climate policy

synthesis article

Economics of climate change: risk and responsibility by world region

U. THARA SRINIVASAN*

Pacific Ecoinformatics and Computational Ecology Laboratory, Berkeley, California 94702, USA

The impacts of predicted climate change will not be distributed evenly around the world. As post-Kyoto negotiations unfold, relating the geographical distribution of projected impacts to responsibility for emissions among world regions is essential for achieving an equitable path forward. This article surveys the current knowledge of regional climate consequences, and delves into the regional predictions of economic assessment models to date, examining how the uncertainties, assumptions and ethical dimensions influence the portrayal of risk at this scale. The few studies that quantitatively compared regional risk and responsibility are reviewed, and the analytical framework from one such study is applied to the 2006 *Stern Review*'s projections to give the first regional comparison to take purchasing power and welfare considerations into account. Synthesizing burden and blame in this way is informative for policy makers; the world's most vulnerable communities – in Africa, the Indian subcontinent, Latin America, and small island states – accounted for less than 33% of global greenhouse gas emissions over the period 1961–2000, but may experience more than 75% of the ensuing climate damages this century. This analysis reinforces the call for industrialized nations to lead mitigation efforts, and to do so decisively and swiftly.

Keywords: climate change; climate debt; climate policy; equity; integrated assessment models; North–South; regional impacts; responsibility

L'impact prédit du changement climatique ne sera pas réparti de manière homogène autour de la planète. Tandis que les négociations sur le post-Kyoto se déroulent, il est essentiel de lier la répartition géographique des impacts prédits et l'origine des émissions entre les différentes régions du monde en vue d'obtenir une trajectoire équitable allant de l'avant. Cet article considère les connaissances actuelles sur les conséquences climatiques régionales et analyse les prédictions régionales des modèles d'évaluation économique produites à ce jour en examinant l'influence des incertitudes, des suppositions et de la dimension éthique sur la représentation du risque à cette échelle. Les quelques études ayant fait la comparaison quantitative entre risques régionaux et responsabilité ont été revues, et le cadre analytique d'une de ces études fut appliqué aux projections contenues dans le rapport Stern de 2006 effectuant la première comparaison régionale à tenir compte des questions de pouvoir d'achat et de protection sociale. Une telle synthèse entre fardeau et responsabilité est utile aux décideurs : ce sont les habitants des régions les plus vulnérables du monde – Afrique, sous-continent indien, Amérique latine, petits états insulaires – responsables de <33% des émissions de gaz à effet de serre planétaire sur la période 1961–2000, qui auraient à subir >75% des effets climatiques néfastes provoqués au cours du siècle dernier. Cette analyse renforce l'appel aux pays industrialisés à mener les efforts de mitigation, et ceci de manière preste et résolue.

Mots clés: changement climatique; dette climatique; équité; impacts régionaux; modèles d'évaluation intégrée; Nord–Sud; politique climatique; responsabilité

**E-mail*: utharas@gmail.com

doi:10.3763/cpol.2009.0652 ISSN: 1469-3062 (print), 1752-7457 (online) www.climatepolicy.com

earthscan

1. Impacts of climate change by world region

In its fourth assessment report (AR4), the IPCC projected the regional impacts of climate change with more confidence and detail than had been done previously, showing marked geographical imbalances (IPCC, 2007). Regions deemed particularly vulnerable included Africa and its megadeltas, Asian megadeltas, small island states, and the Arctic. As UN Secretary General Ban Ki-Moon stated, 'Climate change affects us all, but it does not affect us all equally. Those who have done the least to cause the problem bear the gravest consequences' (Gelling, 2007).

Most of the future climate impacts around the world will be mediated by water. Higher temperatures mean greater evaporation rates for dry regions but more intense rainfall elsewhere. Towards 2100, water availability may be reduced by up to 50% in the semi-arid regions of northeast Brazil, southern Africa and the Mediterranean, but increased by more than 20% in South Asia, northern Europe and Russia. For South and East Asia, the additional rainfall will mostly occur during the wet season, exacerbating the severity and frequency of floods (IPCC, 2007). Consequences for hurricane intensity could be dire; one study predicted the intensity to increase roughly in line with the third power of sea temperatures (Insurance Australia Group, 2005). At the same time, the percentage of land area suffering extreme drought could increase tenfold compared with present levels, with severe shortages predicted for those who depend strongly on glacier meltwater during their dry season: 500 million in India, 250 million in China, and tens of millions in the Andes of South America (Barnett et al., 2005).

In the warm regions of the world, temperature increases are predicted to lower agricultural crop yields, harshly so for Africa, the Middle East, Western Asia, and Central America. Yields in African countries may decline by up to 50% – which is alarming given the current levels of malnutrition and soil nutrient depletion (Stern et al., 2006; IPCC, 2007). In contrast, initially modest warming could extend growing seasons for higher-latitude regions (e.g. the USA, Canada, Europe, Australia and Siberia), although greater warming would probably be damaging (IPCC, 2007). Indeed, by the century's end, large regions of Australia could be too dry for cultivation. Similarly, future heat waves could disproportionately burden tropical populations with health impacts, while people in cooler regions will suffer fewer cold-related deaths and illnesses (IPCC, 2007). For example, malaria exposure in sub-Saharan and East Africa may increase by up to 14% by 2050 (Stern et al., 2006; Warren et al., 2006). Damages from rising sea levels will also be borne unevenly worldwide. The densely populated, low-lying areas of the world may be inundated and eroded; with Vietnam, Bangladesh, Shanghai, the west coast of Africa and the small island states of the Caribbean, Indian and Pacific Oceans especially at risk (Stern et al., 2006; IPCC, 2007). By 2050, one prediction foresaw the creation of up to 200 million environmental refugees (Myers and Kent, 1995).

Serious impacts to ecosystems and biodiversity will not be shared equally, either. If temperature rise exceeds 3.5°C, the IPCC reported that a stunning 40–70% of the plant and animal species studied could face extinction (IPCC, 2007). Thousands of species could disappear due to the drying and demise of parts of the Amazon rainforest; the loss of coastal wetlands, mangroves and coral reefs in South East Asia, the USA and the Mediterranean; and the loss of sea ice in the Arctic. Certain regions will experience especially devastating effects. Mangroves and coral reefs provide important storm protection services, and for small island states, the submergence of these ecosystems, as well as coral damage from warming-induced ocean acidification and the resultant bleaching, will be coupled with the increased intensity of tropical cyclones (Millennium Ecosystem Assessment, 2005a, 2005b).

There is a deepening awareness within the scientific community that large, irreversible changes in the climate system could occur as crucial thresholds are surpassed (Hall and Behl, 2006; Stern et al., 2006; Hansen, 2007; IPCC, 2007; Hansen et al., 2008a, 2008b). Recent information on ice sheet instability suggests collapses may occur over 100–200 years, rather than 1,000–10,000 years as previously believed (Hall and Behl, 2006; Hansen, 2007). In addition, the amplifying role of positive feedbacks, such as the increased absorption of sunlight as ice melts to expose darker surfaces (Hansen et al., 2008a), is likely to be considerable (Torn and Harte, 2006). By 2100, the melting of polar ice sheets already well under way (Hansen et al., 2008a) could submerge 15% of South and East Asia, and warming of the Pacific Ocean could trigger the shutdown of Indian monsoons, with disastrous consequences for food security (Stern et al., 2006; IPCC, 2007). In addition to the loss of ice, other slow feedbacks such as the spread of plants in the high northern latitudes could potentially double the temperature sensitivity of the climate system, meaning that even stabilization at 450 ppm CO_2, heretofore widely believed to be a safe level, may cause dangerous climate change (Hansen et al., 2008b).

In addition to these geographical reasons, citizens of the poorest countries could suffer unduly from climate change because they often live in closer relationships with their ecosystems than people in affluent countries do (e.g. subsistence farming, use of fuelwood, etc.), and poverty levels limit their capacity for adaptation (Tol et al., 2004). Even in wealthy countries, the poor and the elderly members of the population are apt to be more vulnerable (IPCC, 2007), as evidenced by the pattern of mortality from the 2004 Hurricane Katrina in the USA (Thomas and Twyman, 2005).

Turning to the issue of responsibility, anthropogenic emissions of the three main greenhouse gases (GHGs) – carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) – have occurred quite unevenly around the world, with contributions from nations currently classified as developed far outstripping those from developing countries. According to cumulative emissions since 1750, the developed world was responsible by 1995 for ~80% of fossil CO_2 emissions and ~60% of emissions of the three GHGs (Höhne and Blok, 2005). Current emissions pathways, however, reveal a changing situation (Botzen et al., 2008); China may have overtaken the USA as the world's largest CO_2 emitter in 2006 (Auffhammer and Carson, 2008), even though China's emissions are more than four-fold lower on a per capita basis (World Bank Group, 2008).

