	1.10	1.50	1.75
Insect	1.10	1.30	1.50	1.10	1.50	1.75	1.10	1.50	1.75
Landslide	1.00	1.10	1.25	1.00	1.10	1.50	1.00	1.10	1.50
Storm	1.00	1.10	1.50	1.00	1.10	1.50	1.00	1.10	1.50
Typhoon	1.00	1.10	1.50	1.00	1.10	1.50	1.00	1.10	1.50

Note: IS92a climate change scenario

3.5 Comparison of reference and climate change scenarios

The difference between the reference projection of disaster impacts in 2100 and the climate change scenarios is shown in Table 6. The medium estimate is over $250 billion, with a range of almost four orders of magnitude (from near zero to almost $20,000 billion). For comparison, these impacts range from 0 to over 10% of world GDP. This is an enormous range, reflecting the large uncertainties in projecting the change in disasters and their valuation. The majority of the impacts (4/5ths in the medium estimate) are due to the valuation of lives lost. The value of life is not reflected in GDP estimates, so the comparison with world GDP as a benchmark is not a true measure of the impacts.

Table 6. Marginal economic impacts of disasters due to climate change, 2100

	Economic Losses, $m			Impacts, $m		
Disaster	Low	Medium	High	Low	Medium	High
Avalanche	-1	-10	0	-24	-91	0
Civil strife	20	2,930	45,752	242	123,145	9,763,031
Cold wave	-41	-380	0	-45	-438	0
Cyclone	0	2,625	78,800	0	19,859	2,683,113
Displaced	20	1,172	21,439	76	5,980	243,568
Drought	106	12,697	297,835	365	55,577	2,432,208
Epidemic	1	237	4,889	63	7,515	272,745
Famine	0	157	9,713	0	5,450	1,097,311
Fire	105	5,156	122,472	221	15,735	727,905
Flood	0	11,550	273,773	0	20,081	851,729
Food shortage	0	230	4,274	0	232	4,409
Hurricane	0	788	24,000	0	1,175	70,590
Heat wave	0	31	688	0	416	37,776
Insect	0	52	2,574	0	52	2,574
Landslide	0	404	18,635	0	2,594	123,570
Storm	0	5,250	163,800	0	6,973	331,524
Typhoon	0	2,625	76,000	0	4,198	216,335
TOTAL	212	45,512	1,144,642	896	268,453	18,858,390
% of World GDP				0.00%	0.15%	10.76%

Notes: IS92a scenario, not discounted.

3.6 Net present value

The final step relates the impacts in 2100 to a net present value (Table 7). The central estimate used in the ExternE project, with a 3% discount rate, results in a net present value of the incremental impact of disasters due to climate change of over $2,000 billion.

Table 7. Net present value of cost of climate change, 1990-2100, US$M

Discount rate	Low	Medium	High
0%	49,751	14,899,160	1,046,640,630
1%	24,593	7,364,949	517,375,138
3%	7,459	2,233,690	156,912,886
5%	3,025	906,016	63,646,079
10%	733	219,619	15,427,877

Notes: IS92a scenario, linear interpolation between 1990 and 2100.

The OF compares two scenarios, the IS92a and the IS92d. The IS92a reference scenario assumes higher population growth and higher greenhouse gas emissions and greater climate change. Both have significant economic growth – developing countries in 2100 are as rich as OECD countries are in 1990. The OF differentiates between the two scenarios in qualitative sensitivity to climate change. The IS92a is taken to be more of a "business as usual" world whereas the IS92d reflects greater concern for resilient development.

In the case of estimating the impacts of disasters, the difference between the two scenarios is not great. Assumptions of greater resilience, less exposure and less climate change give lower estimates for the IS92d world (Table 7). However, the difference between the two world views is much less than the difference between the high and low estimates (Figure 2). Within either world view, the toll of disasters will be shaped by mitigation policy rather than solely the driving forces of economic growth and population change.

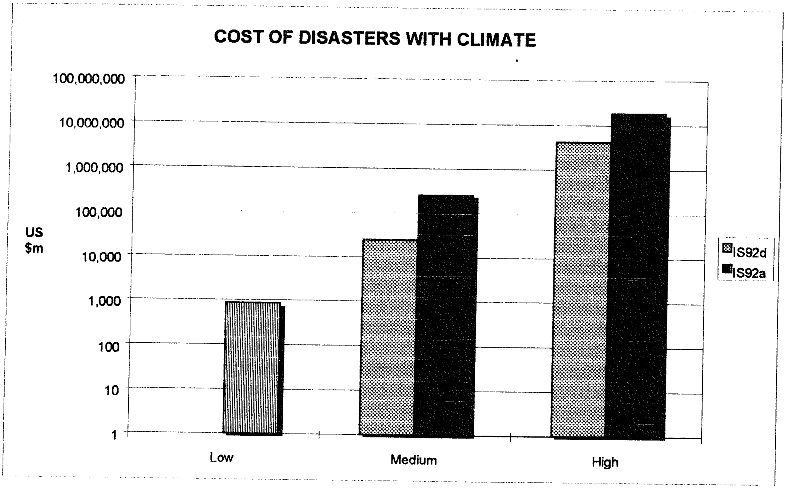

Figure 2. Prospective cost of disasters in 2100 with two scenarios of climate change. Note that the IS92d Low estimate is a slight decrease in disaster costs, which is not shown on the log scale. Values are annual costs in 2100, not discounted.

Table 8. Difference between the cost of disasters in 2100 with and without climate change, US$M

	Low	Medium	High
IS92a	896	268,453	18,858,390
IS92d	-2,029	24,658	4,206,588

Note: Values are annual values (Climate scenario – Reference scenario) in 2100, not discounted.

4. Conclusions

The threat of increased disaster losses is an important aspect of climate change impact assessment. In many sectors, awareness of climate change issues and adaptation strategies are likely to be motivated by shifts in extreme events. For example, a series of anomalous dry summers in the UK preceded requirements that the water utilities include climate change in drawing up their next five-year plans for resource development, leakage control, demand management and pricing. Equally, climate policy and greenhouse gas abatement may be motivated by prospects of severe impacts, the precautionary principle, rather than average damages.

However, the prospects for improving estimates of the costs of future disasters are not promising. Robust scenarios of extreme climatic events at the global or broad regional scale may be forthcoming in the next five to ten years. Local projections are not likely to be available in the near future. Similarly, improved global data bases on vulnerability are possible, but not at the scale of individual and community exposure.

More in-depth local and regional studies could provide the foundation for extrapolating to a global assessment. For example, studies of flood hazard in Europe could be extended to include economic valuation of impacts. Comparison with, for example, the US, China and Mexico would provide insight into the geographical and economic determinants of future damages.

Simulation studies could begin to define the parameters that drive damage estimates. Such exercises would focus on the assumptions that lead to small (or large) damages, rather than attempting to provide a consensus estimate. For example, the regional studies could include a simulation model of the relevant causes of disasters (at different time scales, spanning geophysical, social and economic dimensions). The model could then be tested, and evaluated by key stakeholders, to illustrate potential future costs of climate change.

Perhaps the more pressing policy questions concern adaptation to present hazards, rather than abstract projections of future impacts. The above scenario for the IS92d, one of resilient development, suggests that the difference between high and low vulnerability is more important than the impact of climate change itself. Promising technology in early warning and monitoring, including seasonal climate prediction, should continue to reduce the number of lives lost. Less certain are whether community efforts to reduce vulnerability, particularly in developing countries, will be successful.

5. Acknowledgements

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Appendix 5

Issues of Intragenerational Equity and Income Adjustment

Nick Eyre
Eyre Energy Environment

1. Introduction

The extension of ExternE analysis to climate change makes it impossible to avoid tackling equity issues. Climate change impacts result mainly from emissions of greenhouse gases in developed countries like the EU, but the effects are expected to be felt primarily in developing countries with a lower capacity to mitigate the impacts. Global per capita incomes show a wide disparity, and therefore aggregate willingness to pay (WTP) - for reducing the risk of death, for good health and for environmental protection - is a controversial measure of damage.

The difficulties of including equity considerations are of more than just academic interest. The chapter on damage assessment (Pearce et al, 1996) in the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) presented aggregate damage calculations based on WTP without equity weighting. This proved highly contentious, despite the chapter's discussion of the methods for "equity correction" and a full chapter on equity issues in the same report (Banuri et al, 1996). Underlying the discord is a fear amongst developing countries that their interests will be under-emphasised in international negotiations. Clearly, the use of unweighted WTP-based damage estimates risks doing this, for, as the IPCC chapter on equity issues notes "Any aggregation that evaluates and aggregates impacts in relation to national wealth...yields the result that the impact is less significant if it is poor people, or people in poorer countries, who suffer." (Banuri et al, p.98)

This paper defines a way forward for ExternE on this thorny problem. It seeks an approach which:

- does not offend reasonable interpretations of EU policy and commitments,
- as far as possible uses and develops existing ExternE practice, and
- is consistent with the principles of welfare economics.

2. EU Policy and Commitments

The EU and all its member states are signatories of the Framework Convention on Climate Change (FCCC). This has relevance to the issue of equity because the FCCC explicitly mentions equity three times (Banuri et al, 1996). Two of these concern the scale and financing of programmes to address climate change abatement and mitigation and may broadly be interpreted to mean that the developed world should take the lead in these areas. The third reference has more relevance for damage assessment. It states that "Parties shall be guided, *inter alia*, by ...the need to protect the climate system on the basis of equity and in accordance with common but differentiated responsibilities and respective capabilities..." (Grubb et al, 1993). Whilst this fails to provide a basis for interpreting how equity considerations should be applied, it does establish equity as a principle of the Convention.

The Ministerial Declaration supported by the EU at the second Conference of Parties to the FCCC endorsed the IPCC report as "the most comprehensive and authoritative assessment of the science of climate change, its impacts and response options now available". Thus, although the conclusions of the IPCC report are not binding, they carry considerable weight for EU policy. It is important therefore to note that the IPCC considers developing countries are likely to face the most severe impacts of climate changes for the following reasons:

- they are disproportionately in the tropics where expected impacts are larger,
- they have fewer institutional resources to apply to effective mitigation,
- they are generally more dependent economically on natural resources, and
- more are prone to "extreme vulnerability", that is inundation and desertification.

Any damage analysis has to ensure that these greater impacts in developing countries are not systematically under-valued solely for methodological reasons.

3. Building on the ExternE Methodology

In the ExternE Project, monetary valuation has generally been based on the willingness to pay (WTP) principle. Unless there is an overwhelming case for change, consistency implies that this should be retained for climate change damages. The basis of the monetary valuation is welfare economics and the application of its principles to climate change damages are discussed in the next section.

However, ExternE is not purely a monetary valuation project, it also documents the physical impacts of environmental change. These are useful research results themselves and can potentially serve as substitute indicators where no credible monetary valuation is possible, e.g. for impacts on ecosystems. In general, these physical indicators do not raise the same equity problems, as alternative decision making procedures can include equity criteria explicitly. Documentation of results as physical indicators is therefore a feature of ExternE to be preserved where equity concerns are at issue.

Intragenerational equity concerns have not featured explicitly in ExternE to date. In all cases, the values used, irrespective of income, social class, age, gender, nationality and other factors. To some extent this decision has resulted from the shortage of data on values, which makes any differentiation unreliable. What evidence there is indicates that differences in average values between EU member states may be small. ExternE has therefore used "common unit damages" like the value of statistical life (VOSL) and the value of noise across entire populations.

Whilst the use of "common units damages" is not inconsistent with the principles of welfare economics, it implicitly makes some additional assumptions about the validity of averaging across communities in undertaking social cost benefit analysis. In particular, it implies that society values the life, health, environment and aesthetic values of its citizens equally, even though their preferences (revealed or expressed) in markets may be different. It is important to recognise that this is implicitly a choice about how to address equity.

