Environmental and Resource Economics **21:** 47–73, 2002.

Estimates of the Damage Costs of Climate Change

Part 1: Benchmark Estimates

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Accepted 21 May 2001

Abstract. A selection of the potential impacts of climate change – on agriculture, forestry, unmanaged ecosystems, sea level rise, human mortality, energy consumption, and water resources – are estimated and valued in monetary terms. Estimates are derived from globally comprehensive, internally consistent studies using GCM based scenarios. An underestimate of the uncertainty is given. New impact studies can be included following the meta-analytical methods described here. A 1 °C increase in the global mean surface air temperature would have, on balance, a positive effect on the OECD, China, and the Middle East, and a negative effect on other countries. Confidence intervals of regionally aggregated impacts, however, include both positive and negative impacts for all regions. Global estimates depend on the aggregation rule. Using a simple sum, world impact of a 1 °C warming would be a positive 2% of GDP, with a standard deviation of 1%. Using globally averaged values, world impact would be a negative 3% (standard deviation: 1%). Using equity weighting, world impact would amount to 0% (standard deviation: 1%).

Key words: adaptation, climate change, impacts

JEL classification: Q00, Q25, Q40

1. Introduction

Insight into the impact of climate change is crucially important for deciding on a proper course for greenhouse gas emission reduction policies. However, establishing a comprehensive estimate of the impact of climate on human welfare is exceedingly difficult. This paper contributes by deriving a new set of estimates and by two methodological improvements, regarding method and uncertainty.

Aggregate, monetary impact estimates of climate change are necessary if one wants to engage in a cost-benefit analysis of greenhouse gas emission reduction policy. To date, monetary impact estimates have played a very limited role in policy debates. The rhetoric of climate policy strives for stringent emission reduction targets, while a cost-benefit analysis would suggest more cautious emssion abatement. Although not very prominent in policy advice, monetary impact estimates have been good predictors of real policy (cf. Nordhaus and Yang 1996; Tol 1999).

Previous papers that estimate impacts share a common deficiency: The methods and assumptions behind the numbers are not always clear. The chapter on the social costs of climate change in the Second Assessment Report of Working Group III of the Intergovernmental Panel on Climate Change (Pearce et al., 19996) aroused a storm of protest (Masood and Ochert 1995; Meyer 1995; F. Pearce 1995; cf. D. Pearce 1995; Tol 1997a). Many critical points were raised, ranging from fundamental objections to economic valuation to technical issues about exchange rates, benefit transfers and adaptation. These issues are discussed in Fankhauser and Tol (1996, 1997), Frankhauser et al. (1997, 1998a, b), Tol and Fankhauser (1998) and Tol et al. (1996, 1998).

One critique remains: The climate change damage estimates as presented by Pearce et al. (1996) are to a large extent based on older, perhaps outdated climate and climate impact studies. Although the social cost chapter qualifies the estimates, the estimates were not adjusted. An important reason is that Cline (1992), Fankhauser (1994a, b, 1995), Nordhaus (1991, 1994a, b), Titus (1992), and Tol (1995) do not detail the myriad assumptions needed to derive their comprehensive estimates from the underlying impact literature. A new climate scenario, or new impact estimates, say, for winter wheat, therefore cannot be taken up other than by an elaborate re-analysis by the original author. This pre-methodological state of affairs leaves much to be desired. This paper pays equal attention to numbers and methods. The paper presents a new set of damage estimates for climate change, but also discusses how these estimates are arrived at, by what assumptions gaps in knowledge are filled, and how new studies would affect the assessment. By spelling out the way in which impacts are estimated, the door is opened to a methodological discussion, to improve the obviously deficient methods used here.

The book by Mendelsohn and Neurmann (1998) pays as much attention to methodology as it does not results. It is restricted, however, to market impacts to the USA. This paper looks at market as well as non-market impacts, and covers the whole world.

Besides the impact, its uncertainty is also estimated. The uncertainty about the impact of climate change is known to be large, because:

- climate change itself is rather uncertain in its magnitude and regional patterns,
- research on the impact of climate change needs substantial improvement, and
- the bulk of climate change will occur in a distant future.

So, the uncertainty is large, but no one knows how large (c.f Hammitt 1995; Harvey 1996; Nordhaus 1994b; Morgan and Keith 1995; Pate-Cornell 1996; Schimmelpfennig 1996; Titus and Narayanan 1996; Tol 1995). Pearce et al. (1996) estimate the annual impact of a $2\times CO_2$ climate on the present economy to amount to 1.5–2.0% of world income, but this range is a range of best estimates, not a confidence interval. This paper estimates uncertainty based on a mix of expert judgement and variation between scenarios and impact studies. Omitted impacts are ignored, and models, methods and scenarios are assumed to be free of error and uncertainty, so the estimated uncertainties are lower bounds of the ‘true’ uncertainty.

The paper follows this route. After some more introductory observation in Section 2, Section 3 reviews climate change impact estimates for the following categories: agriculture, forestry, sea level rise, and human health. In each case, climate scenarios derive from General Circulation Models (GCMs). The most comprehensive studies available are used. Each subsection ends with an indication how new results should be incorporated. Section 4 concludes by comparing the results obtained in this paper to the literature.

Part 2 introduces dynamic estimates of the impact of climate change, expressing impact as a function of climate and socio-economic variables.

2. Some Notes on Methodology

Estimates of the impact of climate change are derived from the literature (cf. Watson et al. 1996, for an overview). This literature is to a large extent outside the economic discipline. It is therefore hard to access and appreciate the difficulties. In this paper, only sources are selected that are globally comprehensive, so that the issue of consistency, say, between sea level impact in Europe and Japan, is left to the specialist. Impact categories where such sources are unavailable are not included. As an additional selection criterion, only sources are used that are based on climate scenarios from GCMs. This study is the first to use such strict selection criteria.[1] Fortunately, impact research has progressed far enough that coverage in this study is comparable to that in earlier ones (cf. Pearce et al. 1996). The impact estimates of this study include the effects of climate change on agriculture, foresty, sea level, human health, natural ecosystems, water resources, and energy consumption.

Although underlying climate scenarios derive from GCMs, impact is tied to changes in the global mean temperature, ignoring regional changes and other climate variables. The reason is that the documentation of the underlying impact studies is often not detailed enough to link regional impacts with regional climate change, while the number of reported scenarios is often too limited to separate the effects of, say, temperature and precipitation.