Given the striking contrast between historical blame for climate change and the potential future burden for countries around the world (Grubb, 1995), how should developed and developing nations share the costs of adaptation? For insight into this evolving issue, this article surveys recent assessments of the coming economic impacts through a regional lens, exploring the uncertainties and the ethical dimensions surrounding key assumptions. The existing quantitative analyses of regional risk and responsibility are reviewed, and a new comparison based on predictions from the *Stern Review* is presented as an example for policy makers and a call to action.

2. Regional impact assessments

2.1. Economic models

Several studies have combined climate and economic models into integrated assessment approaches that predict regional impacts as a percentage of the forecast gross domestic product (GDP) for that region. Although aggregated world impacts have drawn the lion's share of attention, the available regional detail is assembled here (Figure 1) from various source studies (Pearce et al., 1996; Mendelsohn and Neumann, 1998; Tol, 1999; Mendelsohn et al., 2000; Nordhaus and Boyer, 2000; Tol, 2002; Nordhaus, 2006; Stern et al., 2006). Estimates are shown for the year in which CO_2 concentrations are predicted to double with respect to the pre-industrial baseline ($2\times CO_2$). The drawback of analysing this ~2050 snapshot is that recent studies (Nordhaus, 2006; Stern et al., 2006) have predicted that

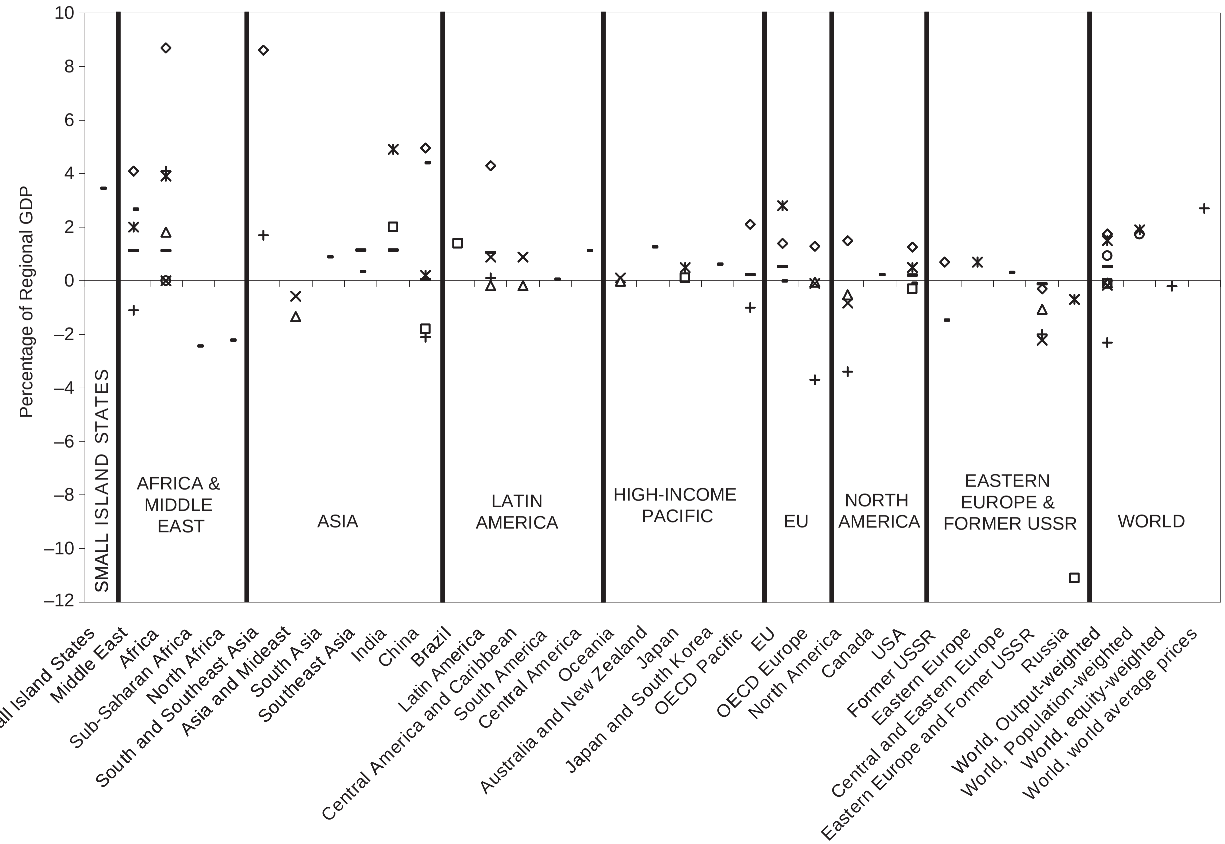


FIGURE 1 Regional impacts of climate change as percentage of regional GDP for a temperature increase of 2–3°C, which corresponds in most cases to a doubling of CO_2 concentrations relative to pre-industrial levels (Pearce et al., 1996 (◇%); Mendelsohn and Neumann, 1998 (□); Mendelsohn et al., 2000 (Δ,×); Nordhaus and Boyer, 2000 (*); Nordhaus, 2006 (O); Tol, 1999 (+); Tol, 2002 (–); Stern et al., 2007 (—)). No discounting of impact percentages is performed. Positive values indicate damages to regions, while negative values represent benefits. Averages are presented where ranges are listed in the original studies. The two sets of values from Mendelsohn et al. (2000) are for a mid-range climate scenario using an empirical impact model (Δ) and a cross-climate economic sector comparison model (×). Two of the studies (Pearce et al., 1996; Nordhaus and Boyer, 2000) predicted impacts for a society with a demographic and economic structure similar to that of the study year, while the others predicted impacts for future societies. There is significant overlap among several of the regional categories listed on the *x*-axis, as all regional groupings from the original studies are retained instead of aggregated into common sets. The category, Oceania, listed under 'high-income Pacific' is dominated by impacts to Australia and New Zealand, but also includes effects to low- and middle-income island states.

damages will accelerate markedly after 2100, heightening the regional contrasts. Nonetheless, Figure 1 provides useful insights. The speculative nature of forecasting is evident in the scatter, but in general the models project damages for most regions, and benefits for northern regions, particularly countries of the former Soviet Union (Tol, 2005). The IPCC's second assessment report (SAR) estimate (Pearce et al., 1996), which synthesized results from the first generation of models, forecast damages for nearly every world region, with developing countries in Africa and South and South East Asia most vulnerable. Recent models, however, have predicted mild short-term benefits to industrialized high-latitude countries for $2\times CO_2$ warming, but significant costs for the poorest low-latitude regions of Africa and India. Even the more optimistic models by Tol (1999) and Nordhaus and Boyer (2000) project losses of ~4% of GDP for Africa. Notably, one model (Tol, 2002) defined a separate category for small island states due to their particular vulnerability to sea level rise.

The large variation in predictions follows from the formidable uncertainties involved, which magnify at every step of calculations (Schneider and Lane, 2006), requiring 'drastic, often heroic simplifications' (Stern et al., 2006) from the assumption of a future global emissions scenario to the sensitivity of the global climate system. To be sure, the regional detail is not intended to be taken literally (Tol, 2005; Stern et al., 2006), as the specifics of regional scenarios are even more uncertain.

The impact assessment models first estimate costs to sectors of the economy where market prices are available. For agriculture, forestry, energy and water consumption, and coastal resources, impacts are predicted in terms of sector GDP values. For each category, models often apply climate response functions derived from detailed empirical studies. Most of these functions were developed using data from the USA or Western Europe (Mendelsohn et al., 2000; Stern et al., 2006). Observational data for developing countries and for the unprecedented high temperatures that could arise in low-latitude regions are either very sparse or missing (Stern et al., 2006). Therefore, estimating sector impacts for other countries or regions requires strong assumptions. Stern et al. (2006) extrapolated EU impacts for seven other world regions using multipliers estimated by their model's author (Hope, 2006), from earlier studies by Tol (1999), Mendelsohn et al. (2000) and Nordhaus and Boyer (2000). Using such weightings, Africa would experience 1.83 times the total $2\times CO_2$ impacts of the EU (Hope, 2006). Tol (1999), in turn, calculated regional impacts for various sectors by synthesizing a host of earlier studies, for instance, averaging agricultural impacts for nine world regions from data in five studies published during the period 1992–1996. Other models have relied on country statistics to adapt US values for other countries. Mendelsohn et al. (2000) translated US agriculture and forestry impacts for other countries using ratios (relative to the USA) of a country's crop and forest area, respectively.

