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How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: A comprehensive indicator-based assessment

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ABSTRACT

While it is generally asserted that those countries who have contributed least to anthropogenic climate change are most vulnerable to its adverse impacts some recently developed indices of vulnerability to climate change come to a different conclusion. Confirmation or rejection of this assertion is complicated by the lack of an agreed metric for measuring countries' vulnerability to climate change and by conflicting interpretations of vulnerability. This paper presents a comprehensive semi-quantitative analysis of the disparity between countries' responsibility for climate change, their capability to act and assist, and their vulnerability to climate change for four climate-sensitive sectors based on a broad range of disaggregated vulnerability indicators. This analysis finds a double inequity between responsibility and capability on the one hand and the vulnerability of food security, human health, and coastal populations on the other. This double inequity is robust across alternative indicator choices and interpretations of vulnerability. The main cause for the higher vulnerability of poor nations who have generally contributed little to climate change is their lower adaptive capacity. In addition, the biophysical sensitivity and socio-economic exposure of poor nations to climate impacts on food security and human health generally exceeds that of wealthier nations. No definite statement can be made on the inequity associated with climate impacts on water supply due to large uncertainties about future changes in regional water availability and to conflicting indicators of current water scarcity. The robust double inequity between responsibility and vulnerability for most climate-sensitive sectors strengthens the moral case for financial and technical assistance from those countries most responsible for climate change to those countries most vulnerable to its adverse impacts. However, the complex and geographically heterogeneous patterns of vulnerability factors for different climate-sensitive sectors suggest that the allocation of international adaptation funds to developing countries should be guided by sector-specific or hazard-specific criteria despite repeated requests from participants in international climate negotiations to develop a generic index of countries' vulnerability to climate change.

1. Introduction

Concerns about international equity are central for the formulation of global climate policy. A comprehensive international agreement on climate protection will only be agreed upon if it is considered fair by all parties involved (Tóth, 1999; Lange et al., 2007; Comim, 2008). Specifically, the distribution of the costs of climate policies across countries needs to consider their responsibility[1] for climate change and their capability to assist whereas the allocation of resources for adaptation across countries should be guided by their vulnerability to climate change,[2] and possibly by additional factors.[3] If the regional distributions of responsibility and capability on the

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[1] In ethical and legal debates the term "responsibility for climate change" can be interpreted in different ways, including as causal responsibility, outcome responsibility, moral responsibility, and remedial responsibility (Miller, 2007; Müller et al., 2009). This paper applies the term "responsibility" to denote "causal responsibility", except if noted otherwise.

[2] The terms responsibility, capability, and vulnerability are mentioned in Article 3 ("Principles") and in other parts of the UNFCCC (United Nations General Assembly, 1992) but they are not clearly defined there. None of these terms can be quantified unequivocally on a scientific basis.

[3] Other relevant factors concern the adaptability of countries (i.e., the ability to reduce vulnerability to climate change by payments to the national government). Adaptability factors are intentionally not considered here because they are more difficult to quantify, and their implications for just adaptation funding are ethically more controversial than for vulnerability. Whereas all conceivable justice concepts will prioritize countries that are highly vulnerable to climate change (assuming that they cannot be blamed for their high vulnerability) over those with low vulnerability, a utilitarian and an egalitarian may well disagree whether limited resources for international adaptation funding should be targeted at countries where adaptation is particularly easy (which implies large benefits for a given amount spent) or where adaptation is particularly difficult (which implies that the needs for adaptation assistance are particularly large). The ethical assessment becomes even more controversial if it considers that countries may be co-responsible for their low vulnerability and adaptability (e.g., due to poor governance).

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one hand, and of vulnerability on the other, were very similar, climate change would not be a cause of major concern for international inequity. However, many countries who have contributed little to causing climate change are strongly affected by its adverse impacts. This asymmetry between responsibility/capability and vulnerability is considered unjust based on many intuitive as well as formalized concepts of justice, including the "no harm" principle and the "polluter pays" principle (Adger et al., 2006; Heyward, 2007; Miller, 2007; Comim, 2008; Grasso, 2009; Klinsky and Dowlatabadi, 2009). This injustice implies obligations for those countries (and individuals) with high responsibility and/or capability, and rights of those countries (and individuals) with high vulnerability.

Negotiators of international climate policy as well as national decision-makers have repeatedly called for developing generic indices of vulnerability to climate change as a supposedly objective basis for identifying regional priorities for planning, implementing and funding adaptation (see Section 4.1). However, there is substantial scientific and political disagreement on the measurement of countries' responsibility, capability, and vulnerability. This paper intends to inform the pertinent political debate on international adaptation funding by providing robust information on the degree of inequity between responsibility/capability and vulnerability for different climate-sensitive sectors and for different conceptualizations of vulnerability to climate change. The choice of countries as the principal analysis unit was motivated by the current reality of global climate change governance, which regards national governments (somewhat ideally) as representatives of their citizen's collective interests.

Several studies have analyzed the inequity between responsibility for climate change or capability to assist on the one hand and economic impacts of climate change on the other. Tol et al. (2004) quantifies the inequities of market damages from climate change based on the FUND 2.6 model. The study concludes that climate change will impact more severely (expressed as a percentage loss of GDP) on the poorer people of the world, because they are more exposed to the weather, because they are closer to the biophysical and experience limits of climate, and because their adaptive capacity is lower. Mendelsohn et al. (2006) compares the market impacts of climate change on rich and poor countries by applying to the whole world impact response functions originally developed for the USA (Mendelsohn et al., 2000; Mendelsohn and Schlesinger, 1999). The study finds that poor countries will suffer the bulk of the damages from climate change and argues that the primary reason that poor countries are so vulnerable is their already warm current climate. Panayotou et al. (2002) and Tol and Verheyen (2004) independently estimate that OECD countries would have to pay up to 4% of their GDP as compensation for climate damages to poorer countries if state responsibility for climate change damages were legally accepted. More recently, Srinivasan et al. (2008) has assessed the distribution of costs for six categories of human-induced environmental changes, including climate change. The study concludes that "*through disproportionate emissions of greenhouse gases alone, the rich group may have imposed climate damages on the poor group greater than the latter's current foreign debt*" (p. 1768). Two studies have compared the distribution of responsibility for climate change with the distribution of non-monetary climate impacts. Patz et al. (2007) show that there is a large disparity between those countries most responsible for climate change (on a per-capita basis) and those where population health is most adversely affected by it; SEGCC (2007) comes to similar conclusions using non-monetary indices of social and agro-economic vulnerability to climate change.

In apparent contradiction with these findings, several recently developed indices of countries' generic vulnerability to climate change suggest that wealthy countries with high emission levels may also be particularly vulnerable to climate change. Yohe et al. (2006a,b) have developed a set of indices of countries' vulnerability to climate change that vary according to different assumptions regarding climate sensitivity, the development of adaptive capacity, and other calibration parameters. The project website[4] displays 144 global vulnerability maps, which differ vastly in the characterization of most vulnerable countries. Interestingly, many of these maps identify Russia as the country that is most vulnerable to climate change. The Environmental Vulnerability Index (EVI) developed by the South Pacific Applied Geoscience Commission (SOPAC) (Kaly et al., 2004) contains a climate change subindex (EVI-CC), which suggests that environmental vulnerability to climate change is highest in most European countries and in small island states whereas it is lowest in most African countries. Despite these counter-intuitive results, the main developer of this index has suggested that it could be used without any modification to measure countries' vulnerability for allocating adaptation funds (IRIN, 2009). The 'indicator of 21st century socioclimatic exposure' (Diffenbaugh et al., 2007) combines data on the severity of regional climate change, economic capacity, and assets at risk. According to this indicator, China and the U.S. East Coast have the highest socioclimatic exposure whereas some of the poorest countries in Africa have very low socioclimatic exposure.