Climate change will occur in the future, and its most pronounced effects may well be beyond 2050. The context in which climate change will impact is highly uncertain, but very important. For example, river floods are influenced by precipitation and hence by climate change; at least as important, however, is the state of the river bed and catchment, which depends on land use and flood protection. A second example is hurricane damage. In developed countries, life losses are low, and capital losses high. In developing countries, it is the other way around. The future balance cannot readily be assessed (cf. Tol 1996, for a more detailed discussion). Another example is food security, treated below.

Instead, the impact climate change would have on the present situation is investigated. Although counterfactual, this approach has the advantage that only one parameter (climate) is varied, so that findings can readily be interpreted. The results are indications of potential pressure points and relative vulnerabilities. The results are not useful as predictors or as input to decision analysis.

The influence of changes in vulnerability to climate change is mitigated as the analysis below looks at an increase in the global mean temperature of 1 °C,[2] a relatively modest climate change expected to occur in the first half of the next century. Tol (2002) discusses impact as a function of both climate change and vulnerability.

The outcomes of a static analysis such as this are hard to interpret. In a number of cases, the study draws on comparative static analyses. In such cases, the impact of climate change equals the difference between two, often partial equilibria. In other cases, the study draws on annual, or annuitised results of dynamic analyses. The two are comparable if a new equilibrium is reached fast (relative to the speed of climate change). Although the estimates are a mixed bag, the results are best interpreted as the annual impacts of climate change, rather than as the equilibrium impacts of a changed climate.

An important drawback of any aggregate estimate is that it hides the distribution of impacts. The estimates in this paper are no exception.

A further problem is associated with more serious impact such as famine and political instability. Famine results from want of food or access to food (e.g., Sen 1981). There is skill in modelling crop yield and food trade (see below) and hence food availability. Parry and Rosenzweig (1994) used food availability to estimate changes in hunger vulnerability due to climate change. Food entitlements, on the other hand, depend on social structures, which are hardly generalisable, let alone modelable. Political instabilities, perhaps triggered by a redistribution of crucial matters such as water and food or by streams of migrants and refugees (Myers 1993; Myers and Kent 1995), depend on socio-political structures. Environmental hardship may be a root cause or a trigger for instability and (armed) conflict, but it is always confounded in a web of other causes and triggers (Homer-Dixon 1991, 1994; Homer-Dixon et al. 1993). Hence, such issues are excluded from this assessment.

Interactions between impacts of climate change are ignored. This reflects the underlying literature. Interactions may be important, for instance, via land use (sea level rise, agriculture, forestry). Integrated assessment models that focus on such interactions, however, are weak in economic analysis (Tol and Fankhauser 1998; Weyant et al. 1996).

Impacts are estimated for 9 regions, viz. OECD-America (excl. Mexico) (OECD-A), OECD-Europe (OECD-E), OECD-Pacific (excl. South Korea) (OECD-P), Central and Eastern Europe and the former Soviet Union (CEE&fSU), Middle East (ME), Latin America (LA), South and Southeast Asia (S&SEA), Centrally Planned Asia (CPA), and Africa (AFR). These regions correspond to the region of *FUND*, an integrated assessment model of climate change (Tol 1997b). The basic data for the regions are taken from the 1995 version of the *World Resources Database* of the World Resources Institute.

Table I. Original estimates of the impact of climate change on agriculture (2.5 °C increase in the global mean temperature, per cent of gross agricultural products).

Study	Kane	Tsigas		Darwin	Reilly			Fisher		
550 CO$_2$?	No	No	Yes	No	No	Yes	Yes	No	Yes	Yes
Adaptation?	No	No	No	Yes	No	No	Yes	No	No	Yes
OECD-A	0.03	−0.31	0.05	0.10	0.03	0.00	0.00	−8.83	−2.38	−0.58
OECD-E	−0.52	−0.73	0.14	−0.41	−0.34	−0.06	−0.02	−7.10	0.55	2.60
OECD-P	−2.08	−1.38	−0.06	0.31	−0.31	−0.04	−0.01	−3.24	−0.28	0.49
CEE & fSU	−0.02	−1.48	−0.07	0.14	−0.18	−0.25	−0.18	−6.84	1.65	3.32
ME	−0.01	−1.48	−0.07	0.14	−0.18	−0.25	−0.18	−9.09	−2.97	−1.93
LA	0.05	−2.18	−0.47	0.10	−0.22	−0.15	−0.16	−13.13	−4.33	−3.08
S&SEA	−0.08	−2.26	−0.32	−0.04	−0.91	−0.17	−0.13	−12.04	−4.00	−2.76
CPA	3.84	−3.97	0.28	0.11	−10.09	0.04	0.53	−1.20	0.82	1.07
AFR	−0.01	−1.48	−0.07	0.14	−1.18	−0.25	−0.18	−5.31	−1.71	−1.11

Sources: After Kane et al. (1992), Tsigas et al. (1996), Darwin et al. (1995), Reilly et al. (1995) and Fisher et al. (1993).

3. A New Set of Damage Estimates

3.1. AGRICULTURE

There are many studies on the impact of climate change on agriculture. See Reilly et al., (1996) for an overview. Most studies are restricted to specific crops or regions. Only five studies look at the impact of climate change on worldwide agriculture, including domestic markets and international trade: Kane et al. (1992), Reilly et al. (1994), Fisher et al. (1993, 1996; see also Rosenzweig et al. 1993; Rosenzweig and Parry 1994), Darwin et al. (1995, 1996) and Tsigas et al. (1996). These five form the basis of the current assessment. See Schimmelpfennig et al. (1996) for a detailed comparison.

The original results had to be manipulated in various ways. The regions of the original studies do not correspond to the regions used here. The original regions are assumed to be homogenous, that is, losses or gains, expressed as a fraction of total agricultural output, are assumed to be the same for all countries in the region. Based on this assumption, the impact on agricultural GDP is derived for each country. Next, the country impacts are aggregated to the regions used here.

Additional work was needed for the study of Fisher et al. (1993). Published national estimates are only available in graphical format. In tabular format, only cross-sections of regional results have been published. Unreported, regional results are filled in by extrapolation. Regional results are translated to national ones as described above. See Table I.