As market prices do not exist for a spectrum of critical impacts, from damages to human health to biodiversity losses, a variety of methods have been created to infer such costs from people's observed decisions, examining what people are willing to pay or accept in payment to either avoid or bear the impacts (O'Connor and Spash, 1999; Farber et al., 2002). For example, people's willingness to pay (WTP) to avoid a specified risk of death may be indicative of how they value their lives. In order to attach monetary values to premature mortality from climate-change-related heat stress and infectious disease, integrated assessment models rely upon 'value of a statistical life' (VSL) estimates. Link and Tol (2004) used a VSL of 200 times annual per capita income, a mid-range value in the literature. For 2006 incomes (World Bank Group, 2008), this translates into $100,000 and $5.7 million for the life of a citizen in a low- and high-income country, respectively. Put this way, the ethical problems are immediately apparent. At the same time, if rich-country values or even common global values are applied to poor countries, climate damages could exceed the poor countries' total income, which some economists reject as being meaningless (Eyre et al., 1997; Torras, 2000).

Similarly, prices may be attached to ecosystem degradation by examining people's monetary decisions regarding the damage in question. The model in Link and Tol (2004) drew estimates of \$4–5 million/km^2 for the costs of wetland and dryland loss in industrialized countries from an earlier study (Fankhauser, 1995). But rather than keeping the cost of a lost square kilometre of these ecosystems constant around the world, modellers have adapted the costs based on regional income, with the underlying assumption that prices are meaningful only in the context of local incomes. Tol (2002) derived the regional costs of wetland loss by adjusting for regional coastal population density and per capita income. As most WTP studies are undertaken in high-income countries, these cost translations are necessarily rough. Moreover, in 2006, per capita incomes varied by a factor of 56 between low- and high-income countries (World Bank Group, 2008), so again, critical equity concerns arise when regional values are eventually compared or summed.

In addition to predicting the regional distribution of impacts in different ways, the models also vary widely with respect to: (1) how comprehensively and with what empirical bases they treat market and non-market impacts, (2) how they deal with adaptation by future societies to a changing climate, (3) how they present the uncertainty in their results, and (4) how they model large, irreversible impacts, given the growing awareness of such risks. Nearly all of the models represented in Figure 1 account for market and non-market impacts; only the analyses led by Mendelsohn (1998; 2000) were restricted to market impacts, which helps explain why these estimates are lowest. Link and Tol (2004) considered several kinds of health impacts, from changes to heat and cold stress to infectious diseases such as malaria and dengue fever, while Nordhaus and Boyer (2000) counted market impacts to the usual sectors described earlier as well as to fisheries, construction and outdoor recreation. Post-1996 models allow for varying levels of adaptation to climate change, such as the development of drought-resistant crops and the building of sea walls, both of which would reduce long-term damages. In particular, Mendelsohn et al. (2000) gave results for two different adaptation assumptions in which the world adapts relatively successfully to warming. By using a response function based on the actual productivities of different climate regions in the USA, the model implicitly accounts for the ways in which economies have already adapted to their climates. This approach tends to underestimate impacts, however, since it does not consider the costs of transition, including migration, as current climate conditions shift toward the poles (Stern et al., 2006).

The considerable uncertainties in model predictions have been described using sensitivity analyses to key assumptions regarding both impacts and scenarios for emissions and climate response (Tol, 2005). For example, Tol (1999) provided confidence intervals, and Nordhaus (2006) gave estimates for different climate scenarios. Dietz et al. (2007a) demonstrated how Stern et al.'s (2006) results were sensitive to a range of decisions from the selection of uncertain parameters to the sensitivity of the climate system. Most significantly, though, is the increasing sense of a larger field of uncertainty with climate change. Palaeo-climatic studies suggest that past transitions between very different climates have occurred over the space of decades or years, not centuries as previously believed (Hall and Behl, 2006). For regional forecasting especially, accounting for the risks of sudden, massive impacts seems essential now.

Analyses by Nordhaus and Boyer (2000) and Stern et al. (2006) pay special attention to such severe impacts. Nordhaus and Boyer surveyed experts to arrive at probabilities for these extreme changes at different levels of warming. Survey data was also used to determine how much people would be willing to pay to avoid the risks, taking into account the different vulnerabilities of regions around the world. Stern et al. (2006), in turn, based their analysis of catastrophic impacts on that of Nordhaus and Boyer. By randomly selecting different ensembles of risk-related parameters, their Monte Carlo simulations included the small chance of large risks. According to their analysis, risks of large regional losses (5–20% of GDP) emerge as global average temperatures increase 5°C beyond pre-industrial levels (Stern et al., 2006). But, despite these efforts, the climate 'flickering' observed in past climate transitions remains a serious challenge to integrated assessment modelling. The current assumption, that one climate equilibrium will be replaced smoothly by a warmer equilibrium and that economies will be in equilibrium with the changing climate, must be revisited in future modelling efforts (Hall and Behl, 2006).

In addition, most models to date omit 'socially contingent' responses to climate change such as migration, conflict, and the movement of capital investment (but see Link and Tol (2004), who considered immigration/emigration costs). These large-scale phenomena are bound to impact poor countries disproportionately. One estimate claims that the secondary effects of reduced investment may nearly double the global costs of 3°C warming (Fankhauser and Tol, 2005). Moreover, the forecast climate-related biodiversity losses have hardly been taken into account in any economic impact assessments to date. So, even though the full range of world damage predictions in the *Stern Review* (2006) are currently the highest in the literature (results for a high-climate scenario – not shown in Figure 1 – put 2150 impacts as high as 22% of world GDP), even these may be conservative.

2.2. Aggregation of impacts

2.2.1. Regional weights

For climate impacts spread around the world over long time-scales, even the seemingly straightforward task of adding up regional impacts to give a global estimate is ethically complex (Tol et al., 2004). For instance, if sea level rise were to wreak catastrophic damages to Bangladesh, even a loss of four-fifths of the country's GDP would equal only 0.1% of world GDP (Schneider and Lane, 2006). In fact, low-income countries contributed just 3.2% to world GDP in 2006, but represented 37% of global population (World Bank Group, 2008). Because the models generally scale a region's market impacts by the GDP of the corresponding sectors, simply summing the dollar values across world regions hides the true distribution of costs (Pearce, 2003; Tol, 2005; Stern et al., 2006). Impacts to rich countries outweigh damages to poor countries, and even mild benefits to the rich can mask heavy costs to the poor. Furthermore, different currencies have different purchasing powers. In pure dollar terms, high-income country citizens currently earn ~60 times more than their low-income counterparts (World Bank Group, 2008). But after adjusting for the different costs of goods and services in low-income countries, per capita incomes instead differ by a factor of 13 (World Bank Group, 2008). Accordingly, regional impacts may be presented in terms of purchasing power parity (PPP)-adjusted 'international dollars', augmenting impacts to poorer regions and also increasing the global estimate.

The ethical objections are framed most clearly with respect to non-market impacts. Relying on willingness-to-pay techniques means that equivalent losses of wetland area or human lives amount to vastly different costs for Bangladesh and the Netherlands, for instance. While portraying a poor country's health impacts in the context of its own GDP is informative, summing such values across countries implicitly assumes that the lives of poorer people are worth less. These dilemmas have prompted many to argue that market impacts, which lend themselves to expression in terms of dollar per ton of carbon emitted ($/tC), should be kept separate from other, non-monetized measures: human lives lost, species lost, and changes to the distribution of income and quality of life around the world (Schneider and Lane, 2006).

Monetary costs are intended to represent value, but value is very much a matter of perspective. Clearly, Bangladesh would be crippled by damages equivalent to 80% of its national income, but it is also true that a 10% loss would be more onerous to Bangladeshis than would the same dollar damage to the Dutch. It is fitting that, in proportion to per capita incomes, a dollar's worth of damage to a poor person should be weighted more heavily than that dollar's worth to a rich person (Azar and Sterner, 1996; Fankhauser et al., 1997; Pearce, 2003). Using a range of techniques, the practice of welfare or 'equity weighting' seeks to define these weights (Azar and Sterner, 1996; Fankhauser et al., 1997). Before totalling impacts for a world estimate, the contribution of a geographical region, g, may be multiplied by the factor $(I_{\text{Wave}}/I_g)^{\varepsilon}$, based on average per capita GDP values for the world (I_{Wave}) and the region (I_g), and the factor ε, the 'elasticity of the marginal utility of income', a measure of relative burden (Pearce, 2003). Values for ε have been empirically deduced from people's savings behaviour, with a range of 0.5–1.2 deemed 'reasonable' (Pearce, 2003). To illustrate: for $\varepsilon = 1$, as used by Eyre et al. (1997) and Clarkson and Deyes (2002), a region's impacts would be weighted in the global sum by a factor inversely proportional to its regional income. In this case, year 2006 impacts to the low-, middle- and high-income groups would be weighted in the global sum by factors of 11, 2.5 and 0.20, respectively, using data from the World Bank Group (2008). Thus poor-country impacts are magnified, rich-country impacts are diminished and, since climate change may disproportionately burden the developing world, the overall effect of equity weighting is to increase costs greatly.