A detailed review shows that each of the vulnerability indices mentioned above suffers from fundamental conceptual, methodological, and/or empirical flaws (see Section 4.1). Nevertheless, these results raise the question whether the widely held view that those countries least responsible for climate change are generally most vulnerable to its adverse impacts may be incorrect, or at least not robust. Which robust statements can be made on the asymmetry between responsibility/capability and vulnerability to climate change, and what are the main reasons for these asymmetries? In response to these questions, this paper presents a disaggregated analysis of the implications of climate change on international equity for four climate-sensitive sectors, which is based on a broad range of national-level indicators of responsibility, capability, and vulnerability to climate change. The key questions addressed by this semi-quantitative analysis are as follows:

1. How unequal are the distributions of responsibility, capability, and vulnerability to climate change across countries for different climate-sensitive sectors and for different conceptualizations of vulnerability?
2. Which findings are robust across different conceptualizations of vulnerability and across alternative indicators of responsibility, capability, and vulnerability?
3. Which factors are most important for the unequal distribution of responsibility and capability on the one hand and vulnerability to climate change on the other?

International adaptation funding raises many challenging ethical, political, and legal questions (Adger et al., 2006; Agrawala, 2008; Grasso, 2009; Hallegatte, 2008; Harris, 2010; Heyward, 2007; Jagers and Duus-Otterström, 2008; Klein and Persson, 2008; Klinsky and Dowlatabadi, 2009; Persson et al., 2009; Verheyen, 2002; Verheyen, 2005). Vulnerability research is developing and debating alternative theoretical models of vulnerability (Cardona, 2003; Downing and Patwardhan, 2004; Füssel, 2007; Kasperson et al., 2005; Kelly and Adger, 2000; Leary et al., 2008; O'Brien et al., 2007; Turner II et al., 2003). In addition, several scholars have developed and/or reviewed generic indices of countries' vulnerability to climate change (Brooks et al., 2005; Eriksen and Kelly, 2007; Füssel, 2009; Gall, 2007; Kaly et al., 2004; Moss et al., 2001;

[4] http://sedac.ciesin.columbia.edu/mva/ccv/maps.html.

Yohe et al., 2006a). However, the purpose of this paper is not to add significant new arguments to the ethical debate or to develop a consistent theory of vulnerability but to provide a robust empirical assessment of the implications of climate change on international inequity that can inform the (ultimately political) decisions on international adaptation funding within the framework of the UNFCCC.

The remainder of this paper is organised as follows. Section 2 explains the methods applied in this study. Section 3 identifies and compares four responsibility and capability indicators for application in the inequity analysis. Section 4 outlines the conceptual framework for the classification of vulnerability indicators, selects 33 vulnerability indicators for four climate-sensitive sectors, and analyzes their relationship with the responsibility and capability indicators identified before. Section 5 synthesizes the results of the inequity analysis, and Section 6 concludes this paper.

2. Methods

An analysis of the implications of global climate change on international equity faces several challenges. First, there are different ways for measuring countries' causal or moral responsibility for climate change (see Section 4). Second, climate change affects nations and communities in different ways, and it interacts in complex ways with existing stressors and problems. Third, there is considerable confusion as to the appropriate conceptualization of vulnerability to climate change (Füssel, 2007; O'Brien et al., 2007), which may lead to very different vulnerability rankings of countries (Eriksen and Kelly, 2007; Füssel, 2009; Gall, 2007) (see also Section 4.1). Finally, it is difficult to include the (sometimes very large) uncertainty about future climate change and its impacts in a single vulnerability metric. As a result, the identification of "particularly vulnerable" countries is primarily a political rather than a scientific challenge (Füssel, 2009; Klein, 2009).

This paper responds to these challenges by analyzing the relationship between several national-level indicators of causal responsibility for climate change and socio-economic capability to assist on the one hand and a broad range of sector-specific vulnerability indicators for water supply, food security, human health, and coastal zones on the other. Such a disaggregated inequity analysis allows identifying the main reasons for the inequity between responsibility/capability and vulnerability, and assessing the robustness of the findings across alternative indicator choices.

The indicator selection for the inequity analysis aims to identify a broad range of indicators based on the following criteria that are deemed crucial for their acceptability in political decisions on adaptation funding: relevance, significance, scientific credibility, public availability, and near-global coverage. Vulnerability indicators are classified according to a conceptual framework derived from the definition of vulnerability to climate change in the glossary of the IPCC Fourth Assessment Report (IPCC, 2007a) (see Section 4.2). The indicators include observed socio-economic and biophysical data from international organisations as well as estimates of recent and future climate impacts from international organisations and from the academic literature.

The indicators selected here exhibit significant overlap with those applied in earlier studies attempting to quantify the responsibility and capability (Höhne et al., 2007; Müller et al., 2007; WRI, 2009) or the vulnerability of countries to climate change (Buys et al., 2007; Expert Group to the Subcommittee of the PPCR, 2009; Gall, 2007; Moss et al., 2001; SEGCC, 2007; World Bank, 2009), for two reasons. First, these existing studies have been scrutinized to identify a broad range of suitable indicators. Second, these studies generally have relied on the same publicly available data sources and have applied similar principles for their indicator selection. In contrast to many of these studies, however, this analysis does not attempt to develop another national-level index but to assess the extent, robustness, and causes of the inequities caused by climate change for a wide range of alternative indicators that have been, or could plausibly be, used to quantify these vague concepts.

The asymmetry between countries' responsibility, capability, and vulnerability is investigated using Spearman's rank correlation coefficient, whereby all countries are weighted equally. In order to avoid spurious correlations, all indicators are normalized so that they do not scale with the population or area of a country. In this way, countries with comparable socio-economic and/or environmental conditions will be treated similarly, independent of their size. A significant positive (rank) correlation between normalized responsibility/capability and vulnerability indicators[5] implies that there is no systematic asymmetry between those countries most responsible for climate change and those most affected by it. In this case, climate change would not raise major concerns for international equity because those countries who suffer most from the impacts of climate change have benefitted most from the emissions of greenhouse gas (GHG), and vice versa. The absence of a significant correlation between responsibility/capability and vulnerability indicators implies that there is a simple inequity because those countries who have benefitted little from GHG emissions will suffer as much from the impacts of climate change as those who have benefitted a lot. A significant negative correlation between responsibility/capability and vulnerability indicators implies a "double inequity" (Stern, 2007) (or double asymmetry) because those countries who have benefitted little from GHG emissions suffer most from the impacts of climate change. In this paper, a "very strong" correlation is understood as a rank correlation $\rho > 0.85$, a "strong" correlation is understood as a rank correlation $\rho > 0.60$, and a "moderate" correlation as a rank correlation $\rho > 0.30$ (as long as the correlation is significant at the 0.1% level).

The unweighted rank correlation was chosen from a number of alternative methods for assessing the asymmetry of two statistical distributions. Pearson's correlation coefficient is unsuitable because many responsibility, capability, and vulnerability indicators are strongly skewed. Equal weighting of countries was preferred over population weighting in order to limit the influence of the two most populous countries, China and India, on the results. However, equal weighting is problematic if there is a systematic relationship between the population size of countries and any of the indicators considered in the inequity analysis. This limitation is most relevant for coastal vulnerability because many small island states with very low population size are particularly sensitive and exposed (see Section 4.8). A compromise between equal weighting and population weighting would have been to weight countries by the square root of their population. Another potential method for assessing the inequity of climate change involves comparing the mean or median of a vulnerability indicator for a few groups of countries defined by their responsibility and/or capability (see Fig. 3 for an example). However, a sensitivity analysis that compares the results of the inequity analysis for different statistical methods is beyond the scope of this paper. Despite the use of one statistical approach only, it is very unlikely that the choice of an alternative statistical method would qualitatively change the results of this study.

[5] The sign of all "vulnerability" indicators was normalized before the correlation analysis so that a large numerical value always corresponds to "high vulnerability". For example, child mortality can be used "as is" whereas the sign of life expectancy needs to be inverted.