Results for different GCMs are scaled to a common global mean temperature change (2.5 °C), that is, all outcomes are multiplied by the climate sensitivity of the GCM used divided by 2.5.[3] Results are averaged over GCMs. The standard deviations are calculated. The Kane et al. (1992) and Tsigas et al. (1996) studies use one GCM only. Their standard deviations are set such that coefficient of variation equals the average coefficient of variation of the other studies.

Four cases are distinguished: whether or not CO_2-enrichment of the atmosphere (at 550 ppm) is considered, and whether or not farmers adapt to the changed circumstances. The average of various adaptation scenarios is taken. None of the five studies considers all four cases. This is unfortunate. The Darwin et al. (1995) study, for instance, is probably most realistic on long-term adaptation but does not include CO_2-fertilization. Therefore, the original estimates are adjusted. The average difference in outcomes resulting from CO_2-fertilization for those studies that do consider this is added to the outcomes of those studies that do not. A similar procedure is used for adaptation.

The five studies are averaged, and the standard deviation is calculated. Table II presents the outcomes. All cases include CO_2-fertilization so that the impacts are only indexed on the global mean temperature. The average of the studies including (or adjusted for) adaptation is taken as the best guess estimate of the impacts of climate change on the long run, that is, the difference in opportunity costs of the future compared to the present. Note that the best guess is an increase in agricultural potential for all regions. Table II also gives the average of the studies without adaptation (or adjusted). The difference between the impact without and the impact with adaptation is taken as the transition cost of climate change, that is, the losses of not being adapted to the changed situation. Note that the transition is estimated to be costly for all regions.

Earlier studies, as reflected in Pearce et al. (1996), all foresee negative impacts for agriculture from climate change. These studies are based on older, partly outdated studies on changes in crop yields due to the enhanced greenhouse effect, often assuming limited capacities of farmers to adapt to changing circumstances. See Reilly et al. (1996) for an overview of the literature.

New comprehensive estimates of the impact of climate change on agriculture could be incorporated by following the protocol described above. Estimates should be scaled to a 2.5 °C temperature increase, and, by assuming intraregional homogeneity, mapped to the same regions. Estimates should then be adjusted for adaptation and CO_2-fertilization (or the adjustment for these factors should be amended with the new evidence), and included in the average. New evidence on the details of agricultural impacts, or alternative climate scenarios should first be run through comprehensive models of domestic and international markets.

3.2. FORESTRY

Knowledge on the impact of climate change on commercial forestry lags slightly behind agriculture. To date, only one study (Perez-Garcia et al. 1996) included the effect of international trade, coupling a detailed model of forest growth (TEM) with a detailed model of the timber market (CINTRAFOR). This study is therefore

Table II. Estimates of the impact of climate change on agriculture, as percentage of Gross Agricultural Product, for a 2.5 °C increase in the global mean temperature.

	Without adaptation		With adaptation	
	Best guess	Standard deviation	Best guess	Standard deviation
OECD-A	−0.25	1.30	0.99	1.33
OECD-E	0.55	1.03	2.09	1.12
OECD-P	−0.15	1.61	0.80	1.62
CEE&fSU	0.94	1.19	2.65	1.13
ME	−0.44	0.41	0.58	0.48
LA	−0.76	0.60	0.55	0.70
S&SEA	−0.66	0.28	0.63	0.33
CAP	1.73	0.98	3.10	1.01
AFR	−0.23	0.23	0.47	0.28

Source: Own calculations, based on Table I.

the basis for the assessment here. Sohngen and Mendelsohn (1996) perhaps better represent economic dynamics and adaptation than do Perez-Garcia et al. (1996), but the former modelling is limited to the United States.[4] Perez-Garcia et al. (1996) report the impact of climate change, according to four GCM-scenarios and two management scenarios, on consumer and producers surpluses by the year 2040 for 43 producer regions and 33 consumer regions. The outcomes – scaled by the global mean temperature of the GCMs used – are averaged, and added to an estimate of the social welfare change in the 9 regions used here.

Perez-Garcia et al. (1996) report results from a transient scenario. Here, climate change impacts on the 1990 economy are estimated. Additional assumptions are therefore needed. The share of the forestry-sector in the economy is assumed not to change between 1990 and 2040. The assumed economic scenario is IS92a. These assumptions are approximations since the present author does not have hold of all the inputs and outputs of the model. Table III presents the results.

Earlier studies, as reflected in Pearce et al. (1996), all foresee negative impacts of climate change on forestry. These estimates are based on older forestry studies, which are outdated by the outcomes of more recent studies using more comprehensive models. See also kirschbaum et al. (1996) and Solomon et al. (1996).

Inclusion of new results on forestry should follow the same procedure as for agricutlure.

3.3. SPECIES, ECOSYSTEMS AND LANDSCAPES

Climate change is expected to impact heavily on species, ecosystems and landscapes. Yet, this aspect has been paid relatively little attention to by economists,

Table III. Estimates of impact of climate change and CO_2 fertilization on forestry and natural ecosystems for a 1 °C increase in the global mean temperature, millions of US dollars).

	Forestry	Ecosystems
OECD-A	218 (24)	−17.4 (17.4)
OECD-E	134 (16)	−14.7 (14.7)
OECD-P	93 (20)	−11.5 (11.5)
CEE&fSU	−136 (17)	−5.4 (5.4)
ME	0 (0)	−0.3 (0.3)
LA	−10 (2)	−0.5 (0.5)
S&SEA	140 (34)	−0.1 (0.1)
CPA	0 (0)	−0.1 (0.1)
AFR	0 (0)	−0.1 (0.1)

Source: Own calculations, after Perez-Garcia et al. (1996), Fankhauser (1995) and Manne et al. (1995).

primarily so because the physical impact is still to a large extent unknown (Watson et al. 1996), but also because the value of an ecosystem or a species cannot be easily estimated (Bjornstad and Kahn 1996; Braden and Kolstad 1991; Freeman 1993; Hausman 1993; Mitchell and Carson 1989; Pearce and Moran 1994). Climate economists thereore face a double problem, i.e., how to derive a value of something which is unknown in quantity and price. Nevertheless, some crude estimates have been made, based on scattered *ad hoc* information on ecosystem change, medicinal value of plants, current wildlife protection expenditures, and surveys. Fankhauser (1995) proposes to use a negative impact of $30 per person per year in the OECD, $8 per person in the middle income countries, and $2 per person in the low income countries. These figures capture use, option and existence values. Pearce (1993) arrives at a value of $9–$107 per person per habitat in the OECD, with an average of $50. The Fankhauser (1995) value of $30 is in the lower part of this range. One habitat lost per year is a conservative assumption as well.