The portrayal of global 2×CO_2 impacts is dramatically shaped by what weights, if any, are applied. Mendelsohn's models (Mendelsohn and Neumann, 1998; Mendelsohn et al., 2000) used none. Tol's recent model, which predicted 2×CO_2 benefits for the USA, the EU and the former USSR, produced a global benefit of 2±1% GDP for 1°C warming (Tol, 2002). Equity weighting erased the benefit, to give impacts of 0±1%, while the use of average global values for impacts around the world resulted in a global cost of 3±1% (Tol, 2002). Thus, the weighting decision alone can change net impacts from positive to zero to negative. Nordhaus (2006) also reported striking results for different weights using his climate response model resolved to 1°×1° (latitude × longitude) grid cells. Weighting geographical impacts by human population in each grid cell, rather than by cell GDP, amplified world damages ~2–3 times, indicating that the most damaging impacts will occur where population density is greatest. Indeed, Stern et al. (2006) asserted that some sort of equity weighting is an ethical requirement, estimating that the use of $\varepsilon = 1$ could increase total climate change costs by more than 25%, which is less than the doubling that Clarkson and Deyes (2002) predicted. Yet despite efforts to adjust global impacts appropriately, equity-weighted regional impacts for interregional comparisons appear to be unavailable to date.

2.2.2. Temporal weights

Another crucial issue, that of discounting, concerns how predicted impacts are summed over future centuries for comparison with the current, estimated costs of emissions reduction. Once again, simple addition is inadequate. Discounting is employed to convert benefits and costs occurring at different times into a 'net present value' (NPV) (Daly and Farley, 2004). At the centre of a lively, contentious debate, the choice of a discount rate is perhaps the largest uncertainty affecting economic predictions of climate impacts today (Weitzman, 2007). Regional fates can be factored in two ways. First, discounting is supposed to account for economic growth. The IPCC A2 scenario has current world GDP increasing by a factor of ~40 by 2200 (Nakicenovic et al., 2000), obviously requiring appropriate weighting of year 2200 impacts for consideration today. Naturally, the actual growth rate of global per capita income will depend on the individual growth rates of regional economies, which will vary greatly depending on the scenario assumed (see discussion below).

Second, discounting attempts to account for how present generations view monetary impacts to future generations, notwithstanding growth in income. Should present and future impacts be weighted equally, or should nearer impacts attract greater weight? From a review of 28 climate-cost studies that employed wide-ranging discount rates with different assumptions regarding this 'time preference', in a few cases the use of a high enough discount rate weighted near-term climate benefits to high-latitude countries over more distant damages to developing regions, resulting in a marginal benefit of additional carbon emissions today (Tol, 2005).

In any case, the discount weighting factor is exponential and decreases rapidly into the future. The standard rate used for short-term investments (~6%) gives damages in 2100 only 1/100 of the weight that they would attract based on a rate of 1.4%, such as Stern et al. employed (Weitzman, 2007). Hence, the choice of a discount rate and the timing of impacts for different world regions interweave to shape the portrayal of regional outcomes.

2.3. Scenarios

How developed and developing countries will share the burden of climate change depends strongly upon the future landscape of the world. Not surprisingly, impact predictions from models are inseparable from the scenarios chosen and the host of underlying assumptions. The scenario determines not only when the $2\times CO_2$ year will occur or when a risk threshold may be crossed, but also how the driving emissions and the resulting impacts may be split between world regions. The most widely cited scenarios, from the IPCC's *Special Report on Emissions Scenarios* (SRES), cover four sets of future worlds with a range of demographic, economic, socio-political and technological profiles (Nakicenovic et al., 2000). All of the IPCC scenarios project that developing economies will grow more rapidly than those of developed countries, but the scenarios differ as to the relative rates. In GDP terms, the scenarios project that the developing world will surpass the developed world between ~2030 and 2060; when GDP is PPP-adjusted, the crossover period is sooner: ~2010–2030.

Under the 'world markets' A1 scenario, for instance, the world experiences rapid economic growth, high emissions, low levels of population growth, and the rapid development and adoption of efficient technologies. Developing group incomes nearly catch up, or converge, with those of the developed group, while total (not per capita) annual CO_2 emissions of the former will outstrip those of the latter in 2100 by 3.5 times under one A1 scenario. The 'national enterprise' A2 scenario family, on the other hand, projects mid-level economic growth, high population growth with fertility rates remaining fairly dissimilar across world regions, a low level of convergence between rich and poor incomes, and mid-level emissions. Under an A2 scenario, the annual emissions by the developing world in 2100 will be 1.9 times that of the developed world. Therefore, while one A1 scenario (A1B) predicts that developing countries will enjoy 1990 levels of developed-country GDP per capita by 2050, A2 says they must wait until past 2100. None of the scenarios project per capita incomes of the two groups to converge completely within the 2100 time horizon (Nakicenovic et al., 2000).

3. Comparing burden and blame

3.1. Quantitative efforts

There are many ways to measure how countries' GHG emissions have contributed to the problem of climate change (Neumayer, 2000; Sagar, 2000; den Elzen and Schaeffer, 2002; Enting and Law, 2002; Höhne and Blok, 2005; Baer, 2006; Rive et al., 2006). Choosing any one metric is controversial, as each bears different justice implications for the portrayal of responsibility among nations (Rive et al., 2006). Since GHG emissions in past years cast a long shadow on climate into the future, a representative metric, which is also relatively simple to estimate and convey, is historical cumulative emissions (Neumayer, 2000; Höhne and Blok, 2005). For a discussion of the issues involved in calculating historical emissions (i.e. what start date to use, which GHGs to include; see Neumayer, 2000; Tol and Verheyen, 2004; Höhne and Blok, 2005).

Few studies have paired the patterns of risk and responsibility in a quantitative manner. One study presented several possible trajectories for the compensation that developed countries could owe developing countries for climate impacts over the next two centuries (Tol and Verheyen, 2004). Calculating cumulative fossil CO_2 emissions starting in 2000 as a responsibility metric, the authors estimated that the rich could owe 0.5–3% of their GDP to the poor in the year 2200, based on model results by Tol (2002) and Nordhaus and Boyer (2000). Another study examined the estimated health impacts alone for climate change in the year 2000, finding a striking contrast between responsibility and burden among 14 income-based groups of countries (Smith and Rogers, unpublished). In terms of disability-adjusted life years, the poorest group was responsible for one-sixteenth of the health impacts it experienced, whereas the richest group imposed 500 times what it shouldered! These results were depicted vividly in two world maps, with country area proportional to responsibility in one and burden in the other (Patz et al., 2007). For the purpose of estimating 'climate debts' between nations and groups of nations, a study by Baer (2006) sketched out the burden–blame comparison in monetary terms. The analysis was meant as illustrative, as the magnitude of overall impacts was an educated guess and country impacts were assumed to be proportional to population size.

In a recent meta-analysis (Srinivasan et al., 2008), regional impact projections were assembled from five models that span the variation in the literature (Pearce et al., 1996; Nordhaus and Boyer, 2000; Link and Tol, 2004; Mendelsohn et al., 2006; Stern et al., 2006). The multi-region projections from the source studies were converted into impacts for high-, middle- and low-income groups of countries, using groups defined by the World Bank Group (2008). For each study and emissions scenario, the authors estimated what fraction of the impacts in each year of the impact period (2000–2100) could be attributed to GHG emissions of the three main gases over 1961–2000 only, using a method described by Höhne and Blok (2005). The study estimated that, over the period 1961–2000, the low-, middle- and high-income (LMH) groups, representing ~32, 50, and 18% of the world population, respectively, were responsible for 13, 45 and 42% of the GHG emissions, but may shoulder up to 29, 45 and 25% of the ensuing climate damages. Compared to *L* citizens, their *H* counterparts were responsible for nearly six times more per capita emissions, while the *L* group as a whole may be 'charged' climate damages for more than twice its own emissions (Srinivasan et al., 2008).