The extension of ExternE to global scale damages raises the question of whether this "common unit damages" approach can be extended outside the EU. The next section considers the theoretical economic concerns. However, it is clear that the "common unit damages" approach has attractions in terms of simplicity, transparency and equity. A methodology which retains these - or at least produces a numerical output which is consistent with them - would be advantageous in avoiding any major changes to the established methodology for other impacts.

4. Consistency with Welfare Economics

The normal practice in the monetary valuation literature is to use WTP as a proxy for welfare. At the individual level the acceptability of this approach follows directly from the postulates of neo-classical economic theory, as each individual is assumed to maximise his or her own utility. There are criticisms of the theory, concerning its adequacy as a model of human behaviour, but there is no reason to believe these have any greater force for climate change damages than other values. There is therefore no theoretical reason, in analyses based on welfare economics, to deviate from a WTP approach simply because global scale impacts are included.

However, global scale damages do raise difficult issues at the level of aggregation of individual WTP. There is no objective analytic approach to this aggregation. Indeed, it has be known for many years that no aggregation to a social welfare function can satisfy all of the properties which are commonly required of individual choice (Arrow, 1963). Aggregation therefore requires some additional assumptions, which are necessarily subjective. This conclusion is widely accepted. Indeed, some of the authors of IPCC chapter on damage assessment, in response to criticism of their work, have commented that: "Much of the controversy seems to have arisen from the fusion of two separate issues: the valuation of environmental damages at an individual level, which is a matter of empirical analysis, and the comparison and aggregation of these effects, which is a political process involving ethical judgements on, amongst other things, the socially desirable distribution of income." (Fankhauser et al, 1997).

Income is expected to be an important component of any differences in WTP - willingness being constrained by ability to pay. (Other cultural factors may play a role in affecting WTP, but these have not been systematically studied and will be neglected here.) Income disparity raises the questions of whether, and if so how, the aggregate values should reflect inequalities. The issue is not new to environmental economics or, more generally, to cost benefit analysis. Adjustments to WTP values to account for income have been used for many years (e.g. Pearce, 1971).

The treatment of the huge disparity in global incomes is critical to the aggregation process for climate change damages. Even within countries there are large income differences, which ExternE (and most similar studies) has to date largely neglected. This has been justified on the grounds that:

- individual societies at the nation state level have arrived at the existing income distribution via the democratic process, and
- that environmental damages do not strongly affect total income distribution.

Whatever the validity of these arguments for general environmental problems, they are clearly inapplicable to global climate change, where:

- international decision making bodies and the institutions for wealth transfers are poorly developed, and
- the potential scale of damages is, at least in some countries, very large.

There is therefore no strong case for assuming that the existing income distribution is just, that it optimises welfare, or that it will be unaffected by climate change. It is therefore important, and quite compatible with the framework of welfare economics, that equity issues are considered explicitly.

5. Proposed Approach

The approach proposed here draws heavily on the equity adjusted approach to constructing a social welfare function which has been developed (Fankhauser et al, 1997) in response to debates about the IPCC report. This paper looks at equity adjustments within the framework of welfare economics. It is argued that, in this paradigm, equity adjustments should be made in the aggregation of individual utility functions rather than in adjustment of individual WTP values. The theory of aggregation is presented and it is shown that global damage can be presented as the weighted sum of individual damages. Equity weightings are always a function of only the chosen social welfare function and the marginal utility of income.

The results are applied to different welfare functions. Attention here is focused on the utilitarian welfare function which most closely resembles the existing ExternE approach. In this case, welfare equals a weighted sum of individual utilities, so that aggregate world damages are given by:

$$D_{world} = \sum_i \left(\frac{\overline{Y}}{Y_i}\right)^e .D_i, \qquad 1$$

where D_i is the individual damage, Y_i is individual income, $\overline{Y}$ is global average income and e is the income elasticity of marginal utility.

The analysis is then applied to the concept of "common unit damages" to test their compatibility with welfare economic theory. It is shown that these values are compatible with a range of assumptions about utility and welfare. For a utilitarian welfare function the results are equivalent to use of "common unit damages", measured at global average WTP, if the income elasticity of marginal utility is unity. (Of course, it is also true that some assumptions which are not unreasonable are incompatible with common unit values.)

Equal per capita values have been proposed by other authors (e.g. Hohmeyer and Gartner, 1992; Meyer and Cooper, 1995) with justifications that are explicitly subjective and ethical (and not always consistent with a welfare economics approach). However, the same effective result can be achieved in a framework entirely consistent with welfare economics, provided that some reasonable subjective assumptions are made about the aggregate social welfare function.

Given, the advantages to ExternE of producing results numerically equivalent to the existing methodology of "common unit damages", it seems sensible to choose as a central approach those aggregation rules which produce this effect. It is therefore proposed to assume:

- a utilitarian utility function with unit elasticity of marginal utility,
- WTP proportional to income (purchasing power corrected), and
- equity weights inversely proportional to income.

The result is that the individual WTP are consistent with observation, but that the aggregate damages do not violate basic conceptions of equity and are broadly consistent with the approach used in ExternE to date. The changes in WTP due to benefits transfer are effectively compensated for in the aggregation. The following discussion considers the VOSL, but applies equally to other health and environmental damages.

The effects of this approach are not only that the risk to life in different countries is valued equally, but that the VOSL used is that relevant to average global per capita income. It is expected that this will produce a VOSL of approximately 1 MECU, compared to the 2.6 MECU for Europe used in ExternE. If the global warming analysis is simply added to existing ExternE results this has one unfortunate attribute. The VOSL used is lower for global warming and therefore dependent upon the environmental causative agent. If the results were applied in cost benefit analysis this could produce inefficiency in resource distribution between addressing different environmental problems in Europe.

An alternative would be to use a value of 2.6 MECU throughout. This would harmonise the treatment of values between different environmental impacts in Europe. It can be argued that this is the correct value to use, even though it is inconsistent with global average WTP, because the countries of the developed world are the principal polluters and have accepted primary responsibility for climate change in the FCCC. Nevertheless, if implemented in cost benefit analysis, it would result in the deployment of resources in developing countries on climate change abatement and mitigation projects which could be better spent in the same countries in other ways, notably in the development of basic health care.

There is no entirely satisfactory resolution to this dilemma. It flows necessarily from any attempt to value damages of a global scale problem equitably in an otherwise inequitable world. With the existing world income distribution, it is not possible to address climate change damages equitably without compromising efficiency in either (or both) of the EU and developing countries. In this work the global average WTP (approximately 1 MECU) is used, so that the results give a genuine measure of global utility change with the utility and welfare functions chosen. However, it should be noted that this value is lower than the normal ExternE value of 2.6 MECU, and therefore will give climate change costs for Europe which are not consistent with other damages calculated in ExternE.

6. Conclusions

It is concluded that consideration of equity is necessary given the commitments of signatories to the FCCC. This implies that potentially serious impacts in developing countries should not be undervalued.

ExternE to date has used "common unit damages" reflecting average WTP in Europe. Whilst equity considerations make it attractive to carry over this approach to global damages, a crude approach would be inconsistent with the underlying economic principles of the project. Instead, equity issues should be addressed in aggregation by applying equity weightings to observed (income dependent) WTP values. This constructs an aggregate social welfare function which is sensitive to equity concerns.

Aggregate results of climate change damages should be presented in two ways, both consistent with the equity approach in welfare economics set out above. In both cases the damages should be estimated using national WTP estimates based on per capita income, and aggregated using weighting factors inversely proportional to per capita income. The difference between the two approaches is in the constant of proportionality, which in the two cases is:

- average global income (leading to a VOSL of approximately 1 MECU), and
- average EU income (leading to a VOSL of 3.1 MECU).

In either case, the results are consistent with using "common unit damages" for global warming impacts. The latter is used in this case to ensure aggregate global warming damages reflect world utility loss with the assumed welfare function. Similar 'global average values' are used for valuing other impacts.

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Appendix 6

Economic Valuation of Regional and Temporal Impacts of Climate Change

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1. Introduction

Why are space and time important in economic evaluations of the impacts of climate change?

Regional assessments of climate change impacts are becoming more common (see for example IPCC, 1998). National governments have commitments under the Framework Convention on Climate Change to report on impacts, in addition to greenhouse gas emissions. Stakeholders often work at the local to regional scales, and so need information at an appropriate resolution in order to plan adaptive strategies.

The importance of the regional scale in economic evaluation of climate change includes (following Easterling 1998):

- Scale discontinuities and non-linear relationships may not be apparent when large regions are used as the unit of analysis or when results are aggregated over large areas. This is the case with climate change scenarios and many environmental impacts.
- Local to regional scale social and cultural determinants of sensitivity to climate change may be important.
- At a higher resolution, more process-oriented impact assessments can be undertaken, taking advantage of regional data sets and social, economic and environmental understanding.
- Global change policy must be relevant across a range of spatial scales. Highly aggregated assessments may not represent the variability within a region, for example Africa.
- Integrated assessments of climate change damage models include regional representations. However, common models have up to a dozen regions and few have addressed the implied question: how many regions are sufficient to calculate a global cost for climate change?

The temporal profile of climate change impacts has received less attention than regional issues. Specific issues are:

- The ability to adapt to climate change is related to the rate of change. Rapid change may preclude learning, leading to higher than expected impacts.
- Critical time periods of impacts, in terms of resources available for adaptation, are likely to occur at different times for different regions.
- Planning adaptive responses is increasingly an international concern. However, few institutional mechanisms now exist to assist regional planning, promote adaptive responses, or to ameliorate the cost of impacts. Understanding when impacts are likely to reach significant levels would promote timely international responses.
- In economic valuations the discounted net present value (NPV) of impacts is sensitive to the timing of impacts. If temporal profiles are different for different sectors or regions, the

NPV may not adequately capture the importance of climate change.

This paper presents new analyses of economic costs of climate change. We present the results of two models that focus on the regional and temporal nature of impacts. Market and non-market impacts are differentiated. The conclusions suggest that both space and time are essential aspects of the economic valuation of climate change.

2. Overview of the Climate Impact Models

Two distinctly different climate impact models are presented (Table 1). The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and the Open Framework for Economic Valuation of Climate Change (OF) allow calculation of marginal damages attributable to pulses of greenhouse gases (GHGs) and comparison of different reference scenarios (see Appendices 1 and 2 for a fuller description of the models). The sequence of steps in calculating climate change damages is similar in both models, but with different resolutions, interactions and assumptions.

FUND was developed to compare the impacts of climate change against the impacts of greenhouse gas emission abatement. It closes the feedback loop from population to economic activity, emissions, climate and impacts, to population and economic activity. In this paper, only the climate change impact module is used, driven by fixed emission, economic and population scenarios. The fact that FUND is able to perform a cost-benefit analysis - with multiple actors and under uncertainty - implies that the impact module is subject to strict demands on computational speed.

A standard five-box carbon cycle model (cf. Hammitt *et al.*, 1992) is used for carbon dioxide concentrations in the atmosphere. The influence of methane and nitrous oxide emissions on concentrations geometrically declines over time, with life-times according to Schimel *et al.* (1996). Other human disturbances of climate are omitted. Changes in radiative forcing follow from Shine *et al.* (1990). Radiative forcing drives the equilibrium change in the global mean temperature, to which actual temperature geometrically converges. Actual temperature determines equilibrium sea level rise, to which actual sea level rise geometrically converges. Equilibrium sensitivities and convergence rates are calibrated to the typical outcomes of simple climate models (cf. Kattenberg *et al.*, 1996; Houghton *et al.*, 1996)
Impact of climate change I_t at time t is modelled as either:

$$I_t = \alpha_t W_t + \beta_t W_t^2$$

or

$$I_t = \alpha_t \Delta W_t + \beta_t \Delta W_t^2 + \rho I_{t-1}$$

with W an appropriate climate variable, and α, β and ρ parameters. W may be the global mean surface air temperature, or the global mean sea level. The parameters α and β differ per impact category, and depend on agricultural production, per capita income, and urbanisation (cf. Tol, 1996). Impact I is measured either in percentage of Gross Domestic Product, or in percentage of population. In the latter case, climate change induced mortality is valued at 240 times the per capita income in the relevant region at the relevant time for each casualty.