The impact of climate change on species, ecosystems and landscapes is here assessed based on the following four assumptions:

- Climate change is unambiguously perceived as bad. Although impacts vary between species, systems, places and time, this assumption reflects that people tend to be conservative (i.e., any change is bad) and that negative impacts tend to attract more attention than positive ones.
- The actual change does not matter, the fact that something has changed does. This reflects the “warm-glow”-effect in the literature (Andreoni 1988, 1989, 1990, 1993; Desvousges et al. 1993; Harrison 1992; Kahneman and Knetsch 1992a, b; Smith 1992; Margolis 1982; Nickerson 1992). Although contested, the warm-glow effect suggest that people’s willingness to pay reflects their

desire to contribute to a vaguely described "good cause", rather than to well-defined environmental good or service.[5] The impact of climate change on nature will be diffuse, hard to measure, and hard to distinguish from other changes. The value is set at an average of \$50 per person in the OECD (Pearce 1993).

- The figures of Pearce (1993) reflect a willingness to pay to preserve through direct action. it is assumed that the willingness to pay to preserve through indirect action (greenhouse gas emission abatement), and the willingness to accept compensation for a loss have the same \$50 value.
- Lastly, the OECD value for 1990 has to be transferred to other regions and other times.

Following Manne et al. (1995), relative values (i.e., in percentage of per capita income) are assumed proportional to

$$\left(\frac{\text{GDP/Capita}}{20,000}\right) / \left(1+\frac{\text{GDP/Capita}}{20,000}\right) \tag{1}$$

which is scaled to unity for the OECD in 1990. This assumes a positive income-elasticity of willingness to pay; see Kristrom and Riera (1996) and Flores and Carson (1997) for a critique. Table III displays the results. The losses are higher than Fankhauser's (1995) and Cline's (1992). For example, \$17 billion for OECD-America compared to Fankhauser's \$7 billion and Cline's \$4 billion. Fankhauser and Cline consider their estimates rather conservative.

New studies are readily taken up. Given the rather crude and sweeping assumptions made here, the estimates of this study should be replaced when better information is available.

3.4. SEA LEVEL RISE

The costs of sea level rise divide into three types: Capital costs of protective constructions, and the costs of foregone land services, conveniently split into dryland and wetland loss. The three damage categories strongly interact with one another. For example, if a piece of dryland is chosen to be fully protected, no dryland services will be forgone, but the costs of protection will be high, and the adjacent wetland may be inundated. The total impact of sea level rise, and its distribution over its categories, thus strongly depends on the adaptive policy chosen. Consequently, the estimated damage depends strongly on the projected policy. For instance, IPCC CZMS (1991) uses the *ad hoc* rule that all dryland with a population density above 10 people per square meter will 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 substantial.

Table IV presents novel estimates of the costs of dryland loss, wetland loss and coastal protection. The coast length of all countries in the world was taken from

Table IV. Impact of a one metre sea level rise.

	Coast length (10^3 km)	Level prot. (%)	Dryland loss (10^3 km^2)	Dryland value (10^6/km^2)	Wetland loss (10^3 km^2)	Wetland value 10^6/km^2	Protection costs (10^9\$)	Emigrants 10^6	Value 10^9\$	Immigrants 10^6	Value 10^9\$	Total costs 10^9\$/year
OECD-A	33	0.77	4.8 (2.4)	1.3 (0.6)	12.0 (8.6)	5.4 (2.7)	83 (74)	0.13 (0.07)	7.5 (5.3)	0.0 (0.20)	2.9 (2.1)	1.6 (0.9)
OECD-E	59	0.86	0.7 (0.4)	13.1 (6.6)	4.0 (2.3)	4.3 (2.2)	136 (45)	0.22 (0.10)	8.2 (5.4)	0.64 (0.32)	3.1 (2.2)	1.7 (0.5)
OECD-P	23	0.95	0.3 (0.4)	13.7 (6.7)	1.0 (1.1)	5.9 (2.9)	63 (38)	0.04 (0.02)	2.8 (2.0)	0.18 (0.10)	1.6 (1.2)	0.8 (0.4)
CEE&fSU	25	0.93	1.2 (2.7)	0.9 (0.5)	0.0 (0.0)	2.9 (1.5)	53 (50)	0.03 (0.03)	0.7 (0.7)	0.03 (0.03)	0.0 (0.0)	0.5 (0.5)
ME	6	0.30	0.6 (1.2)	0.5 (0.3)	0.0 (0.0)	1.3 (0.7)	5 (3)	0.05 (0.08)	0.4 (0.6)	0.04 (0.07)	0.0 (0.0)	0.0 (0.0)
LA	39	0.86	7.8 (7.1)	0.3 (0.2)	50.2 (36.4)	0.9 (0.5)	147 (74)	0.71 (1.27)	3.9 (7.2)	0.64 (1.14)	0.5 (0.9)	2.0 (0.9)
S&SEA	95	0.93	9.3 (9.6)	0.5 (0.3)	54.9 (48.0)	0.3 (0.2)	305 (158)	2.30 (1.40)	3.7 (2.9)	2.07 (1.26)	0.5 (0.4)	3.3 (1.6)
CPA	33	0.93	8.4 (15.1)	0.3 (0.2)	15.6 (17.1)	0.2 (0.1)	171 (126)	2.39 (3.06)	2.5 (3.4)	2.15 (2.75)	0.3 (0.4)	1.8 (1.3)
AFR	35	0.89	15.4 (18.4)	0.4 (0.2)	30.8 (14.8)	0.4 (0.2)	92 (35)	2.74 (2.85)	5.4 (6.3)	2.47 (2.56)	0.7 (0.8)	1.1 (0.4)

Source: Own calculations, after Bijlsma et al. (1996), Hoozemans et al. (1993) and Fankhauser (1994c).

the Global Vulnerability Assessment (Hoozemans et al. 1993), an update of work earlier done for the IPCC (IPCC CZMS 1990). Other sources, such as the proceedings of the 1993 World Coast Conference (Bijlsma et al. 1994), Nicholls and Leatherman (1995a, b) and Fankhauser (1995), use (occasionally widely) different estimates of the length of the coast of particular countries. However, the length of a coast depends on the measurement procedure. The GVA is based on an internally consistent, globally comprehensive data-set. Therefore, the GVA is used here.