3.2. Regional example based on *Stern Review* results

Similar analyses at the regional level, with dollar values also converted using PPP- and equity-weights for comparison, could be very informative to policy makers. For example, the methodology in (Srinivasan et al., 2008) may be applied to the baseline-scenario results from the *Stern Review*. Although the regional analysis by Stern et al. (2006) is subject to the same difficulties of extrapolation seen in prior studies, their analysis was chosen for this example as it covers a broad range of market and non-market impacts, with timely and unique emphasis on the important risk of sudden, large-scale climate changes and ensuing regional losses.

The results are depicted in Figure 2, where monetary impacts to eight world regions are subdivided to indicate the responsibilities of the regions driving the damages. For the responsibility metric, cumulative emissions of the three main GHGs over the period 1961–2000 were used (calculated from data in NEAA, 2006; WRI, 2008).

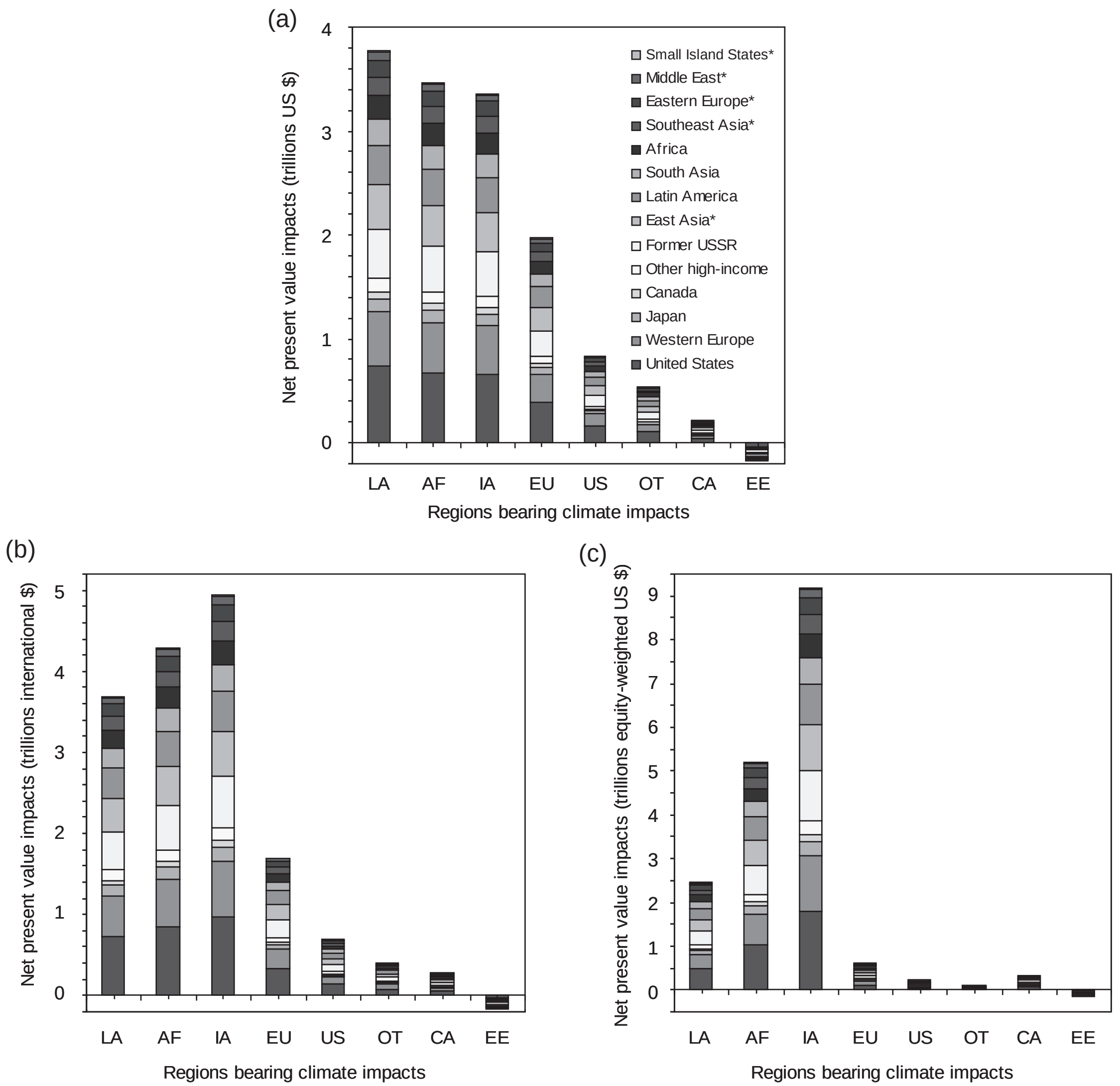


FIGURE 2 NPV projected impacts over the period 2001–2100 to eight world regions due to GHG emissions over the period 1961–2000 using results from the *Stern Review*'s baseline scenario, with bands in each bar representing the division of responsibility among 14 world regions. Small Island States includes Pacific and Indian Ocean States only. The single non-geographical category ('Other high-income countries') consists of rich countries extracted from the five regions marked (*) so that the contribution of the high-income group is easily seen. A discount rate of 1.4% is used. Regional abbreviations on the *x*-axis are as follows: Latin America (LA), Africa and the Middle East (AF), Indian subcontinent and Southeast Asia (IA), European Union (EU), United States (US), Other OECD (OT), China and Centrally Planned Asia (CA) and the former USSR and Eastern Europe (EE). Results are shown in units of (a) 2007 US$, (b) 2007 international $ and (c) 2007 equity-weighted US$.

What is most apparent in Figure 2 is the unequal distribution of blame and burden. The three regions with the greatest predicted damages – Latin America (LA), Africa and the Middle East (AF), and the Indian subcontinent and South East Asia (IA) – were responsible for only 9.0, 7.6 and 8.2% of GHG emissions (25% total), respectively, but together could bear more than 76% of the world damages – nearly four times the USA and Western Europe's potential burden. In addition, the choice of the discount rate *r* strongly influences the presentation of the distribution of costs around the world (see the Appendix for results using $r = 2\%$ and 6%). At the standard short-term interest rate of $r = 6\%$ instead of 1.4% in Figure 2, the share of world damages borne by the groups LA, AF and IA contracts to 48%.

Over the period 1961–2000, the high-income countries were responsible for 42% of the GHG emissions of the three gases (47% of all CO_2 emissions only). Indeed, it was shown that in 1990, regional CO_2 emissions could explain two-thirds of the variation in income levels between the different world regions (Neumayer, 2000). In contrast, China was responsible for approximately one-tenth of world GHG emissions over the 40-year time period in question. However, if cumulative emissions were tabulated through the most recent year for which data is available instead of 2000, both China's and India's shares of responsibility would rise. Alternately, if only fossil CO_2 emissions were used to gauge responsibility, the high-income countries' share of the liability would rise significantly. Using cumulative estimates over the period 1750–1995, it was demonstrated that this switch would inflate developed-world responsibility by ~35% (Höhne and Blok, 2005).

US$ impacts (Figure 2a) belie the differences in relative burden among regions. The use of parity weights (Figure 2b) widens the gulf between developed and developing region impacts, and also shuffles the order of the three highest-impact regions, which now bear 82% of the world burden. Equity-weighting (Figure 2c) puts the inequality into high relief, as the poorest three regions overwhelmingly shoulder the burden (94%). If responsibility fractions were equity-weighted as well, and subsistence emissions were given less weight than luxury emissions (Baer, 2006; Baer et al., 2009), the pattern would be starker still. Viewed in terms of the 'polluter pays' principle (Meyer, 2000), the USA and Western Europe could be called upon to pay US$2.6 and 1.6 trillion, respectively, to the other regions of the world. Politically improbable as this may be, the onus is clearly on the high-income group to take the lead in curtailing emissions.

This example is intended as illustrative, as the particular numbers are tied to one scenario from one study, albeit a recent and prominent one (Ackerman, 2007; HM Treasury, 2008). Granted, the level of uncertainty is substantial; Stern et al. (2006) estimated the standard deviation in 2100 to represent 84% of that year's world damages. Nevertheless, the pattern of risk and responsibility between developing and developed countries is not at all difficult to see.