The Open Framework for Economic Valuation of Climate Change (Downing *et al.* 1996, 1997) follows a sequence of steps in calculating economic damages. A reference scenario, based on the IPCC 1992a scenario, is used to project economic conditions, sensitivity to climatic variations and the climate forcing of global GHG emissions.

Global-average temperature change and sea level rise are calculated by the 1995 version of MAGICC (Raper, Wigley and Warrick, 1995; Wigley, 1995). MAGICC is a relatively simple upwelling-diffusion, energy balance climate model that distinguishes between land and ocean and between hemispheres. In all cases, the default model parameters are used.

Spatial scenarios of climate change are based on the $2xCO_2$ equilibrium run of the general circulation model experiment from the Goddard Institute of Space Sciences (GISS). The GCM scenario was scaled to the global-average temperature projection from MAGICC. This results in a time-dependent climate change scenario consistent with the assumptions of the global emissions. The spatial pattern of anomalies from the GISS equilibrium scenario is retained, however.

Simple impact models are run for the current climate and for the scenario of climate change. The baseline climate is based on the 0.5 degree latitude by longitude climatology of Cramer and Leemans (1994). Climate parameters for the baseline are mean monthly temperature and precipitation for the period of record. These methods of creating scenarios are common in climate change impact assessment (see Viner and Hulme 1993, Carter et al. 1994). The impact variables include heating and cooling degree days, agricultural suitability, and water balance. They are extracted to provide country-average values.

The model calculates costs for seven time slices from 1990 to 2100. However, the spatial impacts are only calculated for 1990 (the base year) and 2100, assuming a linear scaling of the simple impact indicators for intervening time periods.

For coastal impacts (coastal protection, loss of wetlands, loss of drylands, migration and biodiversity), agriculture, energy demand and water, country-level economic impacts are derived from the reference projections, simple impact models, and climate sensitivity-cost equations. The equations vary in form, depending on the availability of previous sectoral studies. Most include changes in supply (from the simple impact models), projected prices (or value of production) and the sensitivity of demand to changes in supply or price. The impacts of natural disasters are only calculated at a global-average level.

The country-level direct costs are summed to a global total. An additional global cost, representing higher order, non-market effects, is calculated as a multiplier on the net damages (i.e. not including the positive impacts of climate change). This is done to provide an estimate of the total cost of climate change, rather than only the costs that have been captured by the sectoral models.

The results presented below include only the sectors that are calculated at a country level, and thus do not represent the total cost of climate change.

Both models include the capability to weight damages according to per capita income. This equity weighting follows the form:

$$D^{world} = \sum \left(\overline{Y} / Y^i\right)^e * D^i$$

Where D is economic damages for the world or individual countries, Y^i is income, in this case national GDP, $\overline{Y}$ is world-average GDP, and e is a coefficient (1 in these analyses).

Table 1. Overview of FUND and the Open Framework

Process	FUND	OF
Baseline	9 regions, annual time step 1990 - 2100 (or beyond)	0.5 degree latitude x longitude climate, country-level economic analysis, aggregated to regions, selected time slices for 1990-2100
Reference scenario	IS92a and others	IS92a or IS92d
Global average climate change	Module for temperature and sea level rise	MAGICC estimates for temperature and sea level rise
Regional climate change	Global values assigned to regions	Equilibrium GCM scenario scaled to global changes, including precipitation
Impact modelling	Based on published studies for reference (2xCO2) warming	First-order models for agriculture, water resources, heating and cooling energy using baseline and climate change scenarios
Economic valuation of impacts	Scaled to regional climate change including both magnitude and rate of change	Country-level analysis, based on various methods
Global costs of impacts	Aggregation, with and without equity weighting, various discount rates	Aggregation, with and without equity weighting, various discount rates

3. Regional Impacts of Climate Change in the Open Framework

The OF builds on national level impacts to make regional and global estimates. In Table 2, the national results are aggregated to nine regions (the same regions as used in FUND). The results are net damages from 1990-2100, in millions of US$, not discounted.[1] The aggregate impacts are equity weighted, with a comparison of unweighted values.

With equity weighting, the majority of the total sectoral damages occur in Africa (over 50%), followed by the former USSR and eastern Europe (40%) and south-east Asia (20%). Regions with net benefits of climate change include the Middle East, centrally planned Asia and the Pacific OECD, but the benefits are relatively small.

At the global level, heating costs are negative, that is, they are a benefit of climate change. However, cooling costs exceed the heating benefit. The water sector contributes over half of the damages, followed by biodiversity (13%). The other sectors in the OF have relatively minor contributions at the global level.

Within specific regions, some of the sectors are particularly prominent. The impacts of sea level rise – coastal protection, loss of drylands and wetlands, and migration -- are largest in Africa and South and East Asia, followed by centrally planned Asia (mostly China). Similarly, the biodiversity costs are concentrated in these regions, especially South and East Asia.

[1] The use of 0% discount rate implies negative discounting, that is future economic growth is valued more highly than present economic well-being. Discount rates of 1% 3% are preferred to represent the actual value of impacts. The choice of discount rate, however, does not substantially change the regional comparison in the OF. Comparisons with global and national GDP or per capita impacts would also be insightful.

Almost all of the adverse effects on agriculture are in Africa and South and East Asia. With the exception of the Middle East, the regional net benefits are small. Almost all of the water costs occur in the former Soviet Union, while centrally planned Asia shows a benefit. Clearly, there is very little heating benefit in Africa, where the largest cooling costs occur. In contrast, the Middle East and former Soviet Union have large heating benefits, with modest cooling costs. In other regions the heating benefits and cooling costs are more equal.

Two features of the regional costs are striking. First, for each sector one or two regions, often including Africa, dominate the total costs. Second, the OECD countries do not show large costs relative to the other regions. Of course, this is the direct result of the equity weighting.

Without equity weighted damages, the results are somewhat different. Total costs for the regional sectors is $\$13.5 \times 10^{12}$, less than half the equity weighted values. The biggest difference is in cooling costs. The heating benefit far exceeds the cooling costs, while the reverse is true with equity weighting. This is because heating (cooling) impacts are relatively more important in richer (poorer) countries. In other sectors, the costs are less by a factor of 2 to 5. However, the relative contribution of each sector remains similar – cooling, water and biodiversity are the largest contributors to the global costs.

Given the model's structure, it is not surprising that the same regions benefit and lose in both the equity and non-equity weighted estimates. However, the regions that benefit without equity weighting benefit to a much larger extent. Again, the benefits are largely due to reduced costs of space heating. The total benefit is 61% of the global net cost, while the total of regions that suffer costs is 161% of the total. There is a clear imbalance in the distribution of the impacts of climate change.

The OF provides an opportunity to examine the importance of regional representation. Figure 1 plots individual country results as a ratio of the corresponding regional average. Table 3 provides a range of statistics for the distribution of country results within each region. The salient results are:

The distributions within each region are highly variable. The coefficient of variation exceeds the average in all regions. Even within a fairly homogeneous region there are large differences among countries, although this also reflects different sizes of each county. For example, China accounts for almost all of the Centrally Planned Asia costs.

With the exception of CP Asia, all regions have countries that benefit from climate change and countries that suffer net costs. Where the distribution is more evenly balanced between benefits and costs, the regional total may be quite modest and not reflect the extreme impacts experienced in some countries. Latin America is a good example of this intra-regional balancing of damages.

The country-level estimates provide a different perspective than is readily apparent from the regional totals. If the regional total costs are summed separately for net benefits and net costs, the total net benefit is about 15% of the total costs (Table 4). However, if the country-level estimates of climate change impacts are summed separately for benefits and costs, the total net benefit is one-half of the total costs. By using nine world regions, the country-level disparities in impacts are underestimated.

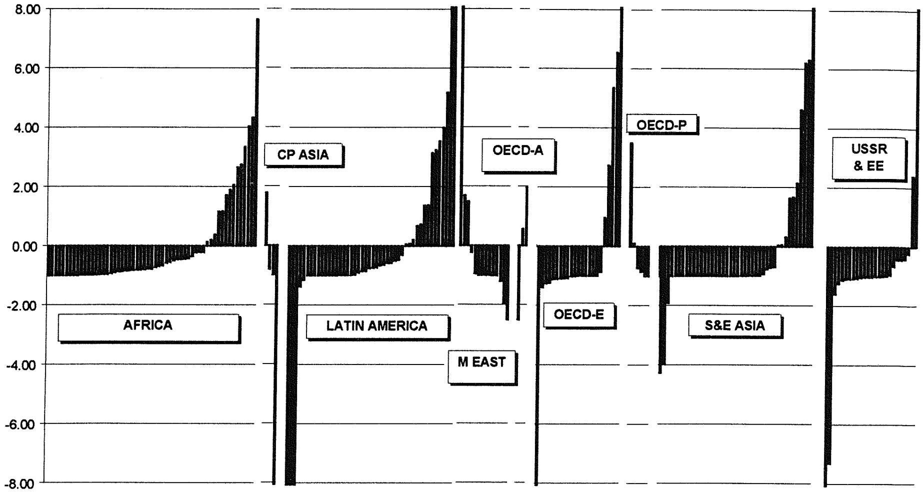

Figure 1. Country costs relative to regional averages. Note that regions with negative averages (benefits) are shown as a descending distribution of country costs. Source: OF, equity weighted, IS92a, 0% discount rate

4. Temporal Impacts of Climate Change in FUND

The temporal profiles of impacts are presented first for the world, comparing market and non-market impacts and with and without equity weighting for both *FUND* and the OF. *FUND* provides annual estimates of impacts, based on both the level and rate of climate change. A detailed regional comparison from FUND shows that regional profiles can be quite different from the world total.

Figure 2 displays the aggregate world impacts. The market impacts first increase, then stabilise and fall. Non-market impacts decline or are almost constant. The weighted and unweighted impacts diverge. China – a winner in climate change in the *FUND* model – contributes to net benefits in the unweighted case. The unweighted non-market impacts are almost constant – the regional tendencies tend to cancel. The weighted non-market impacts start much higher, but then converge to the unweighted impacts, following the assumed convergence of the regional per capita incomes to the world average. Non-market impacts dominate market impacts.

The characteristic profile of increasing then falling impacts is due to relatively more rapid climate change in the early decades. In the later decades, climate change is slower, economies are larger, and sectors have adapted somewhat to climate change. This is an inherent feature of *FUND,* representing a gradual process of reduced sensitivity to climatic variations.

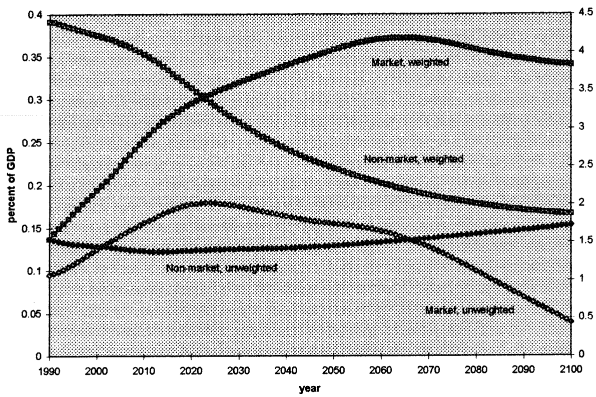

Figure 2. Climate change damages for the world. Non-market impacts are on the right axis.