Wetland losses for a 1 metre sea level rise were taken from the GVA and, where available, replaced with results from country studies as reported by Bijlsma et al. (1995) plus Nicholls and Leatherman (1995a, b). The reasons are:

- the GVA is a desk study which occasionally shows signs of the great haste of its preparation;
- the country studies use local data; and
- land lost because of sea level rise is more obviously estimated than coast length. Bijlsma et al. (1996), however, only report wetland losses in the absence of coastal protection.

The GVA reports wetland losses both with and without coastal protection; the country-specific ratio between the two was used to derive wetland losses with protection according to Bijlsma et al. (1996). The standard deviation of the wetland loss estimates is arbitrarily set at half their means for those countries with country study results, and at their means for other countries.

Dryland losses are not reported in the GVA, but they are by Bijlsma et al. (1996). The GVA reports people-at-risk, which is the number of people living in the one-in-1000-year flood plain, weighted by the chance of inundation. Combining this with GVA's coastal population densities, area-at-risk results. The exponential of the geometric mean of the ratio between area-at-risk and land loss for the 18 countries of the geometric mean of the ratio between area-at-risk and land loss for the 18 countries in Bijlsma et al. (1996) was used as a correction factor to derive land loss for all other countries. The standard deviation of the correction factor is based on the first-order Taylor expansion. The standard deviation of dryland loss reported in Bijlsma et al. (1996) is arbitrarily set at half its mean.

The OECD average of dryland value was set at 4 million US dollar per square kilometre. Regional values follow from correcting for GDP/km^2 (based on population density in the coastal zone, as reported by the GVA, and income per capita). Land values are roughly equal to those in *FARM* (Darwin et al. 1995; Darwin and Tol 1998), but higher than Fankhauser's (1994c). The OECD average of wetland value was set at 5 million \$/km^2, following Fankhauser (1994c). Regional values follow from scaling with (1). The costs of coastal protection follow from the GVA, again where possible replaced by country study results.

The level of protection is derived by Fankhauser (1994c):

$$L = \min\left\{0, 1\frac{1}{2}\left(\frac{PC + WL}{DL}\right)\right\} \tag{2}$$

L is the fraction of the coastline to be protected. *PC* is the net present value of the protection if the whole coast is protected. The GVA reports average costs per year over the next century; *PC* is calculated assuming annual costs to be constant. *WL* is the net present value of the wetlands lost due to full coastal protection. ıDL denotes the net present value of the dryland lost if no protection takes place. See Frnkhauser (1994c) for the derivation of (2). Because of the crude assumptions underlying (2), and the low quality of the database, optimal protection levels should be interpreted with great care for individual countries. Equation (2) is easily put into a dynamic framework. As projections of future sea level rise or future land values change, et present values can readily be recalculated.

Another effect associated with dryland loss is that the people who used to live on the washed land are forced to move elsewhere. 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), and people dislike being forced to move while immigrants are not always welcomed. Table IV displays the estimates. Emigration estimates follow from multiplying the projected loss of drylands with the average population density. The costs of emigration are set to an arbitrary three times the per capita income.

People migrate somewhere. Table IV also displays the immigration estimates. People from the OCED, Central and Eastern Europe and the former Soviet Union are assumed to remain in their regions. Ninety percent of the people from the other regions are assumed to stay there. The remaining ten percent from Africa and Latin America move to OCED-Europe and OECD-America, respectively. Migrants from the Middle East split equally between OCED-America and OECD-Europe. Four percent of the migrants from South and Southeast Asia and Centrally Planned Asia move to OECD-America, and three percent to OECD-Europe and OECD-Pacific. The costs of immigration are set to 40% of the per capita income in the host country (cf. Cline 1992; Fankhauser 1995). The destination of the migrants is arbitrary. Table IV shows, however, that the effect of the impact estimates is small.

Earlier studies are more pessimistic about the costs of sea level rise. For the USA, for instance, costs range from \$7 to \$12 billion a year, compared to \$2 billion, here. Fankhauser's (1995) estimate for the OECD amounts to \$25 billion (for a 50 cm sea level rise) compared to \$7 billion here (for a 100 cm rise). Fankhauser's estimate for the world as a whole of \$47 billion compares to \$13 billion here. This is largely the result of the optimal protection strategy used here as opposed to the arbitrary protection strategy used in earlier studies. Fankhauser finds that a 1 metre sea level rise would cost the OECD some \$9 billion per year if protection is optimized, compared to \$25 billion, his estimate for a non-optimized strategy for a 50 cm rise.

New results on the impact of sea level rise should be taken up in the following manner. National studies are preferred over global studies and their results should therefore replace the results of the GVA, unless consistency is endangered as, for instance, is the case with coast lengths. Multiple studies of comparable quality for a single country should be averaged. New editions of the GVA should replace the second edition used here; alternative GVAs should replace it when they are better, or be averaged if of similar quality.

3.5. HUMAN HEALTH

Climate change affects human health through six broad ways. Firstly, morbidity and mortality is influenced by temperature, both high and low. Secondly, the vectors of infectious diseases are affected by climate and weather. Thirdly, the proliferation of non-vector-borne infectious diseases is in part dependent on weather conditions. Fourthly, air quality affects health and is influenced by weather. Fifthly, floods and storms injure and kill people. Sixthly, human health may be influenced indirectly by climate change, for instance through agriculture or water resources (cf. McMicheal et al. 1996).

To date, only the size of the first two mechanisms has been quantified to some extent. The influence of climate change on heat and cold stress, and malaria, dengue and schistosomiasis are discussed below. Other effects are omitted from the analysis. The analysis is also restricted to human mortality, leaving morbidity to be included in later work. As a consequence, the presented estimates are biased. It is not possible, however, to determine even the sign of the bias. Many food-related infections are affected by temperature, having their annual peaks during summer, and are thus likely to worsen. The effect on water-related infections are at least as uncertain as the effects of the enhanced greenhouse effect on water resources. Rosenzweig and Parry (1994) report an estimate – 12 to +350 million of the additional number of people at risk from hunger due to climatic change. However, their underlying impact estimates for agricultural production are pessimistic compared to the literature, while their methodology is questionable (see above). Therefore, the sign of the bias is indeterminate and probably differs from place to place. The Rosenzweig and Parry estimate make clear, however, that the size of the bias may be substantial.