3. Responsibility and capability indicators

Several metrics have been proposed for quantifying countries' causal or moral responsibility for climate change and their capability to assist (Baer et al., 2008; Baumert et al., 2005; Dellink et al., 2009; Höhne et al., 2007; Müller et al., 2007; WRI, 2009). This section briefly discusses the main controversies with respect to the selection of responsibility and capability indicators, motivates the choice of two responsibility and two capability indicators for the inequity analysis in this study, and assesses their statistical relationship.

3.1. Responsibility for climate change

The main controversies in the quantification of national responsibility for climate change are the inclusion of emissions from land-use change, of non-CO_2 gases, of early emissions, of "subsistence" emissions (in contrast to "luxury" emissions), and the consideration of non-linear effects, of delays between emissions and impacts, and of natural conditions that influence energy demand (e.g., current climate) and energy supply options (e.g., hydropower potential). The debate of these issues refers to empirical arguments (e.g., land-use emissions should not count because they cannot be measured reliably) as well as ethical arguments (e.g., early emissions should not count because they were ignorant).

Eleven potential responsibility indicators were derived from the climate analysis and indicator tool (CAIT) dataset (WRI, 2009). These indicators differ according to (i) the start year of historical responsibility (1850 vs. 1950 vs. 1990), (ii) the type of emissions considered (fossil CO_2 vs. total CO_2 vs. "all" greenhouse gases), and (iii) the aggregation over time (cumulative emissions vs. contribution to current concentrations). A correlation analysis of alternative responsibility indicators (partly shown in Fig. 1) reveals that cumulative fossil fuel emissions per capita for different starting years are very strongly correlated (see Fig. 1a), that cumulative emissions per capita for total CO_2 and for "all" greenhouse gases (data available since 1990 only) are very strongly correlated, and that cumulative emissions and the contribution to current concentrations are very strongly correlated. In contrast, fossil and total (including land-use related) CO_2 emissions are only strongly correlated (see Fig. 1b), and the latter are much more uncertain (Baumert et al., 2005). The fact that the consideration of "early emissions" (here: between 1950 and 1990) is less important for the ranking of countries than the consideration of non-fossil emissions is also evident from a comparison of Fig. 1a and b.

A very strong correlation between two responsibility indices implies that it is largely irrelevant which of them is applied in the inequity analysis. The results of the correlation analysis allowed eliminating several largely redundant responsibility indices. The following two responsibility indices were retained for the inequity analysis:

- Fossil CO_2 emissions per capita cumulated since 1990 ("fossil responsibility") and
- Total CO_2 emissions per capita cumulated since 1990 ("total responsibility"), according to the CAIT dataset (WRI, 2009).

The indicators of fossil and total responsibility are strongly correlated ($\rho = 0.718$, $p = 0.000$). However, some developing countries with low fossil responsibility have a total responsibility that is comparable with those of industrialized countries (see Fig. 1b).

3.2. Capability to assist

The capability of countries to pay for climate policies is typically measured by economic metrics, in particular by its GDP per capita. Controversial issues include the consideration of income below a given development threshold, of inequities within a country, and of non-economic (e.g., social and institutional) factors.

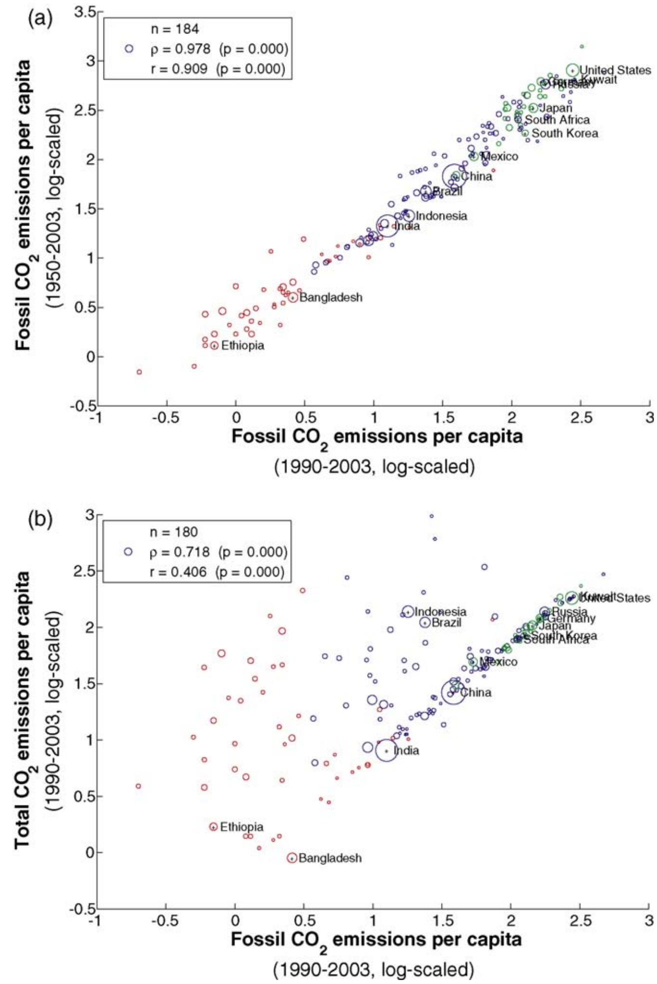

Fig. 1. Scatter plots of national responsibility indices: (a) cumulated fossil CO_2 emissions (per capita and year, log-scaled) since 1990 and 1950; (b) fossil and total CO_2 emissions since 1990. Each circle represents one country, scaled by its population size. Red circles denote least developed countries and green circles denote OECD countries; all other countries are denoted by blue circles.

Six national-level indicators of social and economic capability were initially identified: four social development indices (human development index, human assets index, index of human well-being, and human poverty index) and two indicators of economic capability (GDP per capita according to purchasing power parity UNDP, 2007, and produced capital stock adapted from World Bank, 2006, see Appendix A). Because the four social development indices are very strongly correlated with each other and the two indicators of economic capability are very strongly correlated, only one indicator from each group was retained for the inequity analysis:

- Human development index (HDI) (UNDP, 2007) ("social capability") and
- GDP per capita (purchasing power parity) (UNDP, 2007) ("economic capability").

The two indicators of economic and social capability are very strongly correlated ($\rho = 0.952$, $p < 0.001$).

3.3. Relationship between responsibility and capability

The relative importance of responsibility and capability in assigning duties for mitigating climate change and funding adaptation to climate change is subject to considerable debate (Harris, 2010). How different are the distributions of responsibility and capability across countries? Fossil responsibility is very strongly correlated with the two capability indicators, HDI and GDP per capita ($\rho = 0.869$, $p < 0.001$ and $\rho = 0.883$, $p < 0.001$, respectively) whereas total responsibility is significantly weaker correlated with the two capability indicators ($\rho = 0.601$, $p < 0.001$ and $\rho = 0.621$, $p < 0.001$, respectively). In other words, current social and economic wealth has historically been built on carbon emissions, in particular from fossil fuels. As a consequence, the presentation of the results of the inequity analysis in Section 6 can group fossil responsibility together with the two capability indicators but needs to distinguish between fossil and total responsibility.

4. Indicators of vulnerability to climate change

This section describes the selection of (mostly) sector-specific vulnerability indicators and analyzes their correlations with the four responsibility and capability indicators identified in the previous section. The selection of vulnerability indicators aims to be comprehensive but not exhaustive. Hence, some plausible indicators are not included if a closely related indicator is already included. Section 4.1 briefly reviews several generic indices of vulnerability to climate change and explains why they are not included in the inequity analysis. Section 4.2 presents the conceptual framework for vulnerability indicators, which is motivated by the IPCC definition of (outcome) vulnerability to climate change. Section 4.3 reviews aggregated indicators of regional climate change, none of which is regarded suitable for inclusion in the inequity analysis. Section 4.4 selects indicators of socio-economic capacity that are deemed relevant for all climate-sensitive sectors considered here. Sections 4.5–4.8 discuss the selection of sector-specific vulnerability indicators for water supply, food security, human health, and coastal zones according to the conceptual framework presented in Section 4.2.