Figure 3a displays the impacts of climate change on marketed goods and services in Annex I regions. Impacts in the OECD regions (expressed as a percentage of income) first rise, and then fall. In OECD-Europe, the peak is higher and later than in OECD-America and OECD-Pacific. This is because immigration, largely from Africa, makes up a substantial share of the market impacts. Under the baseline scenario, Africa's economy grows much slower than the economies of Asia and Latin America. As a result, the inclination of Africans to migrate remains higher than for Asians and Latin Americans.

The declining curve for Central and Eastern Europe and the former Soviet Union is due to the positive impact of climate change. There are few regional interactions, resulting in an almost linear profile.

Market impacts in non-Annex I regions show somewhat different profiles (Figure 3b). Changes over time are less, except for Africa. Except for China (CPA), impacts first rise, then stabilise and fall. The explanation is threefold. Firstly, people are less inclined to migrate if they grow richer. Secondly, agriculture becomes less important in the economy. Thirdly, climate changes more slowly over time. Impacts on China, dominated by agriculture, are positive but level off as agriculture becomes less important.

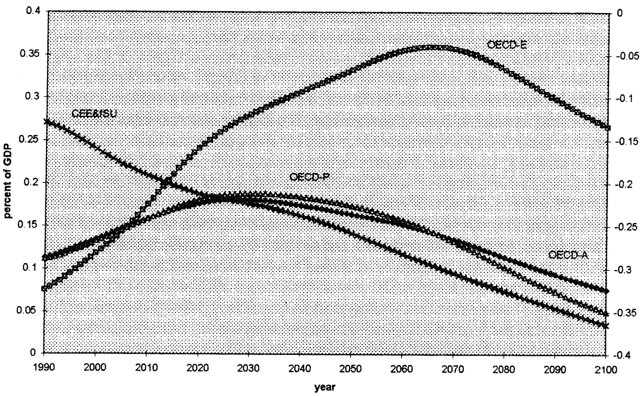

Figure 3a. Market climate change damages for Annex I regions. CEE&fSU is on the right axis.

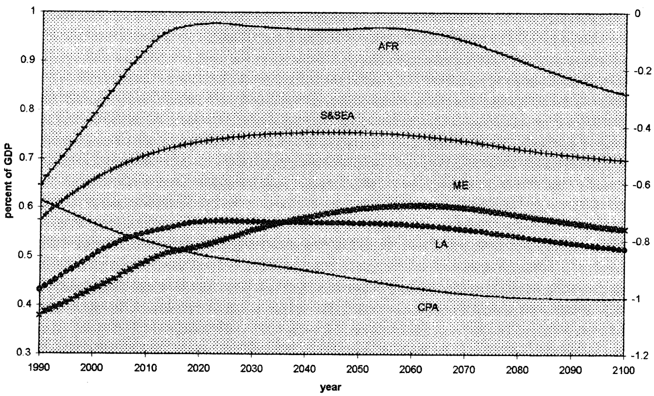

Figure 3b. Market climate change damages for non-Annex I regions. CPA is on the right axis.

Impacts of climate change on non-marketed goods and services are shown in Figure 4a for Annex I regions and Figure 4b for non-Annex I regions. The slower pace of climate change is outweighed by increasing urbanisation (and thus heat stress mortality) and the increasing valuation of impacts.

In the non-Annex I regions the pattern is more involved than in the richer countries. A substantial part of the impact, such as malaria and migration, depends on the level (rather than the rate) of change of climate and sea level. This pushes impacts upwards, particularly in the earlier decades in Africa. Valuation increases with per capita income. This also pushes impacts upwards, particularly in China – from 2030 onwards -- and South and Southeast Asia – from 2080 onwards. However, increasing per capita income reduces the inclination to migrate and improves health care, thus pushing impacts down. This effect dominates in Africa, the Middle East and Latin America in the later decades.

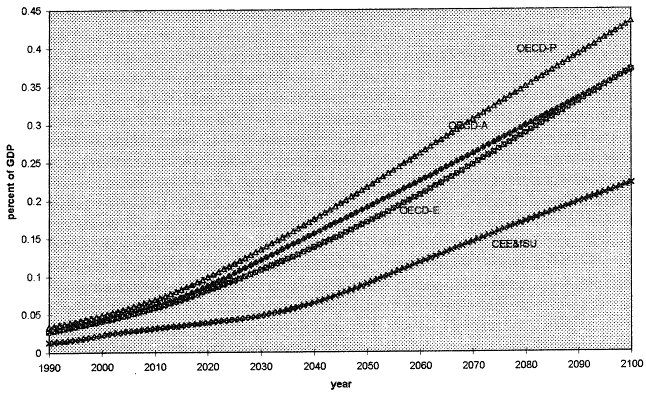

Figure 4a. Non-market climate change damages for Annex I regions.

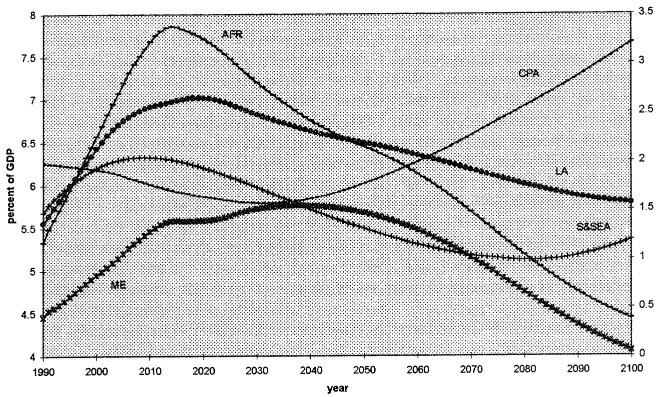

Figure 4b. Non-market climate change damages for non-Annex I regions. CPA on right axis.

Market and non-market damages are aggregated in Figure 5. In both regions, non-market damages dominate the total damages. This results in an upward profile of damages in the OECD countries. In developing countries the aggregated profile tends to show a marked increase, followed by substantial declines. China, however, is the reverse as non-market impacts dominate in the later decades.

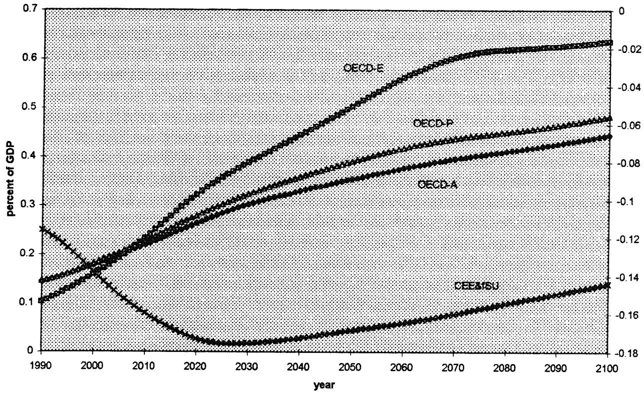

Figure 5a. Aggregate climate change damages in the Annex I regions. CEE&fSU is on the right axis.

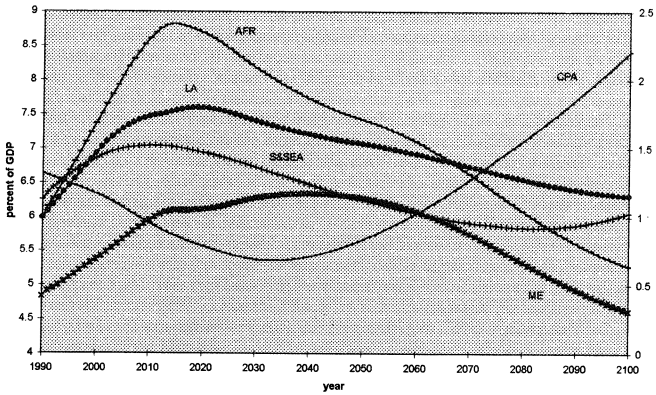

Figure 5b. Aggregate climate change damages in the non-Annex regions. CPA is on the right axis.

5. Conclusions

Both space and time are essential aspects of economic valuations of climate change damages.

Realistic representation of regions is required to capture the spatial distribution of climate change, to understand sensitivity to climate change, and to document the distribution of impacts. The above analysis clearly shows that by aggregating national impacts to a regional level some impacts are averaged together and some extreme cases appear less so.

No specific estimates of secondary effects, socially contingent consequences, or dependence on the scale of impacts have been included in the above results. However, some of the major concerns at the regional level focus on the potential for multiple impacts across a number of sectors that lead to collapse of entire economies. This could be imagined, for example, in a low-lying country vulnerable to sea level rise, tropical cyclones, and loss of agriculture.

Are there winners and losers? We have shown that some regions and many countries have net benefits of climate change (at least for the assumptions of this study). However, within each country, some sectors suffer costs. At the same time, most countries experience some benefits—most from reduced heating costs in the present study. Thus, it may be too simplistic to characterise country or regional costs as net winners and losers.

The prevailing estimates of sectoral damages of climate change have assumed each country or region experiences damages in isolation of each other. In reality, world trade may mitigate or distribute impacts. While trade is an essential basis of integrated assessment models of greenhouse gas abatement, it is less readily accommodated over the long term required for understanding impacts. In many cases, such as agriculture, world trade is likely to mitigate impacts, at least to the extent of reducing the risk of higher order effects. However, it is less clear how trade patterns would respond to persistent decline in resources (agriculture, water, ecosystems), lack of investment and increasingly uncomfortable living conditions (heat stress, climatic hazards). It is quite possible that competition among countries and regions would adversely affect some countries and result in even greater climate impacts than at present.

The temporal dimensions of climate change are also critical. Different regions and different sectors have different temporal profiles of impacts. This can affect the balancing of market and non-market damages, the net present value, and the comparison of impacts between regions. Planning adaptive strategies requires greater understanding of when critical impacts are likely to occur.

The analytical basis of most economic analyses is the individual. Within a country, the impact of climate change is also likely to vary considerably. Some justification for using national analyses derives from the role of the state in negotiating limitations to greenhouse gas emissions. And over time, the impacts change in location, character and extent. Present assessments have barely begun to capture the full geographical and temporal dimensions of climate change impacts.