People suffer from both heat and cold. The lowest mortality rates are found at temperature levels of about 16 °C (Kunst et al. 1993a, b; Mackenbach et al. 1993; Haines and Fuchs 1991; Haines and Parry 1993). A range of diseases, notably cardiovascular and respiratory disorders, are influenced by temperature and thus by climate change. The elderly, very young and sick suffer disproportionally from such diseases. For example, 20–40% of the heat-related deaths would have occurred anyway within the next few weeks. Major determinants of vulnerability are the quality of housing, the availability of air conditioning, and the urban heat island effect (McMicheal et al. 1996).

A number of studies attempt to derive a relationship between climate change and heat and cold related mortality. Best known are the works of Kalkstein and colleagues (Kalkstein 1989, 1991, 1992, 1993, 1995; Kalkstein and Smoyer 1995; Kalkstein and Tan 1995). Martens (1997, 1998) reviews the literature and performs a meta-analysis. This is used as the basif for the analysis here. Martens presents the reduction in cold-related cardiovascular deaths, the increase of heat-related cardiovascular deaths, and the change in (heat-related) respiratory deaths in 17 countries in the world for a 1.16 °C increase in the global mean temperature, using monthly mean temperature scenarios from three transient GCM experiments. World-wide cardiovascular and respiratory mortality changes are estimated as follows. For the 17 countries of Martens' study, the estimated death toll equals the average of the results for the three GCM scenarios, scaled to a 1 °C increase in the global mean temperature. For other countries, mortality changes are extrapolated based on the minimum and maximum monthly mean temperatures. Temperature data are from the Leemans and Cramer (1991) database. Climates in capitols are assumed to be representative for countries. Heat-related cardiovascular mortality is assumed to be mainly an urban phenomenon, cold-related cardiovascular and respiratory morality is assumed to affect the entire population. Following Martens (1998), cardiovascular mortality is split into below 65 and above. The regression equations are

$$C^{65}_{cold} = \underset{(0.5914)}{-2.9787} + \underset{(0.0464)}{0.0946}\, T_{\min} \tag{3}$$

$$C^{65+}_{cold} = \underset{(18.3041)}{-162.6459} + \underset{(1.4367)}{5.6628}\, T_{\min} \tag{4}$$

$$C^{65-}_{heat} = \underset{(0.9599)}{-1.4610} + \underset{(0.406)}{0.0941}\, T_{\max} \tag{5}$$

$$C^{65+}_{heat} = \underset{(3.4570)}{-40.9953} + \underset{(1.6218)}{3.4570}\, T_{\max} \tag{6}$$

and

$$R = \underset{(6.0196)}{-17.9222} + \underset{(0.2545)}{0.8683}\, T_{\max} \tag{7}$$

where C and R denote changes in (urban, for C_{heat}) mortality per 100,000 people for cardiovascular and respiratory diseases, respectively. $T_{\min}$ and $T_{\max}$ are the minimum and maximum monthly mean temperatures. The parameters are estimated based on the 17 'observations' of mortality changes of Martens (1997, 1998). All parameter estimates are significant at the 95% level, but the fit is not impressive: R^2 vary between 22% and 51%. For cardiovascular mortality, the fit can be improved by taking up base cardiovascular mortality. However, extrapolation over space and time would then become too data-intensive. Equations (3–7) reflect

Table V. Number of additional deaths (1000s) per °C increase in global mean temperature.

	Malaria	Schisto[a]	Dengue	C-Heat[b]	C-Cold[c]	Resp.[d]	Total
OECD-A	0 (0)	0 (0)	0 (0)	11.4 (5.9)	−64.4 (4.4)	3.0 (9.7)	−50.0
OECD-E	0 (0)	0 (0)	0 (0)	11.7 (4.0)	−99.8 (2.6)	−2.8 (5.7)	−90.9
OECD-P	0 (0)	0 (0)	0 (0)	3.5 (2.8)	−13.1 (2.2)	1.0 (4.8)	−8.6
CEE&fSU	0 (0)	0 (0)	0 (0)	10.7 (4.4)	−87.5 (5.2)	4.5 (11.)	−72.3
ME	0.2 (0.1)	−0.1 (0.0)	0 (0)	2.5 (0.4)	−8.9 (1.3)	9.9 (2.6)	3.6
LA	1.1 (0.8)	−0.1 (0.0)	0 (0)	8.1 (1.8)	−20.0 (3.5)	11.1 (7.0)	0.2
S&SEA	8.2 (5.9)	−0.1 (0.0)	6.7 (1.2)	17.5 (2.9)	−63.8 (16.9)	141.2 (34.1)	109.7
CPA	0 (0)	−0.1 (0.0)	0.4 (0.1)	24.3 (4.6)	−103.4 (21.7)	62.8 (44.4)	−16.0
AFR	56.5 (40.9)	−0.5 (0.1)	0.3 (0.1)	4.7 (0.5)	−18.2 (6.0)	24.8 (6.0)	68.3

[a] Schistosomiasis.

[b] Heat-related, cardiovascular mortality.

[c] Cold-related, cardiovascular mortality.

[d] Heat-related, respiratory mortality.

Source: Own calculations, after Martens (1997), Martin and Lefebvre (1995), and Morita et al. (1994).

that warmer countries are less susceptible to decreases in winter mortality, and more susceptible to increase in summer mortality.

Table V displays the results for the nine regions. Estimated standard deviations are based on the regression errors of Equations (3–7). In colder countries, and for the world as a whole, the reduction in cold-related deaths outweighs the increase in heat-related deaths. Moore (1998) for the USA and the EUROWINTER Group (1997) obtain similar results for Europe.

Vector-borne diseases (malaria, sleeping sickness, Chagas' disease, schistosomiasis, river blindness, etc. – cf. McMicheal et al. 1996, for an overview) may intensify and spread with warmer and more humid conditions. Currently disease-free areas, such as the highlands of Ethiopia, Kenya and Indonesia (WHO 1990) as well as Australia, Southern Europe and the south of the USA (Haines and Fuchs 1991), may be invaded. Although many studies refer to this effect in a qualitative sense, only a few attempts to quantification have been reported.