4. Conclusions

The unambiguous imbalance of risk and responsibility surveyed here lends further support to the argument that rich countries must definitively lead in addressing climate change, both in targeting deeper, swifter emissions cuts and in providing adequate financial and technological support to developing countries for both mitigation and adaptation. Adjusting for the real differences between world regions in either purchasing power or welfare only heightens the contrast, increasing the urgency of decisive action.

Certainly, economic models of climate change impacts only represent one dimension of this argument. Putting a price tag on human life or the existence of a threatened species (Funtowicz and Ravetz, 1994) is rife with 'conceptual, ethical, and empirical' dilemmas (Stern et al., 2006), prompting many to argue for a variety of numeraires: market impacts in dollar terms, human lives in disability-adjusted life years, numbers of species lost, and indicators of the income distribution and quality of life around the world (Schneider and Lane, 2006). The degradation of ecosystems, humanity's life-support, is not at all easily priced either, and ecological economists question whether it is worthwhile to do so (Daly and Farley, 2004). But even 2°C of global mean warming, once thought to be the threshold below which dangerous climate change could be avoided, may cause dire regional impacts (Baer and Mastrandrea, 2006), so that combining economic, ethical and political reasoning into a multi-pronged argument may be the best hope for spurring strong action. Global mobilization must be swift; to avoid the dangerous consequences of an ice-free world, Hansen and co-workers (2008b) have urged atmospheric stabilization at 350 ppm CO_2 instead of the widely-held goal of 450 ppm, prompting prominent policy makers, scientists, and economists, including IPCC head Rajendra Pachauri and *Stern Review* author Nicholas Stern, to endorse this tougher target (Ackerman et al., 2009).

Clearly, ethical considerations enter into every step of the climate impact modelling process, most influentially when regional impacts are aggregated geographically and over time. Decisions on the discount rate and the monetary unit used have enormous consequences on the portrayal of relative regional impacts, but the choices are often buried in economic language. To its credit, the *Stern Review* called for open, systematic deliberation on these distributional and ethical judgments (Stern et al., 2006). In exploring the ethical perspectives involved in climate risks, Dietz et al. (2007b) quoted Nobel prize-winning economist Amartya Sen: 'the implicit values have to be made more explicit'.

From the start of climate change negotiations, principles of equity have been at the eye of the storm. The 1992 Rio Framework Convention on Climate Change sought stabilization of atmospheric GHG concentrations without hindering sustainable development, and the 1997 Kyoto Protocol was founded on the principle of 'common but differentiated responsibilities and respective capabilities' (UNFCCC, 2010). Although the 2007 Bali Action Plan centred around absolute and quantified reductions for developed nations (Annex I) and 'nationally appropriate' reductions relative to business-as-usual levels by developing nations (non-Annex I or NAI) (UNDP, 2008; UNFCCC, 2010), at Copenhagen, developed countries largely avoided debating aggregate targets; while leading developing countries, notably China, refused legally binding commitments (Copenhagen Climate Change Conference, COP-15, 2009; Miliband, 2009).

Although the Annex I/non-Annex I framework recognizes the different responsibilities and capabilities of countries to mitigate emissions, arriving at particular targets has relied heavily on 'political horse-trading' (UNDP, 2008). As shown by numerous studies and corroborated here, the use of analytical criteria can give clarity – much needed and often eschewed – to issues of global greenhouse equity. Many groups have advocated the use of indices to chart differentiated mitigation paths and payment obligations for developed (Annex I) and developing (Non-Annex I) nations (see review of approaches in UNDP, 2008). For example, Haites et al. (2009) described a country-level indicator that combines per capita values of cumulative CO_2 emissions (representing responsibility), GDP (reflecting ability to pay for mitigation), and non-land-use/forestry GHG emissions (indicating mitigation potential) to help navigate the thorny issue of when a non-Annex I nation might cross over to Annex I status. Taking development rights more explicitly into account, Baer et al. (2009) proposed defining country obligations to a global mitigation fund using a responsibility and capacity indicator based on: (1) PPP-adjusted per capita income above a development threshold (capacity), and (2) cumulative country emissions above consumption levels required to reach the development threshold (responsibility). Similarly, the

Swiss Proposal, which advocated a global CO_2 levy to fund the post-2012 regime, also included country-level exemptions based on a per capita emissions threshold of 1.5 tCO_2 per year (see list of proposals in UNFCCC, 2008).

Naturally, countries lobby for measures that best support their interests. From 1990 to 2003, China's fossil fuel consumption grew by ~70%, and India's by ~80%, while the USA, already starting at a high level in 1990, increased its fuel use by 18% (WRI, 2008). By mid-century, China is projected to surpass the USA even in cumulative emissions dating from 1900 (Botzen et al., 2008), although Chinese emissions on a per capita basis will still be lower. As discussed earlier, the choice of the start date is crucial; while China's fossil CO_2 output exceeded that of the USA in 2006, its cumulative emissions over the period 1950–2006 represented 41% of US levels over the same period (CDIAC, 2009). Although developing nations may contribute as much as three-quarters of the rise in the world's energy CO_2 emissions by 2030 (UNDP, 2008, p.13), they point out that today's developed countries were industrialized without carbon limits.

Thus, international transfers of funding and technology to developing countries to enable low-carbon energy production, energy efficiency, and carbon capture and storage will be critical. Infrastructure deals between developed and developing countries will be most influential (Wara and Victor, 2008), and if international emissions offsets, as promoted by the Clean Development Mechanism (UNFCCC, 2010), are to make a dent, urgent reform to upgrade the environmental integrity of the programmes and filter out business-as-usual projects is needed (Wara, 2007; Wara and Victor 2008; Haya, 2009).

Establishing accepted vulnerability metrics for use in negotiations will also strengthen the case of those most at risk and least to blame, and could help in formulating levels of financial and technology transfers to these countries. According to one indicator, the ten nations most vulnerable to extreme weather events are in Asia and Central America (Harmeling, 2009), while another index locates three-quarters of the 20 most climate-change-vulnerable nations in Africa (Maplecroft, 2010). Monetary and non-monetary impact predictions, although inherently uncertain, must be publicized widely to convey the severity and inequity of harm at stake. As a case in point, Nicholls et al. (1999) predicted that by 2080, 90 million people in South and South East Asia and Africa may experience sea level rise-related flooding, compared with 3 million in the rest of the world.

Regarding international transfers, at Kyoto several Annex I countries pledged to fund the 'full incremental costs' of mitigation by NAI nations as well as transfer the needed technology (UNFCCC, 2010). At Copenhagen, the USA pledged to help mobilize \$100 billion per year by 2020, and six developed countries promised \$3.5 billion to halt and ultimately reverse tropical deforestation (COP-15, 2009). These funds must not be delayed. Still, much more is needed; by 2030, mitigation in developing countries may cost ~\$200 billion per year according to one potentially conservative estimate (UNDP, 2008) given that many studies estimate global mitigation costs as being 1–3% of world GDP (Ackerman et al., 2009). Indeed, given the stark contrast between financial risk and historical responsibility reviewed here, the case could be made for debt forgiveness for the world's poorest and most climate-change-vulnerable nations.

The developed world has begun to accept its share of responsibility, although it is unknown what the road from Copenhagen will hold. Scientific understanding of the pattern of climate risk around the world is also evolving. Mitigation of emissions is not enough; it is also imperative to help poor nations increase their resilience to current climate impacts that will probably worsen (Pielke et al., 2007). Near the end of 2007 in Bali (UNFCCC, 2010), a stronger adaptation fund was launched to aid poor countries in coping with the costs. By 2030, adaptation may cost these countries \$28–67 billion every year by one estimate (UNDP, 2008); a figure that dwarfs the \$30 million that has actually been spent on such efforts (Economist, 2008).

In the final negotiations at Copenhagen, China, India, Brazil and South Africa represented developing-world interests (UNFCCC, 2010), while the voices of the two most vulnerable segments of the world's population – citizens of small island states and the 'poorest of the poor', although resonant (Miliband, 2009), remained underrepresented. Their plight shines a spotlight on greenhouse development rights (Baer et al., 2009) and the fair goal of convergence on equal emissions entitlements for each citizen of the world (Baer et al., 2000; Meyer 2000).

Climate change has been called 'the world's biggest regressive tax' (Economist, 2008). If countries do not cooperate to act decisively over the decades to come, it is very likely that the fates of rich and poor around the globe will diverge still further.

Acknowledgements

I would like to thank Simon Dietz for sharing regional output from the *Stern Review*'s baseline climate scenario; Amber Kerr for compiling and analysing cumulative GHG emissions by world region; and Paul Baer, Barbara Haya, Richard Norgaard, John Heck and Danielle Svehla for constructive criticism.