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Table 2. Regional costs of climate change from the OF, aggregated from 1990 to 2100, US$billion

	Equity Weighted Impacts											Unweighted impacts	
Region	Coastal Prot.	Wetland	Dryland	Migration	Agric.	Water	Bio-diversity	Heating	Cooling	Total	%	Total	%
Africa	601	504	1,913	517	1,562	2,285	1,595	-165	26,319	35,130	52%	3,488	26%
CP Asia	116	139	329	71	-2	-2,590	1,818	-16,022	13,134	-3,008	-4%	-3,784	-28%
Latin America	44	95	108	4	146	451	574	-1,954	1,508	976	1%	1,374	10%
Middle East	6	0	28	3	-124	388	117	-8,872	1,089	-7,365	-11%	-1,903	-14%
OECD-A	6	5	18	0	-2	1,276	231	-2,190	1,102	447	1%	3,082	23%
OECD-E	12	2	40	4	-4	488	62	-1,413	2,605	1,797	3%	3,826	28%
OECD-P	3	0	16	0	0	4	6	-656	104	-523	-1%	-2,518	-19%
S&E Asia	474	422	1,654	506	1,694	1,504	4,147	-8,615	11,516	13,304	20%	3,264	24%
USSR&EE	9	0	126	3	-114	31,578	65	-8,248	3,872	27,289	40%	6,695	50%
Total	**1,271**	**1,169**	**4,231**	**1,108**	**3,156**	**35,382**	**8,616**	**-48,135**	**61,248**	**68,046**	**100%**		
%	2%	2%	6%	2%	5%	52%	13%	-71%	90%	100%			
Unweighted Total	**336**	**388**	**1,189**	**185**	**454**	**19,492**	**4,706**	**-39,779**	**26,551**			**13,523**	**100%**
%	2%	3%	9%	1%	3%	144%	35%	-294%	196%			100%	0%

Table 3. Distribution of country costs relative to regional costs

	Africa	CP Asia	Latin	M East	OECD-A	OECD-E	OECD-P	S&E Asia	USSR&EE	World
No. of	57	3	47	14	3	23	6	42	25	220
Total costs:										
Min	-3,757	-	-504,310	-	-463,372	-435,536	-419,849	-1,511,561	-11,684,002	-11,684,002
Average	635,741	-	27,037	-124,109	309,022	49,139	-93,629	462,444	894,106	318,324
Max	5,503,345	-59,442	862,743	186,546	909,911	667,013	954	7,500,034	35,264,865	35,264,865
Std Devn	1,069,514	3,780,27	193,830	361,020	573,607	193,008	150,122	1,438,477	7,490,829	2,747,543
Sum	36,237,248	-	1,270,75	-	927,067	1,130,20	-561,775	19,422,664	22,352,657	70,031,298
CV	168%	-126%	717%	-291%	186%	393%	-160%	311%	838%	863%
Net costs:										
Count	56	0	41	8	2	11	2	38	10	168
Sum	36,241,005	0	2,612,01	338,099	1,390,43	1,634,83	1,104	22,746,231	40,893,491	105,857,214
Net benefits:										
Count	1	3	6	5	1	12	4	4	15	51
Sum	-3,757	-	-	-	-463,372	-504,632	-562,879	-3,323,567	-18,540,834	-35,825,917
Benefits/costs	0.0	N.A.	0.5	6.0	0.3	0.3	510	0.11	0.5	0.3

Notes: Equity weighted, IS92a, 0% discount rate
Source: OF

Table 4. Comparison of country-level and regional net benefits and costs

	Country-level	Regional
Net benefits	-35,825,917	-11,309,298
Net costs	105,857,214	81,340,595
Total costs	70,031,298	70,031,298
Benefits/costs	0.34	0.14
Benefits/total	0.51	0.16

Notes: Equity weighted, IS92a, 0% discount rate
Source: OF

Appendix 7

Human Health Damages of Climate Change

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1. Introduction

Impacts to human health are widely accepted as one of the most important categories of climate change impacts. Both direct effects of changed temperatures and more indirect effects are potentially important (Haines et al, 1993: McMichael, 1996). The impacts may be subdivided into eight categories as shown in Table 1, which also shows how the different issues are treated in the ExternE Global warming task.

Table 1

Climate Change Effects on Human Health

Climate Process	Health Impacts	Treatment in this Study
Direct Effects		
Temperature change including extremes	Heat and cold related death and illness	Section 2
Other extreme weather events	Storm damage effects	Included under "extreme events"
Indirect Effects		
Range and activity of vectors and parasites	Change in geographic range of diseases	Section 3
Local ecological changes	Change in water and food-borne diseases	Not quantified
Changes in agricultural productivity	Regional malnutrition and hunger	Section 5 and under "higher order effects"
Sea level rise	Direct injuries, infectious diseases and water contamination	Included under "migration"
Air pollution and pollen	Asthma and allergic effects	Section 4
Socio-economic and demographic change	Wide range of potential effects including famine and war	Included under "higher order effects"

Source: based on McMichael (1996)

2. Direct Effects of Temperature

The ExternE approach to public health impacts of air pollution emphasises the differences between acute and chronic effects (see CEC, 1995). In this context "acute" is understood to be the short term health effects (including mortality) in populations affected by an environmental change. This includes effects on vulnerable groups such as children, elderly and sick people. Many of the effects are the exacerbation of already existing health problems in these groups by environmental stress. "Chronic" effects, on the other hand, are understood to be "new illnesses" due to differences in the environment. It is mortality effects which are found to be important in valuation studies. Because of their different characteristics, it is important to distinguish between "acute mortality" and "chronic mortality".

The value of statistical life (VOSL), commonly used in valuing mortality effects is based on studies of otherwise healthy adults. Although the health valuation literature does not allow different values to be distinguished very clearly, there is an obvious case for lower values where deaths result in fewer years of life lost. In the past ExternE has used a VOSL for Europe of 2.6 MECU (see CEC, 1995), but is now changing to a life years valuation approach. In this case mortality is valued as:

Value of mortality = Years of Life Lost (YOLL) x Value of a Life Year Lost (VLYL)

It is assumed that studies estimating VOSL are based on 35-40 YOLL, so that the VLYL is 75 kECU. In cohort epidemiological studies, the YOLL are a direct output, but in acute mortality time series and specific disease mortality studies, some additional assumptions are required to convert numbers of deaths to YOLL.

This is an important consideration in the context of temperature related effects, because the IPCC review (McMichael, 1996) is confined to acute effects. The deterioration of health at both high and low temperatures is well established (e.g. Sakamoto-Momiyama, 1978; Kunst et al, 1993). However, the climate change damage literature has concentrated on acute effects, particularly of heatwaves. The large literature on seasonal variation of mortality and the potential importance of reduced cold stress has been neglected with one or two exceptions (Langford and Bentham, 1993). Neither the timescale of extreme events (of the order of a day) nor seasonal variation is a good analogue for the long term effects of climate change, but the latter is probably more closely related.

Valuation of acute mortality is critically dependent upon the estimate of YOLL for each additional case. For classical air pollution there is evidence that some, but not all, of the effect is "harvesting", that is the death which occurs shortly after a pollution episode is of a person likely to die very shortly in any event. In general it is believed that the majority of the deaths relate to people who are ill. ExternE uses an estimate of 0.75 YOLL per case, i.e. the death is brought forward on average 9 months by pollution. The same sort of harvesting has been identified with temperature related effects (e.g. Kunst et al, 1993). In the absence of a better assumption this paper therefore assumes a similar 0.75 YOLL per case for acute mortality due to heat and cold. This, however, does introduce some uncertainty in the assessments.

Assessment of chronic health effects generally requires the use of cross-sectional studies, i.e. the health status of populations in different locations, which is methodologically more difficult than the study of acute effects using time series data for a fixed population. However, for conventional air pollution effects, increasingly it is found to be the chronic impacts which are potentially more important (e.g. Pope et al, 1995).

In contrast to the acute effects of temperature change, the chronic long term impacts of different climates are extremely difficult to distinguish from confounding social and demographic factors. Some have argued that the effects of changes in average temperature will be small, because of human adaptation. However, it seems unlikely that humans are genetically equally well suited to all climates, and therefore chronic effects cannot be ruled out. It is therefore possible that the most significant direct health impacts of temperature are not well captured by the existing literature.

There is also controversy about the relative importance of health effects of temperature and air pollution. There is agreement in principle that it is likely to be the combination of environmental stresses which is responsible for health effects, but less agreement on which agent is most important. However, the key study used by ExternE for chronic air pollution damages (Pope, 1995) does allow for temperature confounding outside the range 10-16 Celsius. Similarly the better studies on acute temperature effects allow for confounding by pollution. We therefore have reasonable confidence that double counting is limited.

2.1 Acute Heat Impacts

Analysis of the effects of climate change on heat stress, covering urban areas on three continents, identifies a wide range of sensitivity to heat stress (Kalkstein and Smoyer, 1993; Kalkstein and Tan, 1995). The methodology concentrates on acute health effects of heat waves, i.e. on the time scale of days. The methodology typically considers all cause mortality in a given city over the days for which a temperature threshold is exceeded.

Evidence concerning the sensitivity of the heat stress to climate is mixed. No clear effect is observed in many Canadian cities (Kalkstein and Tan, 1995), implying that there may be a temperature below which even unusually high temperatures have no significant mortality effect. However, this can not be generalised to an assumption that higher baseline temperatures induce a larger effect in cities with higher average temperatures, as the threshold for the effect is generally higher here. This may be interpreted as evidence of acclimitisation. The effects of climate change are therefore more likely to depend on the rate of change rather than the temperature level.

Studies of the annual heat stress in different US cities show considerable variation in mortality rate, but no clear evidence of regional or baseline climate variation. There is some evidence that the effect may be lower in cities in Southern states where high temperatures are common (Kalkstein and Smoyer, 1993). Similarly in China, current heat stress deaths are higher in the warm temperate climate of Shanghai than in the less variable (but on average higher) tropical climate of Guangzhou. There is no evidence to assume any strong effect of baseline temperature on the impact.

Socio-economic variables, probably reflecting access to air conditioning and quality of housing, are very important, with impacts much larger in Asia and Africa than North America. Expected effects of a 2.5C temperature change for 6 cities are shown in Table 2.

Table 2

Expected Acute Mortality Effects of Heat Stress in a Range of Cities

City	Heat Stress Acute Mortality (annual deaths per million)		
	Current	at +2.5C	Change
Montreal	26.2	92.0	65.8
Toronto	7.3	41.6	34.3
Shanghai	61.7	319.4	257.7
Guangzhou	41.3	325.8	284.5
New York	26.7	52.7	26.0
Cairo	44.6	121.9	77.3

Source: based on Kalkstein and Tan (1995)

The socio-economic effects are difficult to model. Using per capita income as a proxy for all socio-economic variables, it is clear that there is an inverse correlation, but a variety of functional forms could be used. A reasonable fit is obtained by:

$$D_{heat} = 2200.Y^{-0.41}, \qquad 1$$

where D_{heat} is the annual increase in heat stress mortality rate (deaths per million population) and Y per capita income (in $) in the country considered.

The results are broadly consistent with other studies of temperature related mortality undertaken outside the context of climate change analysis. For example, a time series study in the Netherlands indicates an increased relative mortality of 0.011/°C above 16.5°C (Kunst et al, 1993). Applied to benchmark climate change, it is estimated that this would increase heat dependent deaths by approximately 60 per million, compared to the 40 per million estimated for the Netherlands from equation 1.

Equation 1 may be used to estimate the global benchmark heat stress damage costs. Using IPPC scenario estimates of future population and income (Pepper et al, 1992), a life years valuation and equity corrected, the annual damages are approximately 50 billion ECU. Over 90% are in developing countries.

It is clear from the studies assessed that human beings are sensitive to temperature principally at levels they experience infrequently. Impacts are therefore driven largely by rate of temperature change and there should be considerable adjustment within less than a generation. There is little evidence on which to make any quantitative assessments. The assumptions used are based on assessment of the difference between damages with and without acclimatisation: $\frac{1}{6}$ of the total damages relate to the level of climate change and $\frac{5}{6}$ to the rate of warming, declining geometrically to 1% over a period of 15 years (Tol, 1996).

The level of uncertainty in this assessment is high. For the acute effects measured, it is known that variation between cities is large - a variation of a factor 3, i.e. geometric standard deviation (GSD) of an assumed log normal distribution is found in data on increased death rates in 15 cities of the USA (based on Kalkstein and Smoyer, 1993). The statistical uncertainty in projecting damage as a function of income using data from a smaller number of cities in different countries is a factor of 2.5, implying that the restricted sample may well be unrepresentative. Additional uncertainty due to model structure (assumed functional form, dynamics etc.), valuation (use of YOLL and VLYL) and extrapolation to other climates must also be allowed for. The overall uncertainty in the value for acute heat stress is estimated to be a factor of about 5. Omission of chronic effects of heat stress is potentially very significant but unquantifiable.