4.1. Generic indices of vulnerability to climate change

Calls to develop generic indices of countries' vulnerability to climate change are repeatedly being made by negotiators of international climate policy (Klein, 2009). For example, Australia requested in the negotiations of the UN Framework Convention on Climate Change (UNFCCC): "*To prioritise international efforts towards the most vulnerable countries, the AWG-LCA should resolve a general scale of vulnerability for Parties in terms of physical impacts and capacity to respond.*" (UNFCCC, 2008b) (p. 13). Similarly, Bangladesh requested "*Development of vulnerability index criteria to assess the adaptation needs of LDCs and SIDS as well as drought and flood prone countries for preferential treatment in accessing the funds in times of need*" (UNFCCC, 2008a) (p. 13). The Adaptation Fund Board has issued a request to the IPCC to report on vulnerability indices as a basis for identifying eligible countries or to prioritize among countries (Adaptation Fund Board, 2010).

Various scholars have attempted to develop generic indices of countries' vulnerability to climate change. However, the available scientific reviews conclude that these generic vulnerability indices are unsuitable for guiding international climate policy due to severe conceptual, methodological, and/or empirical deficiencies. Eakin and Luers (2006) express serious concerns regarding the validity of national-scale vulnerability assessments noting that "*Ranking and comparing vulnerability across countries [. . .] is challenged by everything from the quality of the available data, to the selection and creation of indicators, to the assumptions used in weighting of variables and the mathematics of aggregation*" (p. 377). Eriksen and Kelly (2007) have reviewed five national-level indices of social vulnerability to climate change: vulnerability-resilience indicators (Moss et al., 2001), the Environmental Sustainability Index (Esty et al., 2005), dimensions of vulnerability (Downing et al., 1995), Index of Human Insecurity (Lonergan et al., 1999), and a preliminary version of the Predictive Indicators of Vulnerability, denoted as country-level risk measures (Brooks et al., 2005). This review finds that there is "*relatively little agreement regarding which particular countries are the most vulnerable*" (p. 502), and that "*a lack of a clear theoretical and conceptual framework for the selection of indicators has hampered the robustness, transparency and policy relevance*" (p. 504) of these indicator studies. However, part of the low agreement between the vulnerability indicators assessed in this study may be related to differences in the period and countries covered.[6]

Füssel (2009) has shown that three recent national-level indices of vulnerability to climate change not covered by Eriksen and Kelly (2007) cannot be used either in a climate policy context due to fundamental conceptual, methodological, and/or empirical flaws.[7] The Global Distribution of Vulnerability (Yohe et al., 2006a,b) suffers from severe methodological flaws (e.g., division by an ordinal-scaled variable), from inconsistent documentation, and it does not include data on the sensitivity of populations or ecosystems to climate change. Furthermore, the 144 variants of this index do not provide a consistent picture which countries are most vulnerable to climate change, which prohibits their use in this inequity analysis (and in any conceivable policy context). The EVI-CC (Kaly et al., 2004), which aims at identifying the vulnerability of ecosystems to climate change, is defined based on 13 indicators of hazards, resistance and acquired vulnerability. These indicators include contested data on the magnitude of recent climate change, on the exposure and sensitivity of ecosystems, on land area, and on population density but no data on the vulnerability of populations. The index of socioclimatic exposure (Diffenbaugh et al., 2007) also suffers from fundamental methodological flaws, in particular the summation of an index that is proportional to population and two indices that are normalized by population, which prohibits a meaningful interpretation of the results. Furthermore, the summation of a wealth index and a poverty index reveals a lack of focus.

Other studies have found that several generic vulnerability indices express strong sensitivity to the selection of specific proxy variables as well as to variations in the mathematics of index construction (Gall, 2007; Moss et al., 2001; Schmidtlein et al., 2008), and that the aggregation of indicators does not consider recent findings on the substitutability of different component indicators (Tol and Yohe, 2007). No generic vulnerability index is included in the global inequity analysis due to severe doubts regarding their validity.

4.2. Conceptual framework for vulnerability indicators

The selection of vulnerability indicators for the inequity analysis is motivated by the definition of vulnerability to climate change in the glossary of the IPCC Fourth Assessment Report (IPCC, 2007a): "*Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation*

[6] This fact was pointed out by an anonymous reviewer.

[7] Section 1 gives an overview of the most vulnerable countries identified by these three indices.

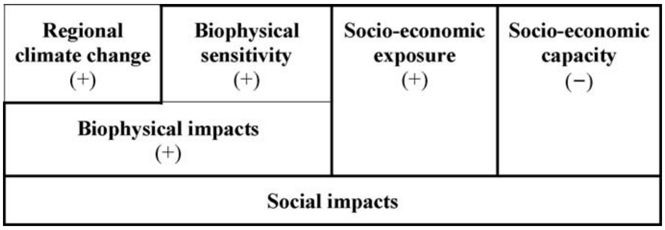

Fig. 2. Conceptual framework for vulnerability indicators. The sign (+/−) next to an individual factor indicates the direction of the influence of this factor on the compound factor below (see text for details).

to which a system is exposed, its sensitivity, and its adaptive capacity." (p. 883). The underlying vulnerability concept has been denoted as end-point (in contrast to starting-point) vulnerability (O'Brien et al., 2004), as outcome (in contrast to contextual) vulnerability (O'Brien et al., 2007), and as integrated cross-scale vulnerability (Füssel, 2007). The vulnerability of a country according to this definition can be loosely translated as "adverse social impacts of a given level of climate change, considering feasible adaptations".

Fig. 2 shows the conceptual framework of vulnerability indicators applied here. The four groups of vulnerability factors at the top reflect those factors mentioned in the IPCC definition of vulnerability to climate change: *regional climate change* denotes the magnitude of regional climate change for a given level of global climate change, *biophysical sensitivity* denotes the level of adverse biophysical impacts for a given magnitude of regional climate change, *socio-economic exposure* denotes the importance of a climate-sensitive system or sector for a country, and *socio-economic capacity* denotes the availability of economic, social, and institutional resources to cope with and adapt to the impacts of climate change.[8] These four vulnerability factors together determine the *social impacts* of climate change as follows. Everything else being equal, high *socio-economic capacity* decreases *social impacts* (indicated by a minus sign) whereas high scores for the other vulnerability factors increase the *social impacts* (indicated by a plus sign). The term 'social impacts of climate change' is used here instead of 'vulnerability' or 'outcome vulnerability' to avoid the possible confusion associated with the latter terms.

Section 4.3 argues that there are no reliable aggregated indicators of *regional climate change*. For this reason, indicators of regional climate change will not be included in the disaggregated inequity analysis. Instead, indicators of *biophysical sensitivity* are grouped together with those of *biophysical impacts* of climate change on a system, which integrate its *biophysical sensitivity* and the magnitude of *regional climate change* (Füssel and Klein, 2006). Hence, the thick lines in Fig. 2 denote the conceptual framework of vulnerability factors applied in this study, which distinguishes biophysical sensitivity and impacts, socio-economic exposure, socio-economic capacity, and social impacts. Note that the exact meaning of these categories differs somewhat between those systems and sectors where climate impacts are always adverse (e.g., coastal zones vulnerable to sea-level rise) and those where climate change can have beneficial as well as adverse impacts (e.g., water supply and food security).

The following subsections select indicators for each of these four categories for all climate-sensitive sectors and systems considered in this analysis (see Fig. 4 for a summary of the selected indicators). It was possible to identify valid indicators for the first three categories (biophysical sensitivity and impacts, socio-economic exposure, and socio-economic capacity) for all sectors considered here. Valid indicators for social impacts, however, are not available for all sectors. The implications of this data gap are discussed in the respective subsections.