References

Ackerman, F., 2007, *Debating Climate Economics: The Stern Review vs. Its Critics*, Report to Friends of the Earth-UK [available at www.ase.tufts.edu/gdae/Pubs/rp/SternDebateReport.pdf].

Ackerman, F., Stanton, E.A., DeCanio, S.J., Goodstein, E., Howarth, R.B., Norgaard, R.B., Norman, C.S., Sheeran, K.A., 2009, *The Economics of 350: The Benefits and Costs of Climate Stabilization*, Economics for Equity and Environment [available at www.e3network.org/papers/Economics_of_350.pdf].

Auffhammer, M., Carson, R.T, 2008, 'Forecasting the path of China's CO_2 emissions using province level information', *Journal of Environmental Economics and Management* 47, 47–62.

Azar, C., Sterner, T., 1996, 'Discounting and distributional considerations in the context of global warming', *Ecological Economics* 19, 169–184.

Baer, P., 2006, 'Adaptation: who pays whom?', in: W.N. Adger, J. Paavola, S. Huq, M.J. Mace (eds), *Fairness in Adaptation to Climate Change*, MIT Press, Cambridge MA, 134–153.

Baer, P., Mastrandrea, M., 2006, *High Stakes Designing Emissions Pathways to Reduce the Risk of Dangerous Climate Change*, Institute for Public Policy Research, London.

Baer, P., Harte, J., Haya, B., Herzog, A., Holdren, J., Hultman, N.E., Kammen, D.M., Norgaard, R.B., Raymond, L., 2000, 'Equity and greenhouse gas responsibility', *Science* 289, 2287.

Baer, P., Athanasiou, T., Kartha, S., 2009, *The Right to Development in a Climate Constrained World: The Greenhouse Development Rights Framework*, Heinrich Böll Foundation, Berlin, Germany.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005, 'Potential impacts of a warming climate on water availability in snow-dominated regions', *Nature* 438, 303–309.

Botzen W.J.W., Gowdy, J.M., van den Bergh, J.C., 2008, 'CO_2 emissions: shifting international responsibilities for climate debt', *Climate Policy* 8, 569–576.

CDIAC (Carbon Dioxide Information Analysis Center), 2009, 'Top 20 emitting countries by total fossil-fuel CO_2 emissions for 2006' [available at http://cdiac.ornl.gov/trends/emis/tre_tp20.html].

Clarkson, R., Deyes, K., 2002, *Estimating the Social Cost of Carbon Emissions*, GES Working Paper 140, HM Treasury, London.

Copenhagen Climate Change Conference (COP-15), 2009, http://en.cop15.dk/.

Daly, H.E., Farley, J., 2004, *Ecological Economics*, Island Press, Washington, DC.

den Elzen, M.G.J., Schaeffer, M., 2002, 'Responsibility for past and future global warming: uncertainties in attributing anthropogenic climate change', *Climatic Change* 54, 29–73.

Dietz, S., Hope, C., Stern, N., Zenghelis, D., 2007a, 'Reflections on the Stern Review. 1. A robust case for strong action to reduce the risks of climate change', *World Economics* 8, 121–168.

Dietz, S., Hepburn, C., Stern, N., 2007b, 'Economics, ethics and climate change', Social Science Research Network [available at http://ssrn.com/abstract=1090572].

Economist, 2008, 'Climate change and the poor: adapt or die', *Economist*, 13 September, 50.

Enting, I.G., Law, R.M., 2002, *Characterising Historical Responsibility for the Greenhouse Effect*, CSIRO Atmospheric Research Technical Paper No. 41, CSIRO, Aspendale Victoria, Australia.

Eyre, N., Downing, T., Hoekstra, R., Rennings, K., Tol, R.S.J., 1997, *Global Warming Damages*, ExternE Project, European Commission, Brussels.

Fankhauser, S., 1995, 'Protection versus retreat: the economic cost of sea level rise', *Environment and Planning A* 27, 299–319.

Fankhauser, S., Tol, R.S.J., 2005, 'On climate change and economic growth', *Resource and Energy Economics* 27, 1–17.

Fankhauser, S., Tol, R.S.J. Pearce, D.W., 1997, 'The aggregation of climate change damages: a welfare theoretic approach', *Environmental and Resource Economics* 10, 249–266.

Farber, S.C., Costanza, R., Wilson, M.A., 2002, 'Economic and ecological concepts for valuing ecosystem services', *Ecological Economics* 41, 375–392.

Funtowicz, S.O., Ravetz, J.R., 1994, 'The worth of a songbird: ecological economics as a post-normal science', *Ecological Economics* 10, 197–207.

Gelling, P., 2007, 'Bali climate talks find focus in fund for poor nations', *International Herald Tribune* [available at www.iht.com/articles/2007/12/12/news/climate.php].

Haites, E., Yamin, F., Höhne, N., 2009, *The São Paulo Proposal for an Agreement on Future International Climate Policy*, Discussion Paper 2009-31, Harvard Project on International Climate Agreements, Belfer Center for Science and International Affairs, Harvard Kennedy School, Cambridge, MA.

Hall, D.C., Behl, R.J., 2006, 'Integrating economic analysis and the science of climate instability', *Ecological Economics* 57, 442–465.

Hansen, J., 2007, 'Why we can't wait: a 5-step plan for solving the global crisis', *Nation*, 7 May, 13–14.

Hansen, J., Sato, M., Ruedy, R., Kharecha, P., Lacis, A., Miller, R.L., Nazarenko, L., Lo, K., Schmidt, G.A., Russell, G., et al., 2008a, 'Dangerous human-made interference with climate: a GISS modelE study', *Atmospheric Chemistry and Physics* 7, 2287–2312.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L., Zachos, J.C., 2008b, 'Target atmospheric CO_2: where should humanity aim?', *Open Atmospheric Science Journal* 2, 217–231.

Harmeling, S., 2009, *Global Climate Risk Index 2010*, Germanwatch, Bonn [available at www.germanwatch.org].

Haya, B., 2009, *Measuring Emissions Against an Alternative Future: Fundamental Flaws in the Structure of the Kyoto Protocol's Clean Development Mechanism*, Energy and Resources Group Working Paper ERG09-001, University of California, Berkeley, CA [available at http://erg.berkeley.edu/working_paper/2009/ERG09-001.pdf].

HM Treasury, 2008, *Stern Review on the Economics of Climate Change, Comments on the Review*, HM Treasury and Cabinet Office, London [available at www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm].

Höhne, N., Blok, K., 2005, 'Calculating historical contributions to climate change: discussing the Brazilian Proposal', *Climatic Change* 71, 141–173.

Hope, C., 2006, 'The marginal impact of CO_2 from PAGE2002: an integrated assessment model incorporating the IPCC's five reasons for concern', *Integrated Assessment Journal* 6, 19–56.

Insurance Australia Group, 2005, *Evidence to the Stern Review*, Insurance Australia Group, Australia [available at www.iag.com.au/sustainable/media/Submission%20Stern%20Final.pdf].

IPCC, 2007, *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the IPCC, Cambridge University Press, Cambridge, UK.

Link, P.M., Tol, R.S.J., 2004, 'Possible economic impacts of a shutdown of the thermohaline circulation: an application of FUND', *Portuguese Economic Journal* 3, 99–114.

Grubb, M., 1995, 'Seeking fair weather: ethics and the international debate on climate change', *International Affairs* 71, 463–496.

Maplecroft, 2010, *Climate Change Risk Atlas 2010* [available at www.maplecroft.com/portfolio/climate_change/report_2010/].

Mendelsohn, R., Neumann, J. (eds), 1998, *The Economic Impact of Climate Change on the United States Economy*, Cambridge University Press, Cambridge, UK.

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

Mendelsohn, R., Dinar, A., Williams, L., 2006, 'The distributional impact of climate change on rich and poor countries', *Environment and Development Economics* 11, 159–178.

Meyer, A., 2000, *Contraction and Convergence: The Global Solution to Climate Change*, Green Books for the Schumacher Society, Devon, UK.

Miliband, E., 2009, 'The road from Copenhagen', guardian.co.uk, 20 December 20 [available at www.guardian.co.uk/commentisfree/2009/dec/20/copenhagen-climate-change-accord].

Millennium Ecosystem Assessment, 2005a, *Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group: Cultivated Systems*, Island Press, Washington, DC, 747–794.

Millennium Ecosystem Assessment, 2005b, *Ecosystems and Human Well-being: Scenarios: Drivers of Change in Ecosystem Condition and Services*, Island Press, Washington, DC, 173–222.