2.2 Acute Cold Effects

The most widely quoted study in the climate change damage literature on the impacts of climate change on cold related deaths is based on US estimates (Kalkstein, 1989). It concludes that the death rate will be reduced by 9 per million at $2xCO_2$, or 4 per million if there is some allowance for physiological (but not socio-economic) adaptation.

Estimates based on the seasonal mortality studies are considerably higher. A study of monthly death rates over most of the UK (Langford and Bentham, 1993) has been used to estimate the effect of temperature on mortality. It is concluded that, without other changes, there would be a reduction in winter deaths of 9000 at a temperature change typical of $2xCO_2$. This implies a death rate reduction of 150 per million based on inter-seasonal variation.

A better analogue for the impacts of climate change is probably inter-annual variation in excess mortality as a function of temperature. The literature in this area is very sparse. An analysis for most of the UK (Curwen, 1991) indicates a relationship between excess winter deaths (EWD), excluding influenza effects, and mean winter temperature of the form:

$$EWD = 28\,900 + 5090(T_0 - T), \qquad 2$$

where T_0 is the mean winter temperature. This implies a temperature sensitivity of acute mortality of -100 deaths/°C, equivalent to -250 deaths per million at benchmark climate change.

However, this cannot be assumed typical of all countries, or even all OECD countries. Time series data on mortality in the Netherlands, indicates that at temperatures below 16.5°C (i.e. most of the year), the effect of temperature is a decrease in mortality of 0.0045/ °C (Kunst et al, 1993). This implies an impact of benchmark climate change of a decrease of 80 deaths per million.

Differences in excess winter mortality occur throughout the developed world, but the level is very variable (Curwen, 1991). Figure 1 shows the excess winter death index (EDWI) - defined as the percentage excess of mortality in the four winter months over the remaining 8 months - as a function of per capita income for various countries. It can be seen that there is a tendency for EWDI to decline with income although there is a large scatter. Within more homogeneous groups of countries there is a clearer trend, for example in the EU countries included in Figure 1, the lowest EWDI are in Germany and Finland with the highest in Portugal and Ireland - pointing to socio-economic rather than climatic effects being predominant.

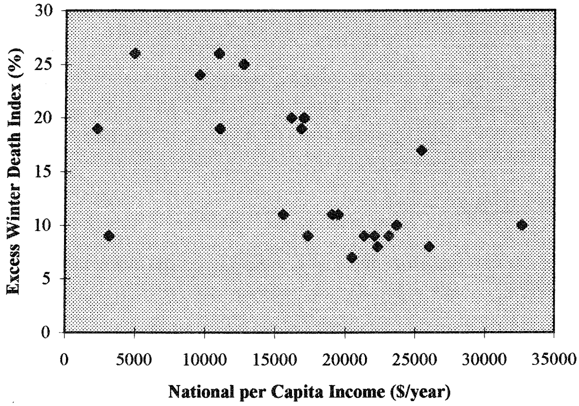
Additional confidence that there is indeed a income effect comes from time series analyses within individual countries. In most developed countries, excess summer deaths due to illnesses such as gastro-enteritis have been largely eliminated by modern medical practice and improved public health (Sakamoto-Momiyama, 1978). A declining excess winter death rate with increasing incomes has then been observed in the Netherlands (Kunst et al, 1990), the UK (Curwen, 1991), the USA and Japan (Sakamoto-Momiyama, 1978). There is also evidence of a negative correlation between EWDI and income within countries (Curwen, 1991).

The international dataset in Figure 1 is used here to derive an income dependence. A reasonable fit of a relatively simple function to the data is a logistic of the form:

$$EWDI = \frac{422\,000}{Y + 17\,700}. \qquad 3$$

Figure 1

Excess Winter Death Index as a Function of Income



The UK data point (income $16 100, EWDI 21) is anomalously high - a factor 1.7 above the curve. Taken together with equation 2 this implies that a representative expression for benchmark climate change impact on excess winter deaths is of the form:

$$EWD = \frac{-5.2x10^{6}}{Y + 17\,700} deaths\ per\ million \qquad 4$$

Clearly it is not appropriate to apply this in regions where cold stress in not currently a problem. Ideally there should be some temperature (or heating degree day) functionality to achieve this, although for the reasons given above this cannot be established with any confidence from existing data. In the absence of the information required to achieve this, it is proposed that cold stress should only be considered for regions where there are large populations are outside tropical and sub-tropical climates, say above latitude 30 degrees. Without introducing much additional error this can be assumed to be the whole of the OECD and transitional economy regions, 80% of the Middle East, 50% of Centrally Planned Asia, 25% of Africa and 10% of both Latin America and South and East Asia.

Equation 4 and the previous paragraph may be used to estimate the global benchmark cold stress damage costs. Using IPPC scenarios for future population and income (Pepper et al), a life years valuation and equity corrected, the annual benefits are approximately 50 billion ECU. This is very similar in sign, but opposite in magnitude, to the benchmark heat stress damages estimated in the previous section. As humans are reasonably adapted to a temperature close to global mean average this is not too surprising. Of course the uncertainty in each calculation is large, so the result implies it is not possible with current knowledge to determine whether the heat stress damages or cold stress benefits will be the larger.

However, it is clear that the costs and benefits are likely to be unevenly distributed. It is assumed that tropical and sub-tropical climates suffer no cold stress effects. In most of Africa, South and East Asia and Latin America temperature change due to global warming will be a cost. In contrast, the benefits of reduction in cold stress in OECD regions, the economies in transition and China are larger than the heat stress costs of climate change.

It is clear from the rather weak correlation between winter temperatures and excess winter deaths that there is scope for adaptation in human populations. However, both the theoretical considerations of optimum temperature for humans and empirical evidence indicate that the temperature level may be responsible for a bigger fraction of the effect than is the case with heat stress. It is assumed that 4/9 of the effect is level related and 5/9 is rate dependent (Tol, 1996).

The uncertainties are assumed broadly similar to those of heat stress, i.e. a geometrical standard deviation of five. Once again, the absence of studies on genuinely chronic effects (i.e. the effect of temperature on long term mortality rate) is a major weakness of existing analyses.

3. Vector-Borne Diseases and Parasites

Most disease agents are sensitive to temperature and other conditions. But agents which are transmitted directly from person to person are mainly in the highly controlled environment of the human body. The diseases most likely to be sensitive to climate change are therefore those involving vectors. The most serious are some tropical diseases, typically involving transfer via an insect or other arthropod.

It should be noted that climate sensitivity of tropical diseases is more than a purely theoretical problem. Already in areas where local climates have been significantly affected by deforestation, the combined effects of climate change, migration and urbanisation have produced significant increases in the infection rate of malaria, American trypanosomiasis and leishmaniasis (Almendares et al, 1993).

Characteristics of the diseases which might have the largest consequences for global health are summarised in Table 2.

It can be seen that malaria is the most widespread geographically, produces the largest number of infections and is judged by the IPCC (McMichael, 1996) to be the most sensitive to climate change. Although the fatality rate is significantly lower than some other diseases, like trypanosomiasis and some strains of leishmaniasis, the climate change related incremental malaria (mortality and morbidity) is likely to be dominant amongst these diseases. Attention is therefore confined here to malaria.

Table 2

Main Characteristics of Tropical Diseases Potentially Sensitive to Climate Change

Disease	Vector	Population at Risk (M)	Total (annual) infections (M)	Climate Change Sensitivity
Malaria	Mosquito	2 400	(350)	highly likely
Schistosomiasis (Bilharziasis)	Water Snail	600	200	very likely
Lymphatic Filariasis	Mosquito	1 100	120	likely
African Trypanosomiasis (Sleeping sickness)	Tsetse fly	55	(0.28)	likely
American Trypanosomiasis (Chagas' disease)	Triatomine Bug	100	18	likely
Leishmaniasis	Sand fly	350	(0.5)	likely
Onchocerciasis (River blindness)	Black fly	120	18	likely
Dengue	Mosquito	1 800	(20)	very likely

Source: based on McMichael (1996)

The simple model for the (monetary) damages, D, of any illness which is compatible with health valuation practice elsewhere in ExternE is:

$$D = P.R.\left[f.T.VLYL + (1-f)).SVI\right], \qquad 5$$

where P is the population in areas at risk, R is the rate of infection, f is the fatality rate once infected, T is the average number of life years lost, VLYL is the value of a life year lost and SVI the statistical value of (non-fatal) illness.

The relative importance of mortality and morbidity is difficult to judge. The VLYL used in ExternE is 75 kECU at current OECD-Europe income levels. ExternE typically uses 8 for the YOLL due to a chronic illness caused by air pollution. For malaria, the impacts are concentrated in countries with lower life expectancy, but some of the fatalities are children (Martin and Lefebvre, 1995), so the average loss in life expectancy may be similar. The value of SVI depends of the seriousness of the illness. Malaria will clearly viewed as more serious than a minor illness, but less so than an illness with very grave or permanent effects (e.g. cancer or physical disability). Based on previous ExternE work (CEC, 1995) a value of 10,000 ECU at OECD-Europe income levels is a reasonable estimate, but this is very uncertain. At this level, morbidity has greater damages than mortality when the value of f falls below 1.6%. Estimates of f indicate that it is currently 0.4% (McMichael, 1996), so morbidity damages may be significant. If public health programmes improve over time, so that the value of f falls, the costs of morbidity may ultimately be dominant.

Using these assumptions, the general case of equation 5 applied to malaria is:

$$D = P.R.[0.004 \times 8 \times 75{,}000 + 10{,}000]ECU, \qquad 5a$$

For vector borne tropical illnesses, climate change can obviously affect both the population at risk and the rate of infection. The latter could also be affected by economic development both through improvements in sanitation and control programmes. Climatic and social conditions are therefore potentially important. The assessments of the effects of climate change on malaria tend to avoid the complications of socio-economic dependence by concentrating on the potential for changed rates of epidemic, implicitly with unchanged socio-economic characteristics (e.g. Martens et al, 1995; Martin and Lefebvre, 1995; Matsuoka and Kai, 1995). Results for the change in malaria potential at benchmark climate change (where appropriate linearly scaled to 2.5K temperature rise) are shown in Table 3.

Table 3

Impacts of Benchmark Climate Change on Malaria Potential

Study	% increase in Malaria Potential at 2.5K
Martens et al, 1995	3-13
Martin and Lefebvre, 1995	7-28
Matsuoka and Kai, 1995	10-30

There is reasonable agreement about the scale of the expected effect - an increase in the range 3-30%. An estimate of 10% is used here. This implies an increase in the global number of malaria cases of 35 million per year in 2050, of which 150,000 might be fatalities.

A significant part of the areas in which malaria epidemic potential might increase substantially are in the developed world - much of the USA and Japan, Southern and Central Europe. The Martens et al study excludes the population in these areas from the risk estimate on the grounds that malaria control will be likely to remain effective in developed economies. If this is assumed, the benchmark impact is approximately 9 per thousand increase in annual cases (and 36 per million increase in death rate) in the developing country economy regions, with ranges of 3-30 per thousand and 12-120 per million respectively. The "best guess" is half the figure quoted by Tol, using the same sources, although the range is much the same (Tol, 1997). The difference arises from the greater weight given here to the Martens et al range, because of its consistency with assumptions about control in developed countries.