For malaria, three model studies support the analysis here. Martin and Lefebvre (1995) indicate under $2\times CO_2$ an increase of 7–28%, depending on the GCM used, in the land areas where malaria can be potentially transmitted. Martens et al. (1995, 1997; cf. Martens 1997) expected several millions of additional malaria cases by the year 2100. Morita et al. (1995) indicates a 10–30% increase in the number of people at risk from malaria under $2\times CO_2$. For these three studies, the GCM-specific estimates of the increase in global malaria death toll have been scaled by the corresponding increase in the global mean temperature and then averaged. Next, the averages of the three studies has been averaged. The yearly, regional death toll due to malaria was taken from Murray and Lopez (1996), expressed as fraction of total population. Relative mortality is assumed to increase uniformly over the world.

For dengue and schistosomiasis, only Martens et al. (1997) report model results. The same procedure was followed as above: the average of the estimated global change in death toll is assumed to hold for the relative, regional mortality taken from Murray and Lopez (1996).

Table V shows the estimated changes in mortality due to a 1 °C rise of the global mean temperature. Standard deviations reflect the variation over the scenarios and the studies. Life loss is valued at 200 times the per capita income, about the middle of the range reported by Cline (1992).[6] The estimates differ substantially from those of Fankhauser (1995) and Cline (1992). Based on older work of Kalkstein (1989, 1991), both authors assume that increased heat-related mortality outweighs decreased cold-related mortality. Here, it is the other way around. Unlike Cline and Fankhauser, this study includes selected vector-borne diseases. On balance, however, climate change seems to reduce mortality. The difference between this and earlier studies is exacerbated by the higher assumed value of a statistical life.

New studies that report global mortality changes for malaria, dengue or schistosomiasis based on GCM-derived scenarios can be incorporated along the lines described above, while results for new diseases can also be readily added. Ideally, the underlying literature should move away from reporting only global estimates, so that regional and national differences can be derived.

3.6. ENERGY CONSUMPTION

Climate change affects the consumption of energy mainly through changed demands for space heating and cooling. Various studies quantify the effect on the US (Rosenthal et al. 1995) and on the UK (CCIRG 1996), but there is only one global study. Drawing heavily on SEI (1993), Downing et al. (1995, 1996) develop a country-specific model which relates the energy used for space cooling and heating to degree days, per capita income, and energy efficiency. Economic impacts follow from assumed energy price scenarios. Eyre et al. (1998) report the net present costs and benefits for *FUND*'s nine regions, which were annuitized and scaled to a 1 °C global warming. Downing et al. (1995, 1996) use an income elasticity of 0.2 to extrapolate their UK-based findings to the rest of the world. This was replaced by an income elasticity of 0.8 (Mori and Takahashi 1998), so as to get more realistic estimates for the poorer regions. Table VI displays the results. Standard deviations are arbitrary set equal to the mean.

These estimates differ substantially from earlier studies, pointing to benefits rather than damages. For the USA, Pearce et al. (1996) report costs of \$1 to 10 billion per year for a 2.5–4.0 °C increase in the global mean temperature. This compares to a \$10 billion gain for a 1.0 °C increase for the USA and Canada.

Table VI. Impact on water, heating and cooling, 1 ° increase in global mean temperature, in billion dollars.

	Water	Heating	Cooling
OECD-A	−3.4 (3.4)	22.1 (22.1)	−10.9 (10.9)
OECD-E	−1.5 (1.5)	13.1 (13.1)	−20.2 (20.2)
OECD-P	−0.0 (0.0)	6.9 (6.9)	−1.0 (1.0)
CEE&fSU	−76.0 (76.0)	46.0 (46.0)	−18.6 (18.6)
ME	−0.5 (0.5)	7.9 (7.9)	−0.9 (0.9)
LA	−1.0 (1.0)	2.8 (2.8)	−1.9 (1.9)
S&SEA	−1.7 (1.7)	3.9 (3.9)	−4.1 (4.1)
CPA	2.4 (2.4)	17.1 (17.1)	−12.4 (12.4)
AFR	−2.4 (2.4)	0.0 (0.0)	−5.1 (5.1)

After Downing et al. (1995, 1996).

The estimates are not readily compared, since the studies underlying Pearce et al. (1996) are largely restricted to electricity, and thus biased towards cooling.

3.7. WATER RESOURCES

Climate changes affects both supply and demand of water. Many studies look at this issue from a range of perspectives including hydrology, economics and law (e.g., Frederick and Major 1997; Mendelsohn and Bennett 1997; Miller et al. 1997). In the present author's knowledge, Downing et al. (1995, 1996) is the only comprehensive global study with results relevant for this study. Country-specific water supply follows from a modified version of the Thornthwaite equation. Country-specific water demand depends on water deficits, per capita incomes and (constant) water prices. Eyre et al. (1998) report the net present costs and benefits for *FUND*'s nine regions, which were annuitized and scaled to a 1 °C global warming. Table VI displays the results. Standard deviations are arbitrarily set equal to the mean.

The estimates here are comparable to earlier ones. a damage about $3 billion is foreseen for the USA and Canada for a 1 °C increase in the global mean temperature. Cline (1992) finds a damage of $7 billion for 2.5 °C, Fankhauser (1995) a damage of $16 billion for 2.5 °C, and Titus (1992) a damage of $11 billion for 4 °C, each for the USA only. The estimate for the world as a whole, a loss of about $84 billion, is considerably higher than Fankhauser's damage of $47 billion.

3.8. OMITTED IMPACTS

The list of omitted impacts is long. It includes amenity (cf. Frijters and Van Praag 1995; Nordhaus 1996; Maddison 1997; Maddison and Bigano 1997; Moore 1998;

Table VII. Annual impact of a 1 °C increase in global mean temperature.

OECD-A	175 (107)	−30	3.4 (2.1)
OECD-E	203 (118)	23	3.7 (2.2)
OECD-P	32 (35)	−24	1.0 (1.1)
CEE&fSU	57 (108)	6	2.0 (3.8)
ME	4 (8)	−5	1.1 (2.2)
LA	−1 (5)	−16	−0.1 (0.6)
S&SEA	−14 (9)	−37	−1.7 (1.1)
CPA	9 (22)	2	2.1 (5.0)
AFR	−17 (9)	−19	−4.1 (2.2)

Source: Own calculations.