4.3. Regional climate change

The impacts of climate change in a region are partly determined by the magnitude and type of regional climate change. For example, two currently water-scarce regions will experience very different impacts if global climate change leads to increasing precipitation in one of them but to decreasing precipitation in the other. The complex changes in regional climate cannot be objectively aggregated into a single index because they involve changes in the mean and variability of several incommensurable climate variables (e.g., temperature, precipitation, cloudiness, wind speed, and sea level) at various temporal scales. Nevertheless, two aggregated national-level indices for climate change have been published in the scientific literature: the climate change index (CCI) (Baettig et al., 2007) and the national climate change index (NCCI) (Diffenbaugh et al., 2007; Giorgi, 2006). These two indices do not agree where climate change will be most severe. The rank correlation between the CCI and the NCCI is actually slightly negative ($\rho = -0.11$) but not statistically significant. The main reasons for these differences are that the CCI evaluates projected changes in seasonal and annual temperature and precipitation in the context of current climate variability whereas the NCCI does not, and that the NCCI considers the effects of sea-level rise whereas the CCI does not. As a result of their questionable validity, neither of these indices is considered in the inequity analysis.

4.4. Socio-economic capacity

Most vulnerability indicators included in this inequity analysis are sector-specific. However, the capacity of a community or a nation to cope with, and adapt to, a variety of climate impacts is strongly influenced by several generic factors, including economic resources, effective government institutions, and a well-educated healthy population (Brooks et al., 2005; Yohe and Tol, 2002). Five indicators have been selected to represent the economic, social, and institutional coping capacity of a country:

- Produced capital stock per person (adapted from World Bank, 2006, see Appendix A),
- Human development index (HDI) (UNDP, 2007),
- Human assets index (HAI) (UNCTAD, 2008), extended to cover most countries of the world,
- Index of human well-being (HWI) (Prescott-Allen, 2001), and
- Government effectiveness (Kaufmann et al., 2008).

All indicators of socio-economic capacity are strongly or very strongly correlated with each other and with the four responsibility and capability indicators selected in Section 3. In fact, the distinction between the terms *capability* and *capacity* is primarily a notational convenience, which emphasizes the different potential roles of these variables in international climate policy. *Capability* denotes variables that may be applied to allocate duties to countries whereas the term *capacity* denotes variables that may be applied to assess outcome vulnerability, and eventually to allocate rights to international adaptation funding. There is significant overlap between these concepts, and the same variable (e.g., the HDI) may be applied to assess a country's *capability* to assist as well as its *capacity* to cope and adapt. The correlation of the responsibility and capability indicators with government effectiveness is consistently weaker than with the other four capacity indicators, which are dominated by economic factors.

[8] Many scholars distinguish between coping capacity (focusing on short-term actions) and adaptive capacity (focusing on long-term actions) but this distinction is neglected here.

4.5. Water supply

The vulnerability of water supply to climate change is described by eight indicators.

4.5.1. Biophysical sensitivity and impacts

Biophysical sensitivity and impacts is measured by the change in regional water supply for a given level of global climate change. It is described by three indicators, all of which are expressed as percentage of the current precipitation or runoff:

- Median of the projected change in precipitation and
- Standard deviation of the projected change in precipitation between 1961–1990 and 2040–2069, based on an ensemble of 19 general circulation models (GCMs) that have contributed to the IPCC Fourth Assessment Report (IPCC, 2007b) (see Appendix B), and
- Median of the projected change in runoff simulated by the global hydrological model LPJmL 3.3 for the same period and GCM ensemble (Gerten et al., 2007, 2008).

None of the responsibility and capability indicators is significantly correlated with the median change in precipitation or runoff but all of them are moderately negatively correlated with the standard deviation (i.e., the uncertainty) of future precipitation change. In other words, future changes in water supply are, on average, more uncertain in countries with low responsibility and capability.

4.5.2. Socio-economic exposure

Exposure to climate change impacts on water supply is quantified by three indicators of current water availability:

- Current population-weighted precipitation, calculated based on data from (Balk and Yetman, 2004; Mitchell and Jones, 2005),
- Renewable water resources per person, and
- Water use ratio (Mila i Canals et al., 2009).

These three indicators measure water availability from renewable sources relative to the inhabited area, the population size, and the current water use, respectively. None of the responsibility and capability indicators is significantly correlated with water availability per area or per person but fossil responsibility and capability are moderately positively correlated with the water use ratio. In other words, countries with high fossil responsibility and capability are, on average, using a higher fraction of their renewable water resources. This is not surprising given that the extensive use of water resources requires infrastructure that typically exists only in countries above a certain level of development.

4.5.3. Socio-economic capacity

Socio-economic capacity is represented by two indicators:

- Percentage of households with improved water supply and
- Percentage of households with improved sanitation (WHO/UNICEF, 2006).

Both indicators are strongly or very strongly positively correlated with fossil responsibility and capability whereas the correlation with total responsibility is only moderately positive.

4.5.4. Social impacts

There is no obvious indicator to quantify the social impacts of climate change on water supply in a robust manner. Compound indices, such as the closely related water poverty index (Lawrence et al., 2002), climate vulnerability index (Sullivan and Meigh, 2005), and water wealth index (Sullivan et al., 2006) combine some of the vulnerability factors considered here but they do not include projections of future climate change. Hence, these indices are not compatible with the conceptual framework of vulnerability applied here. Global modelling studies also do not provide a robust picture of the distribution of beneficial and adverse impacts of climate change on water supply across poor and wealthy countries (Alcamo et al., 2007; Arnell, 2004; Milly et al., 2005; Nohara et al., 2006). For these reasons, it cannot be established unequivocally whether there is a double inequity between responsibility/capability and social impacts of climate change on water supply. However, any changes in physical water availability, whether beneficial or adverse, will impact stronger on poorer populations because of their limited adaptive capacity.

4.6. Food security

The vulnerability of food security to climate change is described by eight indicators, which focus on consumers whose food security depends primarily on regionally produced food. This population group includes subsistence farmers as well as consumers who purchase food on local markets.

4.6.1. Biophysical sensitivity and impacts

Biophysical sensitivity and impacts is quantified by three indicators that represent the change in farm productivity for a given magnitude of global climate change. Two indicators are derived from the two leading global crop modelling studies that include multiple crops and multiple GCM projections. Studies that consider only a single GCM scenario are not considered because regional changes in crop production are very sensitive to the specific GCM scenario applied (Fischer et al., 2002, 2005). The third indicator is based on Ricardian analysis:

- Simulated change in rainfed yields of 83 cereals according to the G-AEZ model applied to climate projections from three GCMs (Fischer et al., 2002),[9]
- Simulated change in rainfed yields of four staple crops (wheat, rice, coarse grains, and soybeans) according to the DSSAT/IBSNAT crop models applied to climate projections from four GCMs (Parry et al., 2005; Rosenzweig and Iglesias, 2006), and
- Agricultural impact of climate change on farm values based on Ricardian analysis (Cline, 2007, based on Mendelsohn et al., 1994; Mendelsohn and Schlesinger, 1999).

The second and third indicators are moderately or strongly positively correlated with all responsibility and capability indicators whereas the first indicator shows only a weak positive correlation. In other words, the biophysical impacts of climate change on agriculture are projected to be worse in countries with low responsibility and capability.

4.6.2. Socio-economic exposure

Socio-economic exposure is represented by two indicators:

- Share of agriculture in labour force and
- Share of agriculture in GDP (WRI, 2009).

The two exposure indicators are strongly or very strongly positively correlated with fossil responsibility and capability, and they are moderately correlated with total responsibility. In other words, the populations of countries with low responsibility and

[9] Data available at http://www.iiasa.ac.at/Research/LUC/SAEZ/app/dwnxls.htm?f=xls/data14.xls.