The assumption of limited impacts in the developed world raises the more general issue of the socio-economic dependence of the impacts. Both the infection and mortality rates are likely to be sensitive, although the importance of the latter is not so great because the morbidity costs are independent of it. Current differences in total malaria death rate between countries is not alone a reliable approach as activity of the mosquito vector is strongly anti-correlated with development. It is again assumed that income, Y, can be used as a proxy for socio-economic conditions. The simplest assumption would be that total impacts are weighted inversely proportional to regional per capita income. However, this leads to unstable values at low incomes and therefore an adjusted version incorporating a logistic term is included (c.f. Tol, 1997), so that infection rates, R_i in each developing region, I, are modelled as:

$$R_i = 9000.\frac{1000}{Y_i + 500} \textit{ annual cases per million}, \qquad 6$$

where Y_i is the regional per capita income (in $) and the constant $500/year is chosen as approximately equal to the lowest current per capita regional income.

The damages are calculated by using equation 6 in equation 5a for the developing country regions with equity correction. The benchmark damages calculated are 300 billion ECU annually. This of course is strongly dependent on the assumption made for statistical value of illness, years of life lost and the dependence of infection rate on income. The damage estimate is significantly larger than those relating to heat and cold mortality. This contrasts with some other studies. The difference arises because of the use of life years lost valuation coupled to the small number of YOLL assumed for each direct temperature mortality case and because of different equity weighting assumptions.

The effect is purely level dependent with no assumed adaptation. It will therefore tend to grow over time at past the benchmark warming level.

4. Air Pollution Impacts

In principle almost all air pollution impacts could be affected by climate change. Atmospheric stability, wind speed and direction affect pollution dispersion; rainfall affects deposition rates; temperature and insolation affect reaction rates in the atmosphere. However, changes to atmospheric stability, winds, rainfall and insolation, although poorly understood, are likely to be of both signs and therefore, globally, the aggregate effects will tend to cancel. Attention is here therefore confined to temperature effects.

Most pollutants of the greatest concern (particulates, sulphur dioxide, NO_x, and some toxic hydrocarbons) are primary pollutants. Although they are removed from the atmosphere, to a greater or lesser extent, by reactions which are temperature dependent, this is a second order effect in determining their overall impacts. For ozone, the situation is different. It is a secondary pollutant entirely created by reactions involving NO_x and VOC, with temperature dependent rate constants. Ozone concentrations are therefore far more temperature dependent than those of the other major air pollutants. This is confirmed by examination of the variation in the propensity of ozone to form from its precursors between both different climatic zones and different seasons of the year.

Exact estimates of ozone related damages are not available. The best values available for Europe indicate that average European damages are of the order of 1500 ECU/t for NO_x and 900 ECU/t for VOC (Rabl and Eyre, 1997). Of these totals, 1100 ECU/t NO_x and 700 ECU/t VOC relate to human health. Europe is more densely populated than other major emitting regions, but the climate is generally less favourable to ozone formation than in regions with warmer summers, therefore these values are likely to be broadly typical. With projected global anthropogenic emissions in 2050 of approximately 200 Mt of both NOx and VOC (Pepper et al, 1992), the expected annual global damages with current climate would be approximately 360 billion ECU, evaluated at current European values. Global average per capita incomes at benchmark warming are 70% of the current European average in IPCC scenarios (Pepper et al, 1992), so a valuation of 250 billion ECU is used here.

Damages are not consistent across different climatic zones. In Europe, the marginal damages per unit of pollution emitted are approximately a factor of two higher in Southern Europe than in Northern Europe (Rabl and Eyre, 1997; Simpson, 1992). There is a variety of meteorological factors which influence this differential damage, but temperature is a major causal factor. Mean temperatures differences between northern and southern Europe are typically 5°C, implying that ozone damages might differ from the mean by about 15%/°C. Climate change to the benchmark level of 2.5°C is therefore estimated to increase global ozone damages by 40%.

A first estimate of the increased damages due to benchmark climate change is therefore of the order of 100 billion ECU. This assessment should be treated as an order of magnitude estimate only. Nevertheless, it is clear from the analysis that climate change impacts on ozone damage are potentially significant, compared to other categories of health damage.

5. Higher Order Effects

The treatment of higher order effects of climate change on human health, and particularly mortality is responsible for the biggest divergence in estimates of global damages of climate change. Most of studies reviewed by IPCC Working Group III (Pearce et al, 1996) exclude higher order health effects due to food and water shortages. In some damage studies, this exclusion is made explicit (e.g. Tol, 1997) in others, the exclusion is not commented upon, and therefore it is not clear whether the authors do not believe such impacts will occur or that the data to quantify them is too uncertain. What is clear is the result - that these potential impacts on health, although addressed by IPCC Working Group II (McMichael, 1996), are not reflected in the Working Group III damage review. This is potentially a significant omission, as studies which have included estimates of higher order health damages tend to find high values (e.g. Hohmeyer and Gärtner, 1992; Ferguson, 1994; Kuemmel and Sørensen, 1997).

The effects of changes in temperature and precipitation on agriculture and water resources are complex issues which are addressed elsewhere in the ExternE Global Warming task. The best estimates seem to indicate that climate change may not change the global resource availability by a large amount. However, it is clear that there will be significant shifts in regional distribution. In some cases, the "losers" will be in countries which currently have a very limited capacity to respond effectively. The extent to which these losers suffer food and/or water shortage (with consequential serious health impacts), therefore depends on the extent to which that capacity is increased by both domestic socio-economic improvements and international resource transfers.

It is therefore clear that the higher order health impacts of climate change will depend mainly on socio-economic factors independent of climate change. IPCC scenario projections indicate per capita income increases in the poorest countries in the range 120%-500% by 2050 (Pepper et al, 1992). The differences between the two ends of the range, and the underlying inequalities between and within countries are unstated. Our ability to estimate the capacity of the poorest countries to deal with the threats of climate the middle of the next century is therefore very poor.

The only study on food security referenced by the health assessment chapter of IPCC Working Group II estimates a potential increase due to climate change in the numbers at risk of hunger of 40-300 million (Rosenzweig et al, 1993). Subsequent papers give a similar range (e.g. Rosenzweig and Parry, 1994). Calculating the health impacts of such a change is fraught with difficulty. It is assumed here that the main impact is an increased mortality rate, but the category of "at risk of hunger" does not easily convert to a mortality risk, especially where evaluations are far into the future. Vulnerability to food shortage, or lack of food security can be analysed at a series of levels - national, household, individual. A variety of different indicators may be used leading to very different conclusions and most analyses use rather aggregated data which cannot capture the social and cultural dimensions of the problem.

As a first indication of the potential scale of the impact, we use the current variation in life expectancy between countries with high and low numbers at from food insecurity. In countries identified as having "very low" food security (Downing, 1992), life expectancy is 50±5 years (United Nations, 1996). In a set of countries with similar (very low) per capita incomes, but better food security, similar calculations reveal a life expectancy of 56±5 years. The equivalent figures for mortality rate with a stable population are 0.02 and 0.018. Whilst this is not a carefully controlled analysis, and the uncertainty is high, it indicates that mortality rates may depend significantly on national food security status. It is reasonable to assume that much of the difference will be in the parts of the population at risk of hunger. Elevated mortality rates in this section of the population may therefore be of the order of 0.01.

It cannot be concluded that nutritional effects alone increase mortality rates by this amount. The definition of food insecurity itself uses health data, and clearly food insecurity may be exacerbated by inequality, social instability and conflict, all of which may affect mortality rate by means other than nutrition. However, from the combination of *a priori* considerations and the data on life expectancy, it seems probable that risk of hunger contributes to raised mortality rates. If it is assumed that 10-100% of the change noted above is directly nutritionally related, then the elevated mortality rate in the population placed at risk of hunger by climate change is 0.001 to 0.010.

Applying this change to the increased number of people at risk of hunger at benchmark climate change estimated by Rosenzweig et al (1993), the increased annual mortality due to climate change impacts on food insecurity is given by:

$$\text{Increased annual deaths} \quad = (40 \text{ to } 300) \times 10^6 \times (0.001 \text{ to } 0.010)$$
$$= 0.04 \text{ to } 3 \text{ million per year.}$$

It seems likely that a significant proportion of these cases will be children who would otherwise live to adulthood. The YOLL per death will therefore be rather high, and therefore there is no reason to apply a valuation different from the normal ExternE valuation of changed mortality rate (i.e. twice the VOSL). In an equity weighed analysis, it is appropriate to use the standard ExternE value (2.6 MECU at 1990 prices) weighted from current European to future (say 2050) global average per capita income, which yields a value of approximately 1.7

MECU. The resulting damages are therefore in the range 140 to 10,000 billion ECU per year. Even the bottom end of this range is a large damage. The upper end is more than an order of magnitude larger than the sum of damages in most studies reported by IPCC Working Group III.

Two comments on this large damage value are appropriate. First, it is based on the estimate of increased risk of hunger provided by Rosenzweig et al (1993), not the agricultural impacts consistent with ExternE analyses. The socio-economic assumptions underpinning these calculations are within the Basic Linked System world food trade model used by Rosenzweig et al. It is not clear how sensitive the results are to different socio-economic assumptions. Secondly, the monetary valuation is based on an equity adjusted aggregation of welfare. It might be argued that to use such an aggregate welfare function implies a value judgement which is incompatible with a world in which large numbers of people are allowed to suffer from food insecurity even though there is no aggregate food shortage. This is undoubtedly a reasonable criticism. The alternative approach would be to use simple aggregation of money values with no equity correction. This might be more consistent with the existing social order in which it is an observed fact that there are people at risk of hunger in a world with adequate food. However, such an approach is inconsistent with the usual assumption of declining marginal utility of income, with most ethical approaches and, arguably, with the equity commitments of the Framework Convention on Climate Change. It is clear that neither approach is ethically neutral, and for that reason we use the normal assumption of declining marginal utility of income, but investigate the sensitivity to simple money value aggregation.

6. Conclusions

The best estimates of benchmark climate change health damages are shown in Table 4.

Table 4

Benchmark Climate Change Health Damage Estimates

Damage Category	Damages at 2xCO_2		Uncertainty (geometric standard deviation)
	$ billion	% GDP	
Heat stress	50	0.02	5
Cold stress	-50	-0.02	5
Tropical diseases	300	0.13	5
Air pollution	100	0.05	10
Higher order impacts	140 - 10,000	0.1 - 4.5	>10

It can be seen that earlier studies which concentrate on the impacts of heat stress are a very incomplete picture. The cold stress benefits are probably of the same order. Tropical diseases are estimated to have larger damages. The reasons for this difference with earlier studies are the use of life years valuation (with rather low estimates of YOLL for the direct temperature effects) and the use of equity corrected welfare aggregation.

Health damages of air pollution (increased ozone impacts) are also potentially significant, although very uncertain because of the difficulties in modelling ozone concentrations. The higher order damages resulting from public health effects of food and water shortages are potentially the most important, but also the most uncertain. The top end of the range presented is calculated from very uncertain estimates of an increase in 300 million in the population at risk of hunger, suffering an increase in annual mortality rate of 0.01. It corresponds to about 5% of global GDP at benchmark warming.

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Appendix 8

Ecosystems and Biodiversity

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1. Introduction

The IPCC Second Assessment Report, WG III describes the state of the art concerning monetary valuation of biodiversity impacts of climate change as follows: "Perhaps the category in which losses from climate change could be among the largest, yet where past research has been the most limited, is that of ecosystem impacts. Uncertainties arise both because of the unknown character of ecosystem impacts, and because of the difficulty of assessing these impacts from a socioeconomic point of view and translating them into welfare costs. Existing figures are all rather speculative. There is a serious need for conceptual and quantitative work in this area" (Pearce et al, 1996, p.200). Against this background, this paper:

- reviews some general new work concerning indicators of biodiversity and ecosystem health (referring to the need of conceptual work),
- reviews specific new work concerning ecosystem impacts of climate change,
- makes some suggestions for the handling of biodiversity within the global warming sub-task of ExternE, phase III and
- tries to draw attention to some specific further research needs for both conceptual and empirical work.