Myers, N., Kent, J., 1995, *Environmental Exodus: An Emergent Crisis in the Global Arena*, Climate Institute, Washington, DC.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., et al., 2000, *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

NEAA (Netherlands Environmental Assessment Agency), 2006, *Emission Data (EDGAR-HYDE 1.4)* [available at www.mnp.nl/edgar/model/100_year_emissions/], accessed 1 December 2006.

Neumayer, E., 2000, 'In defence of historical accountability for greenhouse gas emissions' *Ecological Economics* 33, 185–192.

Nicholls, R.J., Hoozemans, F.M.J., Marchand, M., 1999, 'Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses', *Global Environmental Change* 9, S69–S87.

Nordhaus, W.D., 2006, 'Geography and macroeconomics: new data and new findings', *Proceedings of the National Academy of Sciences* 103, 3510–3517.

Nordhaus, W.D., Boyer, J.G., 2000, *Warming the World: Economic Models of Global Warming*, MIT Press, Cambridge, MA.

O'Connor, M., Spash, C.L., 1999, 'Valuation and the environment: theory, method and practice', Edward Elgar, Cheltenham, UK.

Patz, J.A., Gibbs, H.K., Foley, J.A., Rogers, J., Smith, K.R., 2007, 'Climate change and global health: quantifying a growing ethical crisis', *EcoHealth* 4, 397–405.

Pearce, D., 2003, 'The social cost of carbon and its policy implications', *Oxford Review of Economic Policy* 19, 362–384.

Pearce, D.W., Cline, W.R., Achanta, A., Fankhauser, S., Pachauri, R., Tol, R., Vellinga, P., 1996, 'The social costs of climate change: greenhouse damage and the benefits of control', in J.P. Bruce, H. Lee, E.F. Haites (eds), *Climate Change 1995: Economic and Social Dimension*s. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 183–224.

Pielke, R., Prins, G., Rayner, S., Schwartz, D., 2007, Commentary: 'Lifting the taboo on adaptation', *Nature* 445, 597–598.

Rive, N., Torvanger, A., Fuglestvedt, J.S., 2006, 'Climate agreements based on responsibility for global warming: periodic updating, policy choices, and regional costs', *Global Environmental Change* 16, 182–194.

Sagar, A.D., 2000, 'Wealth, responsibility, and equity: exploring an allocation framework for global GHG emissions', *Climatic Change* 45, 511–527.

Schneider, S., Lane, D., 2006, 'Dangers and thresholds in climate change and the implications for justice', in W.N. Adger, J. Paavola, S. Huq, M.J. Mace (eds), *Fairness in Adaptation to Climate Change*, MIT Press, Cambridge, MA, 23–52.

Srinivasan, U.T., Carey, S.P., Hallstein, E., Higgins, P.A., Kerr, A.C., Koteen, L.E., Smith, A.B., Watson, R., Harte, J., Norgaard, R.B., 2008, 'The debt of nations and the distribution of ecological impacts from human activities', *Proceedings of the National Academy of Sciences* 105, 1768–1773.

Stern, N., Peters, S., Bakshi, V., Bowen, A., Cameron, C., Catovsky, S., Crane, D., Cruickshank, S., Dietz, S., Edmonson, N., et al, 2006, *Stern Review: The Economics of Climate Change*, HM Treasury, London.

Thomas, D.S.G., Twyman, C., 2005, 'Equity and justice in climate change adaptation amongst natural resource dependant societies', *Global Environmental Change – Human and Policy Dimensions* 15, 115–124.

Tol, R.S.J., 1999, 'The marginal costs of greenhouse gas emissions', *Energy Journal* 20, 61–81.

Tol, R.S.J., 2002, 'Estimates of the damage costs of climate change. Part 1. Benchmark estimates', *Environmental and Resource Economics* 21, 47–73.

Tol, R.S.J., 2005, 'The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties', *Energy Policy* 33, 2064–2074.

Tol, R.S.J., Verheyen, R., 2004, 'State responsibility and compensation for climate change damages: a legal and economic assessment', *Energy Policy* 32, 1109–1130.

Tol, R.S.J., Downing, T.E., Kuik, O.J., Smith, J.B., 2004, Distributional aspects of climate change impacts', *Global Environmental Change* 14, 259–272.

Torn, M.S., Harte, J., 2006, 'Missing feedbacks, asymmetric uncertainties, and the underestimation of future warming', *Geophysical Research Letters* 33, L10703.

Torras, M., 2000, 'The total economic value of Amazonian deforestation, 1978–1993', *Ecological Economics* 33, 283–297.

UNDP, 2008, *Climate Change Mitigation Negotiations, with an Emphasis on Options for Developing Countries*, UN Development Program, University of Cape Town, South Africa.

UNFCCC, 2008, 'Ideas and proposals on the elements contained in paragraph 1 of the Bali Action Plan: submissions from Parties' [available at http://unfccc.int/resource/docs/2008/awglca4/eng/misc05.pdf, http://unfccc.int/resource/docs/2008/awglca3/eng/misc02.pdf].

UNFCCC, 2010, http://unfccc.int/2860.php.

Wara, M., 2007, 'Is the global carbon market working?', *Nature* 445, 595–598.

Wara, M.W., Victor, D.G., 2008, *A Realistic Policy on International Carbon Offsets*, Program on Energy and Sustainable Development at Stanford University Working Paper #74, Stanford, California, USA.

Warren, R., Arnell, N., Nicholls, R., Levy, P., Price, J., 2006, *Understanding the Regional Impacts of Climate Change: Research Report Prepared for the Stern Review on the Economics of Climate Change*, Tyndall Working Paper 90, Tyndall Centre, Norwich, UK.

Weitzman, M.L., 2007, 'A review of the *Stern Review on the Economics of Climate Change*', *Journal of Economic Literature* 45, 703–724.

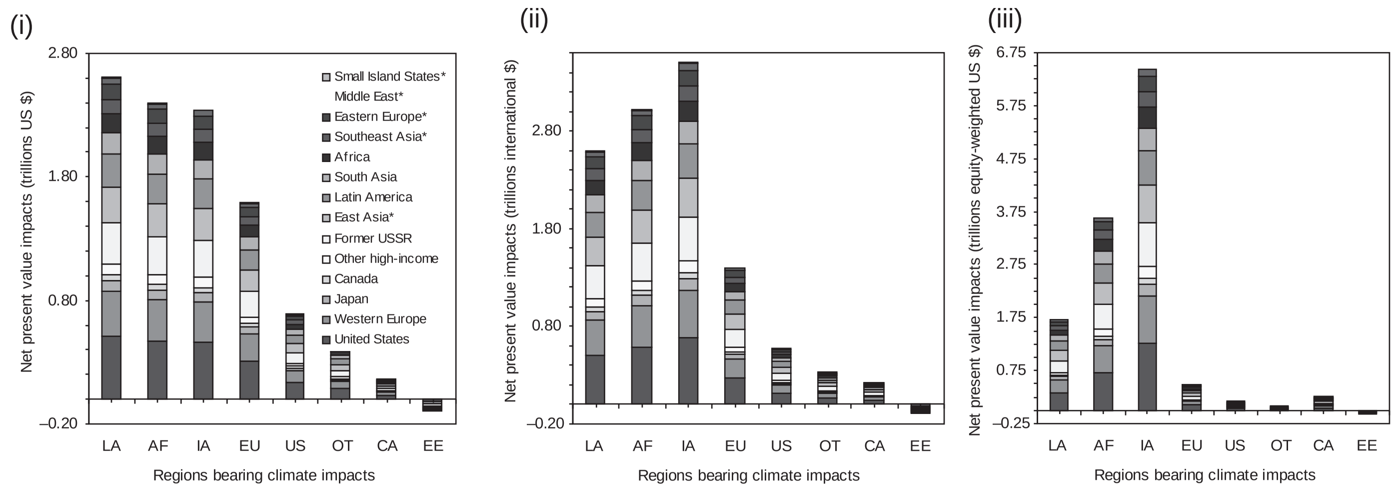
World Bank Group, 2008, *World Development Indicators Database* [available at http://publications.worldbank.org/WDI/indicators].

WRI (World Resources Institute), 2008, *EarthTrends Database* [available at http://earthtrends.wri.org/], accessed 2 June 2008.

Appendix

Sensitivity analysis of Figure 2 to discount rate *r*. (a) *r* = 2% and (b) *r* = 6%. Panels show impacts in (i) 2007 US$, (ii) 2007 international $ and (iii) 2007 equity-weighted US$.

(a) r = 2



(b) r = 6