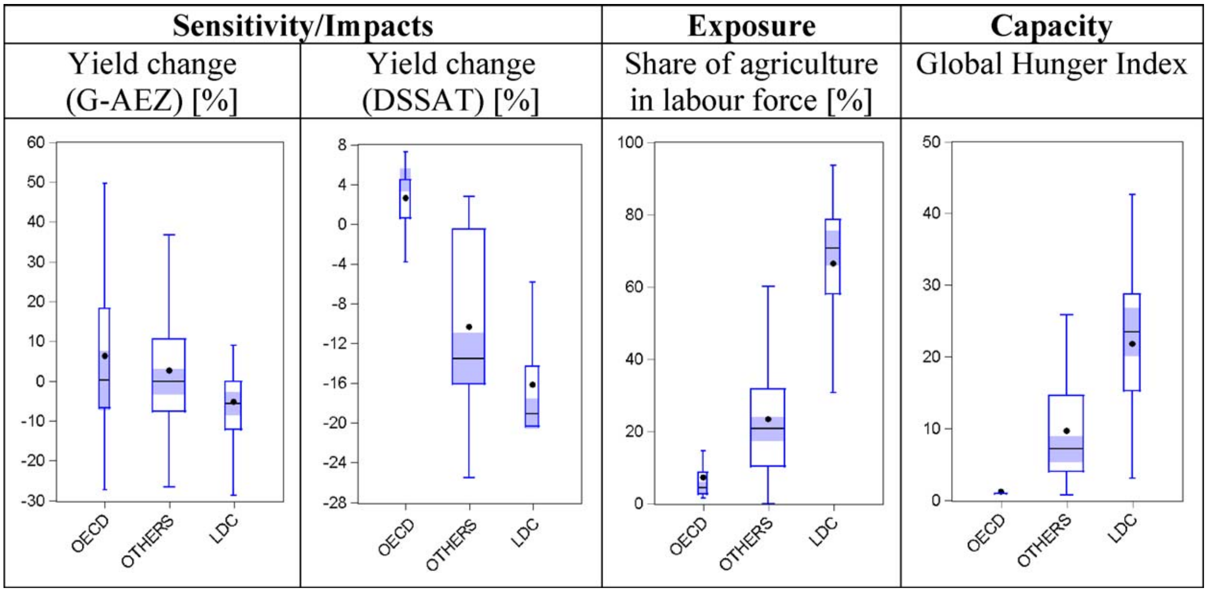

Fig. 3. Box plots of four vulnerability factors for food security across three country groups (see text).

capability are, on average, more exposed to the impacts of climate change on agriculture.

4.6.3. Socio-economic capacity

Socio-economic capacity (or the lack thereof) is represented by three indicators:

- Prevalence of undernourishment based on data from household surveys (FAO, 2008),[10]
- Prevalence of underweight children (de Onis and Blossner, 2003),[11] and
- Global Hunger Index, which combines the above two indices and the child mortality rate (von Grebmer et al., 2008; Wiesmann, 2006).

The three indicators are strongly or very strongly correlated with each other even though they disagree on the specific regions where hunger is most severe (FAO, 2003). Socio-economic capacity as identified by (the inverse of) these three indicators is strongly or very strongly positively correlated with fossil responsibility and capability, and it is moderately correlated with total responsibility.

4.6.4. Social impacts

There is no obvious indicator for the social impacts of climate change on food security. Projected changes in the risk of hunger from global modelling studies are largely determined by the underlying socio-economic scenario and by assumptions regarding the direct effects of elevated atmospheric CO_2 levels on crop production under field conditions (Parry et al., 2004, 2005; Schmidhuber and Tubiello, 2007). These studies do not provide robust projections of global or regional changes in the risk of hunger. However, the results above show that countries with low responsibility and capability are, on average, more negatively affected by, more exposed to, and less able to cope with the impacts of climate change on food security. The double inequity between responsibility/capability and all pertinent vulnerability indicators suggests that there will also be a double inequity between responsibility/capability and the social impacts of climate change on food security.

[10] Data available at http://www.fao.org/faostat/foodsecurity/index_en.htm.

[11] Data available at http://www.who.int/nutgrowthdb/publications/en/.

Fig. 3 illustrates the double inequity between responsibility/capability and two sensitivity indicators, one exposure indicator, and one capacity indicator. Each boxplot shows the arithmetic mean (black dot), the median (black line), the 95% confidence interval of the median (blue shading), the interquartile range (blue box), and the extremes (whiskers) of an indicator for three groups of countries: OECD members, least developed countries (LDCs), and all other countries.

4.7. Human health

Assessments of the impacts of climate change on human population health are complicated by the large diversity of causal pathways, which exhibit very different sensitivity to climatic factors, and by the lack of quantitative models for most of them (McMichael et al., 2006; Patz et al., 2000). Hence, any global assessment of the vulnerability of population health to climate change will be rather fragmentary. The indicator selection in this study aims to include available data that is relevant for assessing the regional distribution of important climate-sensitive health risks, including those of weather-related disasters. The distinction between biophysical and social impacts is generally irrelevant for human health because any biophysical impact on humans (e.g., morbidity, mortality) is by definition also a social or human impact. Five indicators were selected to represent the vulnerability of human population health to climate change.

4.7.1. Biophysical sensitivity and impacts

Biophysical sensitivity and impacts is represented by one indicator:

- Current population-weighted temperature, which is a proxy for the health risks from increasing heat waves, calculated based on data from (Balk and Yetman, 2004; Mitchell and Jones, 2005)

This indicator is moderately negatively correlated with all responsibility and capability indicators, whereby the correlation with total responsibility is weakest. In other words, countries with low responsibility and capability are generally much warmer, and thus face higher health risks from heat waves, than countries with high responsibility and capability.

4.7.2. Socio-economic exposure

Socio-economic exposure is represented by one indicator:

- Share of national population in highest risk areas from at least one hazard (Dilley et al., 2005). This indicator comprises weather-related hazards (cyclones, droughts, floods, and land-slides) as well as non-weather-related hazards (earthquakes and volcanoes) but more specific data is not easily available.

This exposure indicator is moderately negatively correlated with all responsibility and capability indicators. In other words, the populations in countries with low responsibility and capability are, on average, more exposed to natural hazards than those in countries with high responsibility and capability.

4.7.3. Socio-economic capacity

Socio-economic capacity is represented by two indicators:

- Child mortality (UNDP, 2007), which is an indicator of current health status and
- Predictive indicator of vulnerability (Adger et al., 2004), which was constructed on the basis of 11 socio-economic indicators that correlate strongly with mortality from weather-related disasters at the national level.

Both capacity indicators are strongly or very strongly correlated with fossil responsibility and capability, and moderately correlated with total responsibility.

4.7.4. Social impacts

In contrast to water supply and food security, a valid indicator of the social impacts of climate change on population health is available:

- Mortality caused by observed climate change, which was estimated for 14 world regions in the WHO Global Burden of Disease assessment (Campbell-Lendrum and Woodruff, 2006; McMichael et al., 2004).

This indicator is strongly correlated with fossil responsibility and capability, and moderately correlated with total responsibility. In other words, countries with low responsibility and capability are already experiencing the largest health impacts from climate change. This double inequity has been noted earlier by Patz et al. (2007).