In a first step, candidates for general indicators of biodiversity and ecosystem impacts will be analysed (section 2). Furthermore, specific biodiversity and ecosystem impacts of climate change are described (section 3). Two further sections deal with monetary valuation (section 4 mainly with values for single species, section 5 with a new study estimating values for whole ecosystem functions). Finally, some conclusions will be drawn.

2. Biodiversity and Ecosystem Indicators

In the international discussion about environmental indicators, the Pressure-State-Response approach of the OECD is commonly used as a reference framework (OECD 1994, Rennings/Wiggering 1996, p. 30). According to the OECD framework, indicators have to be subsumed under one of the following categories:

- Pressure: Pressure indicators try to answer the questions about the cause of problems. Biodiversity indicators in this category include e.g. stressors like land use for transport and intensive agriculture.
- State: State indicators answer questions about the state of the environment. Biodiversity indicators in this category include e.g. lost and endangered species.
- Response: Response indicators try to answer questions about what is done to solve the problem. Biodiversity indicators in this category include e.g. the size and number of protected areas.

Table 1: Indicators of Biodiversity and Habitat Protection

Candidates for indicators	Relevance for Biodiversity/ Ecosystems	Availability of Data
Pressure		
Land use changes of natural areas	not so important	very poor
areas of intensive agriculture	very important	good
area used for traffic and settlements	important	good
Development of areas used for agriculture and forestry	not so important	good
cutting off effects caused by traffic routes	important	good
length of traffic routes	not so important	good
cutting off effects by pipelines, electricity etc.	not so important	poor
tourism in protected or natural areas	not so important	moderate
State		
threatened or extinct species as a share of total species known	very important	good
threatened habitats	important	good
Development of population of inidicative („key") species	important	moderate
Development of geograhical information systems concerning habitats	important	poor
Potential natural vegetation	not so important	good
Change of landscape structure (CORINE data)	important	poor
Response		
Protected areas as a share of total area (IUCN classification)	important	moderate
Protected areas (National parks, country specific classifications)	very important	very good
Protected areas (National parks, country specific classifications) as a share of total area	very important	very good
Size of protected areas	important	moderate
share of protected areas for specific types of habitats	important	poor
Policy measures for extensive agriculture	very important	moderate
Linkage of single habitats	very important	poor
charges, fees for conservation	not so important	moderate

Source: Walz et al. (1996), p. 122

Obviously, the damage pathway approach of ExternE and the corresponding monetary valuation needs state indicators as a basic information. But, as Table 1 shows, data is only available for two important state indicators:

- threatened or extinct species as a share of total species known,
- threatened habitats.

Furthermore, it is important to mention for a damage pathway approach like ExternE that causal relationships between pressure and response indicators of biodiversity can not be quantified on the basis of present knowledge. This is the case not only for the pressure of global warming, but also for stressors like e.g. agriculture and traffic.

Furthermore, in the discussion of biodiversity indicators, a tendency can be observed towards geographical information systems (GIS) (Hammond et al. 1995, Billharz/Moldan 1995). Numbers of lost and endangered may be useful as a starting point, but GIS have some advantages. Habitat areas are easier to monitor than species, and governments normally have responsibility for certain landscape units rather than species. Thus, GIS help to derive risk indicators for certain habitats or regions. The kind of information delivered by GIS is e.g. that a certain coastal ecosystem is at high or medium risk. Such spatial indicators can then be used to set priorities for the protection of marine areas.

From the perspective of monetary valuation, it is important to mention that such kind of information does no give the data which is needed for estimating damages. Risk indicators do not inform us, at least not quantitatively, about the probability and the extent of a certain negative ecosystem impact. Information about specific damages, however, are a prerequisite for accounting damage costs.

More generally, even the consensus about the importance of biodiversity for ecosystem health is weak, if it exists at all. The relation between diversity and stability is still uncertain (Hauepler 1993, p. 99). While some stabil ecosystems can be characterised by a high diversity of species (rain forests, coral reefs), other ecosystems remain intact with a low diversity (arctic) or depend on human interventions (agriculture, forests). The majority of ecologists has come to the conclusion that ecological stability can not only be explained by diversity (Haber, 1993, p. 271). However, more evidence seems to exist for a link between diversity and resilience (Pearce, Hamilton and Atkinson, 1996).

A last example for illustrating problems with biodiversity data comes from the German federal state Baden-Württemberg who has commissioned a study for deriving a regional set of indicators for sustainable development. In the summary of this study, the current development path for all driving forces is visualised by red, green or yellow traffic lights. Only for biodiversity, the authors did not use coloured lights but three question marks to make the existing ignorance visible (Akademie für Technikfolgenabschätzung in Baden-Württemberg, 1997). This may illustrate the data situation even for a region which has established one of the most elaborated environmental information systems in Europe.

3. Biodiversity and Ecosystem Impacts of Climate Change

The effect of climate change on biodiversity and ecosystem health is still poorly understood. Significant losses of species due to climate change are expected, and experts judge them as the possibly most important impact of climate change (Kirschbaum, Fischlin et al., 1996, p. 113).

However, while only few quantitative data is available about state indicators of biodiversity, causal relations to pressures like climate change are only described qualitatively in the literature. For example, global warming impacts on biodiversity for specific types of ecosystems are described extensively in the 1995 report of IPCC Working Group II, but mainly in a qualitative way. Generally it is stated that climate change may have an effect on biodiversity of soil microbial and faunal population by changing the soil moisture and the temperature, but that it is impossible to predict the effects. Higher CO_2-concenration may change the composition of organic carbon compounds by getting into soil through roots and root exudates. However, it is stated that ecosystem impacts caused by climage change seem to be much smaller than impacts caused by land use changes (Kirschbaum et al., 1996, p. 66).

According to IPCC WG II, biodiversity impacts for specific types of ecosystems are:

- Forests

With regard to biodiversity, forests are the most important ecosystem type and highly sensitive to climate change. They harbour about tow-thirds of all species on earth, tropical forests alone at least half of all species. It is mentioned that, as a consequence of a 10 percent reduction of the size of forest areas, about 50 % of species become extinct. Based on that relationship, the IPCC WG II report mentions a study estimating that a temperature rise of 2 C° would lead to a loss of 10 - 50 % of the species in the boreal great Basin mountain (Kirschbaum, Fischlin et al., 1996, p. 112). However, the IPCC report does not recommend to use this number. Other impacts are only described qualitatively.

- Rangeland

Climatic warming may cause tundra to become a net source of carbon dioxide. Temperature increases in the tundra will reduce species richness (Allen Diaz et al., 1996, p. 133).

- Deserts

Conditions in deserts may even improve because of rainfall changes, but these effects are poorly uunderstood (Noble, Gitay et al. 1996, p. 161).

- Oceans

The effects on biodiversity are likely to be much less severe in the oceans than in estuaries and wetlands. Most migratory organisms are expected to be able to tolerate a rise in temperature. However, some sedentary species like corals will be affected, but it is expected that other environmental stresses like pollution are more important factors for their degradation (Ittekkot et al., 1996, p. 278).

- Mountain regions

The IPCC WG II states that climate change may exacerbate fragmentation and reduce key habitats. Especially mountaintop-endemic species are endangered by additional climate stress (Beniston, Fox, 1996, p. 193).

- Coastal zones and small islands

Climate change has the potential to affect coastal biodiversity. It may lead to a change in population sizes and distribution of species, alter the species composition and geograghical extent of habitats and ecosystems, and increase the rate of species extinction (Bijlsma et al., 1996, p. 289., S. 304).

4. Monetary Valuation of Biodiversity and Ecosystem Impacts

Even if better biodiversity indicators would be available, the indicators need an assessment in a further valuation process. As the German Council of Environmental Advisors (SRU) remarks, ecological risk indicators can not tell us which risk we should take. "Ecology can only describe conditions, processes and interrelations, but ecology itself does not offer measures for the question whose perspective should be preferred in the valuation of the system. Even key words like equilibrium, stability or biodiversity are not per se basic ecological values" (SRU 1994, p. 70). Additional social judgements are necessary to derive values and targets. As far as values are tangible, economists try to measure them in monetary units.

With regard to biodiversity, an extensive empirical literature already exist. Many contingent valuation surveys have been brought up asking people for their willingness to pay for the protection of endangered species (see for a survey Loomis/White, 1996; Pearce/Moran, 1994; Perrings et al., 1996). In most cases, values have been derived for single species and for the recreational use of certain areas. Additionally, some estimates are available for the value of plant species for medicinal purposes (Pearce et al., 1996, p. 200).

Monetary estimates of species losses due to global warming have been made by Cline, Fankhauser and Tol (an overview is given in Fankhauser/Tol 1995, p. 5). Due to the data problems described above, all authors have used ad hoc assumptions about the impact of climate change on biodiversity.

5. Biodiversity, Ecosystem Impacts and Ecosystem Services

In a recent study Costanza et al. (1997) have estimated the current economic value of 17 services of the world's ecosystem to be US $ 33 trillion per year, which is nearly two times as high as the global gross national product (around US $ 18 trillion per year).

About 50 percent of the total value of global ecosystems are calculated for nutrient cycling as one of the main life support functions of ecosystems. This indicates that the work of the Costanza group can not be subsumed under the category biodiversity but values all ecosystem services. In the approach of the ExternE project and the corresponding sub-task on global warming, the function of ecosystems as food suppliers belongs to categories like health and higher order effects (higher order effects are, as explained in section 3.4 of the final report, not quantified in the FUND and Open Framework model).

Due to different approaches, the work of ExternE and the Costanza group is not directly comparable. However, in the Costanza study, climate regulation has been explicitly one of the ecosystem services being investigated. Climate regulation is defined as regulation of the global temperature, precipitation, and other biologically mediated climatic processes at local or global levels. If these functions are disturbed, damages may occur in several areas, e.g. the main impact areas identified in the ExternE Global warming sub task (health, agriculture, water supply, sea level rise, ecosystems and biodiversity, extreme events). This again shows that the Costanza approach values the total sum of *all ecosystem services which can be expressed as market or non-market benefits* of climate regulation, and does not focus especially on the benefits of biodiversity and ecosystem protection. The values used by the Costanza group are mainly taken from the literature, i.e. they *do not create new information about biodiversity and ecosystem impacts of climate change*.

Thus, again, the results can not easily be compared with the ExternE results. While ExternE measures marginal values, the Costanza study focuses on the total value of ecosystems. It is easy to imagine that the total value of all natural capital exceeds the gross global national product (in this case, one has to think about the damages due to a total loss of all ecosystem services), while marginal impacts of power plants contribute only a fraction to these damages.

6. How to Handle Biodiversity in the ExternE Global Warming sub task?

Within the ExternE project, no monetary values have been quantified up to now for impacts on water, forests or ecosystems. For acidification and eutrophication, at least physical indicators have been estimated within the sub task sustainability indicators of ExternE phase III (Mayerhofer 1997). However, such risk indicators can not be transferred directly into damage costs. They indicate a certain level of risk, not damages, and neither probabilities nor scenarios for certain damage paths are given. Compared with climate change, it is at least possible to quantify these risks in physical units. For climate change, a comparable methodology measuring ecosystem risks does not exist up to now. It may be useful if future studies would apply approaches to biodiversity which are similar to the methodology that has been tested for eutrophication, acidification, radioactivity and freshwater resources in the sustainability indicators sub-task of ExternE (Atkinson et al., 1997).

It has been shown in section 1.3 of this paper that the description of ecosystem impacts of climate change is largely qualitative and, as far as quantitative estimates have been made, they seem not reliable. Against this background, no physical threshold or monetary indicator can be recommended for the monetary valuation within the current phase of ExternE.

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