Van Praag 1988) recreation (CCIRG 1996), tourism (Maddison 1997), extreme weather (Downing et al. 1996, 1998), fisheries (Everett et al. 1996), construction, transport, energy supply (Acosta Moreno et al. 1996; Scott et al. 1996), morbidity (McMicheal et al. 1996) and so on. The reason for omitting is that no comprehensive, quantified impact studies have been reported.

3.9. AGGREGATION

Table VII summarizes the climate change impact estimates derived above. For comparison, the results of my earlier study (Tol 1995) are also given. The estimates are the total annual impact of a 1 °C increase in the global mean temperature, and a 0.2 metre sea level rise, changes that are expected to occur over the first half of the 21st century. In the OECD, Middle East and China, impacts are on balance positive. In other regions, impacts are on balance negative. In all cases, uncertainties are substantial, so that not even the sign of the impact can be known with reasonable confidence. Uncertainties as estimated here really are lower bounds of the ‘true’ uncertainty.

Table VIII displays the impact on the world as a whole. Simply aggregating estimated impacts across regions leads to a positive impact (i.e., a benefit) of about $448 billion per year, equal to 2.3% of total world income. The standard deviation is a little less than half of that, at $197 billion or 1.0% of income.

The interpretation of simple aggregation is not obvious. In fact, the estimate is a potential Pareto improvement, but compensation is unlikely. A global impact estimate is useful to a (non-existent) global decision maker, or a group of cooperating regional decision makers. In either case, the sum of regional estimates ignores the wide disparity between these regional estimates. Also, different monetary values are used for similar impacts, notably statistical lifes are valued differently.

Table VIII. Annual impact of a 1 °C increase in global mean temperatures on the world for three different rules of aggregation.

	Billion dollar	Percent of income
Simple sum	448 (197)	2.3 (1.0)
Average value	−522 (150)	−2.7 (0.8)
Equity-weighted sum	40 (257)	0.2 (1.3)

Source: Own calculations.

One solution is to use globally averaged prices to value non-market goods and services. Table VIII displays the result. World impacts are estimated at a negative \$522 billion, or 2.7% of income, with a standard deviation of \$150 billion, or 0.8% of income. The sign switch is largely due to the impact of climate change on mortality. In numbers of deceased, the reduction in mortality in the OECD is smaller than the increase in mortality in developing countries. Using regionally differentiated values, the welfare gain in the OECD is higher than the welfare loss in developing countries. This is not the case with globally averaged values. The standard deviation of the world impact decreases because the difference between regions are smaller when using globally averaged values.

Another solution is advocated by Fankhauser et al. (1997). When added, different regions' impact estimates should be given weights. These 'equity weights' reflect the regions' risk aversion and the world inequality aversion. A mild version is to use the ratio of global to regional per capita income as an equity weight. Table VIII displays the result. World impact is again positive, at \$40 billion or 0.2% of income. The standard deviation is substantially larger, at \$257 billion or 1.3% of income. The difference with the simple summation is explained by the higher weight attached to the poorest regions, which are generally estimated to be negatively affected by climate. The increase in the standard deviation is due to the same reason, since impact estimates in developing rely more heavily on extrapolation and are therefore more uncertain.

4. Conclusions

This paper established three things. Firstly, a new set of impact estimates of climate change is derived, based on a suite of globally comprehensive impact studies. Secondly, a lower bound to the uncertainty about the impact is estimated. Thirdly, methods are sketched to incorporate new impact studies into the economic assessment.

Comparing these results to the state-of-the-art as discussed in the opening sections, progress was made. However, a lot needs to be done before one can place any confidence in the estimates, and base rational emission reduction policies on them. Firstly, the underlying studies need to improve in quality, increase in number, and extend to other impact categories. Secondly, the static assessment here has to be made dynamic, including both other climate changes and altered socio-economic circumstances. Thirdly, the underlying studies have to be made consistent, with regard to scenarios and assumptions about adaptation – to name a few obvious examples – and also with regard to the effects one sector would have on others (e.g., water and agriculture).

The question whether a little climate change is bad or good depends on one's location. One cannot, however, draw any conclusion with regard to optimal emission reduction from this study. The climate change analyzed here is one to which we are already committed. The marginal costs of moving beyond 1 °C may be positive or negative, a question beyond this paper.

This analysis reconfirms that the distributional aspects of climate change are profound, and that the uncertainty about the impacts is huge. The finding that the greenhouse gas emissions of the rich are doing damage to the poor may be an argument for emission abatement. The sheer uncertainty of how a warmer world would look like is also a reason one may want to limit climate change.

Acknowledgements

A special world of thanks goes to Martin Parry, who first openly stated the problem, and helped pointing the way to a solution. Hadi Dowlatabadi, Tom Downing, Stale Navrud, Xander Olsthoorn, Pier Vellinga, Harmen Verbruggen, Aart de Vos and two anonymous referees provided helpful comments on (parts of) earlier versions, or were good discussion partners on the subject matter. The EU DG Research Environment and Climate Programme through the ClimNeg, Inasud and ExternE projects (JOS3-CT95-0002, ENV4-CT96-0179; JOS3-CT97-0015; ENV4-CT98-0810), the US National Science Foundation through the Center for Integrated Study of the Human Dimensions of Global Change (SBR-9521914) and the Michael Otto Foundation provided welcome financial support. All errors and opinions are mine.

Notes

1. Cline (1992), Nordhaus (1994), and Mendelsohn (1998) extrapolate US estimates to the world. Fankhauser (1995) and Tol (1995) combine extrapolations from OECD countries with a few global studies. All authors mix GCM-scenarios and synthetic scenarios.
2. The estimates for agriculture and sea level rise follow different conventions so as to stay in line with the underlying literature; this inconisistency is rectified in the aggregate impact estimates.
3. Other impacts are normalised at 1 °C; the literature uses 2.5 °C, or rather a doubling of atmospheric carbon dioxide, as a standard. Since the normalisation used is linear, and the effect of CO_2 fertilization is not separated out, this does not really matter.
4. This work is being extended to the world.
5. Strictly, the act of giving enhances welfare, rather than furthering the cause.
6. Note that Cline (1992) uses a more conservative estimate.

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