It would have been desirable to include an additional impact indicator for human health with a focus on weather-related disasters. Because the effects of climate change on weather-related disasters will in general be strongest in those regions where the population is already suffering from the adverse impacts of current climate variability, a preliminary inequity analysis included historical mortality from weather-related disasters in the 1970–2008 period according to the EM-DAT database[12] as a proxy for the mortality impacts of future weather-related disasters caused by climate change. Surprisingly, the rank correlation between this impact indicator and all responsibility and capability indicators is insignificant. This result seems to contradict the findings of many other studies, which conclude that poor countries, and poor people in all countries, are most strongly affected by weather-related disasters (Blaikie et al., 2004; de Haen and Hemrich, 2007; Roberts and Parks, 2007), including similar analyses based on mortality data for the 1980–2002 period from the same dataset (Kahn, 2005; Roberts and Parks, 2007). Further analysis reveals that the qualitatively different results between the 1970–2008 period and the 1980–2002 period are caused by the effects of the 2003 European summer heat wave, which caused substantial premature mortality in many high-income countries. However, it took several years, and a dedicated international research project, to determine the full mortality impact of this heat wave based on a comprehensive statistical analysis of multi-year mortality time series (Robine et al., 2008). Hence, the premature mortality caused by a similar event in a poor country would likely go largely unnoticed. This result confirms the findings of other studies that available data on mortality from weather-related disasters is systematically biased and can be very sensitive to individual events (Patt et al., 2010), and that disaster loss estimates lack comparability across time, agencies and regions (Gall et al., 2009).

It would be possible to modify the mortality indicator for weather-related disasters by excluding slow-onset weather events such as heat waves and droughts where mortality reports are considered particularly unreliable but such ad hoc modifications are not fully satisfactory. Because a detailed analysis of the mortality from extreme weather events at different levels of socio-economic development is beyond the scope of this paper, no such mortality indicator is included in the inequity analysis.

4.8. Coastal zones and their populations

The vulnerability of coastal zones and their populations to climate change is described by seven indicators. Note that the inequity analysis of coastal vulnerability is restricted to coastal countries. The inclusion of land-locked countries would markedly change some of the results because these countries are strongly represented in the group of LDCs, which are characterized by particularly low responsibility and capability.

4.8.1. Biophysical sensitivity and impacts, and socio-economic exposure

The two categories biophysical sensitivity and socio-economic exposure to sea-level rise are discussed jointly here because the selected indicators use the same data sources. Two sensitivity indicators and two exposure indicators have been derived from the two leading studies with (nearly) global scope that assess the exposure of coastal regions to sea-level rise based on an integration of population and coastal topography datasets.

- Percentage of land area below 1 m elevation and
- Percentage of population below 1 m elevation, based on two studies by the World Bank (Buys et al., 2007; Dasgupta et al., 2007). The two studies together cover most countries, except for economies in transition and most small island states. In order to avoid a systematic bias in the inequity analysis, data for countries not included in the two studies was estimated based on the PLACE-II dataset (SEDAC, 2007).
- Percentage of land area below 5 m elevation and
- Percentage of population below 5 m elevation according to the PLACE-II dataset (SEDAC, 2007), which contains data for all countries. Because the original dataset does not distinguish between low-lying coastal and inland areas, land-locked countries were manually excluded.

The two indicators of biophysical sensitivity are the fraction of land area below 1 m and below 5 m elevation (from the extended World Bank dataset and the PLACE-II dataset, respectively). The two indicators of socio-economic exposure are the fraction of population below 1 m and below 5 m elevation from the same datasets.

The share of area and population below 1 m elevation is moderately positively correlated with fossil responsibility and

[12] http://www.emdat.be/.

capability. The larger population shares in very low-lying areas in wealthy coastal countries compared to poor coastal countries is not surprising given that countries with large economic, technical, and institutional capacity (e.g., the Netherlands) can afford to protect large population shares in very low-lying areas (including below sea level) in a way that is not feasible for poor countries. The share of area and population below 5 m elevation is not significantly correlated with any of the responsibility and capacity indicators. Furthermore, total responsibility is not significantly correlated with any sensitivity or exposure indicator.

4.8.2. Socio-economic capacity

Socio-economic capacity is represented by one indicator:

- GDP per capita (purchasing power parity) (UNDP, 2007). This indicator is not specific to coastal protection. However, in the absence of more specific information it has generally been used as a proxy for coastal protection levels in other global studies of coastal vulnerability to sea-level rise (Delft Hydraulics, 1993; Hinkel, 2008).

This capacity indicator is very strongly correlated with fossil responsibility and capability, and strongly correlated with total responsibility.

4.8.3. Social impacts

The social impacts of climate change are represented by one indicator each from the two leading global studies of coastal vulnerability to sea-level rise that consider the biophysical impact potential together with socio-economic coping capacity:

- Increase in the percentage of population annually flooded according to the global vulnerability assessment (Delft Hydraulics, 1993; Hoozemans et al., 1993) and
- Increase in the percentage of population annually flooded according to a study using the DIVA model (Hinkel, 2008).

Both indicators assume that the current level of coastal protection (estimated based on GDP per capita and population density) is kept constant. It would have been desirable to additionally include indicators that assume improving coastal protection but this information is not consistently available from global studies. Both social impacts indicators are strongly positively correlated with fossil responsibility and capability, and moderately correlated with total responsibility. In other words, the population of poor coastal countries faces larger risks from sea-level rise than that in wealthy coastal countries even though the population share in very low-lying regions is larger, on average, in wealthy coastal countries than in poor coastal countries. This asymmetry between the distributions of exposure and impact indicators emphasizes the importance of socio-economic capacity in determining population risks from sea-level rise.

5. Synthesis of inequity analysis

Fig. 4 summarizes the results of the disaggregated inequity analysis of climate change impacts, which is based on the rank correlations between the four national-level responsibility and capability indicators identified in Section 3 and the 33 vulnerability indicators identified in Section 4. These vulnerability indicators refer to four climate-sensitive sectors and are classified according to the conceptual framework presented in Fig. 2. The basic colour of each cell denotes the sign of the correlation between responsibility/capability and vulnerability indicators (after normalization of their sign so that a large numerical value always denotes high vulnerability): red shading denotes a significant negative correlation (i.e., a double inequity), blue shading denotes a significant

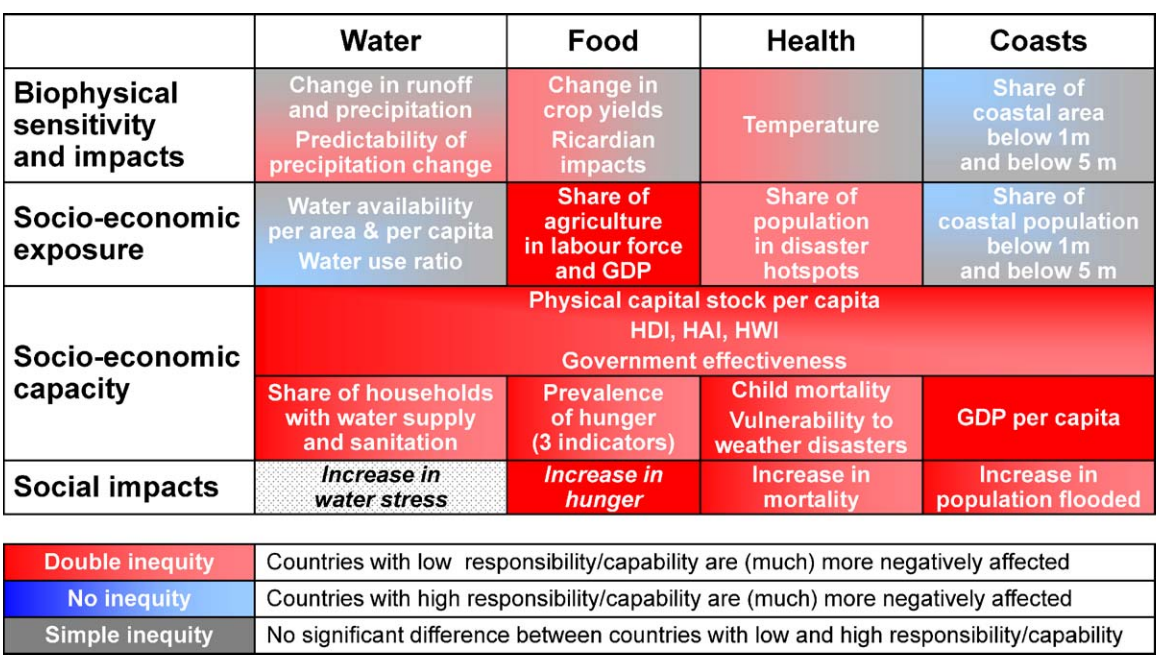

Fig. 4. Disparity between the distributions across countries of indicators of responsibility/capability and of vulnerability to climate change for key climate-sensitive sectors. All indicators are normalized so that they do not scale with the size or population of a country. Red (blue) cells denote a double (no) inequity between responsibility/capability and vulnerability. Dark (light) colours denote that the absolute value of the rank correlation between responsibility/capability and vulnerability indicators is above 0.6 (between 0.3 and 0.6). The left (right) part of a cell refers to the correlation of vulnerability indicators with fossil responsibility and capability (total responsibility). The top (bottom) part of a cell refers to the correlation of responsibility/capability with the top (bottom) vulnerability indicator(s). *Italic* fonts denote social impacts of climate change in sectors where no appropriate indicator could be identified.

positive correlation (i.e., no systematic inequity), and gray shading denotes an insignificant correlation (i.e., a simple inequity). The intensity of the colour denotes the strength of the relationship: dark colours (only for red) denote that the majority of rank correlations are above 0.6, and light colours (for red and blue) denote that the majority of rank correlations are between 0.3 and 0.6. Rank correlations below 0.3 or correlations that are not significant at the 0.1% level are considered insignificant.

If the rank correlations between all responsibility and capability indicators and all vulnerability indicators in a grid cell are similar, the whole cell is shaded with the same colour. This case allows robust statements on the inequity between responsibility/capability and vulnerability. Cells shaded with two different colours indicate substantial differences in the rank correlations for different combinations of capability/responsibility and vulnerability indicators. The shading of the left part denotes the correlation of the pertinent vulnerability indicators with the fossil emissions indicator and the two capability indicators whereas the shading of the right part denotes the correlation with the total emissions indicator. The shading of the upper and lower part refers to the upper and lower vulnerability indicator(s) in this cell, respectively. Social impacts of climate change in two sectors are stated in *italics* to indicate the lack of suitable data with (near) global coverage. The inequity between responsibility/capability and social impacts of climate change cannot be determined unambiguously for water supply (see Section 4.5) but can be concluded from the underlying vulnerability factors for food security (see Section 4.6).

The main findings on the inequity between countries' responsibility for climate change, their capability to assist, and their vulnerability to its adverse impacts, are as follows:

1. The two indicators for social and economic capability (HDI and GDP per capita) and the fossil emissions indicator are very strongly correlated with each other, and their correlations with any vulnerability indicator are very similar. Hence, fossil responsibility and the two capability indicators can be considered jointly in the context of this semi-quantitative inequity analysis.
2. All capability and responsibility indicators are strongly or very strongly correlated with all generic and sector-specific indicators of socio-economic capacity. The capability and responsibility indicators are correlated more strongly with capacity indicators that focus on economic resources than with those that do not. The capacity indicators, in turn, are correlated more strongly with fossil responsibility and the two capability indicators than with total responsibility.
3. There is a double inequity between all responsibility and capability indicators and the social impacts of climate change on food security, human health, and coastal populations. For several reasons, it is not possible to unambiguously determine whether there is also a double inequity for the social impacts of climate change on water supply.
4. If vulnerability is interpreted narrowly as the lack of socio-economic capacity to cope and adapt (i.e., as contextual vulnerability, see Section 4.2), the assertion that those countries least responsible for climate change are at the same time most vulnerable to its adverse impacts is easily shown to be correct. If vulnerability is interpreted comprehensively as the magnitude of adverse social impacts for a given level of climate change (i.e., as outcome vulnerability, see Section 4.2), the assertion that those countries least responsible for climate change are most vulnerable to its adverse impacts is correct for all impact categories except water supply where it cannot be decided unambiguously.
5. All vulnerability indicators are correlated more strongly with fossil responsibility and the two capability indicators than with total responsibility. Hence, the double inequity between responsibility and (outcome) vulnerability found in most sectors is more pronounced if responsibility for climate change is restricted to carbon emissions from the burning of fossil fuels than if it also includes emissions from land-use change. The results of this semi-quantitative inequity analysis are rather insensitive to other choices in the quantification of responsibility (e.g., the start year of historic responsibility).
6. The distribution of biophysical sensitivity and of socio-economic exposure across countries with low and high responsibility/capability varies substantially between climate-sensitive sectors. The analysis finds a double inequity between the distributions of responsibility and capability on the one hand and of biophysical sensitivity and socio-economic exposure on the other for food security and human health but not for water supply and coastal zones.
7. Coastal countries with low responsibility and capability are projected to experience higher social impacts on coastal populations despite their somewhat lower sensitivity and exposure. Hence, indicators of biophysical sensitivity and socio-economic exposure alone are unsuitable for assessing even the broad distribution of (outcome) vulnerability to climate change across countries.

6. Summary and conclusions

This paper has presented a robust assessment of the implications of climate change on international inequity by analyzing the asymmetries between countries' responsibility for climate change and their capability to assist on the one hand and their vulnerability to climate change on the other. To this end, two responsibility indicators, two capability indicators, and 33 sector-specific vulnerability indicators were selected based on their relevance, significance, scientific credibility, and public availability. The vulnerability indicators cover four climate-sensitive sectors: water supply, food security, human health, and coastal populations. They are classified based on a conceptual framework derived from the IPCC definition of vulnerability to climate change, which applies an integrated (or outcome) interpretation of vulnerability. This framework distinguishes the biophysical sensitivity and impacts, socio-economic exposure, and socio-economic coping capacity, which together determine the social impacts of climate change in a given climate-sensitive system or sector. Application of this conceptual framework required some flexibility to accommodate sector-specific circumstances, such as differences between sectors where climate change can have adverse as well as beneficial impacts (e.g., water, food, and health) and sectors where climate impacts are consistently adverse (e.g., coastal zones). Indices of the magnitude of regional climate change and of countries' generic vulnerability to climate change have not been included in the inequity analysis because all of them have severe conceptual, methodological, and/or empirical flaws that preclude their application for determining countries' duties and rights in international climate policy.

The degree of inequity was assessed semi-quantitatively, and its causes were determined, by analyzing the rank correlations between all responsibility and capability indicators on the one hand and all vulnerability indicators on the other. If vulnerability is interpreted narrowly as a lack of socio-economic capacity and entitlements to cope with the adverse impacts of climate change, the common assertion that those countries least responsible for climate change are most vulnerable to its impacts is clearly true. If land-use change emissions are included in the measurement of responsibility for climate change, however, there are some countries with high vulnerability *and* high responsibility. If vulnerability to climate change is interpreted more comprehensively as the expected social impacts of climate change considering current adaptive capacity, the analysis finds a double inequity between countries' responsibility/capability and vulnerability for food security, human health, and coastal populations. The equity implications of climate change for water supply are more complex (because alternative indicators of current water scarcity differ substantially), more uncertain (due to large uncertainties about changes in water availability in some regions), and more difficult to express by a single metric (because even regions where a "best-guess" climate change scenario projects increasing water availability may have to prepare for potential decreases in water availability projected in other plausible projections).

The relative importance of different vulnerability factors varies substantially across climate-sensitive sectors. In a sector where climate impacts can be adverse as well as beneficial, the sign of social impacts is determined by the sign of its biophysical sensitivity, and their magnitude is largely determined by its socio-economic capacity. In a sector where climate impacts are always adverse (e.g., coastal zones), socio-economic capacity is generally a more important factor for the distribution of social impacts across countries than biophysical sensitivity. Thus, if scientific uncertainties preclude a reliable assessment of the biophysical climate change risks across countries, socio-economic capacity can be a key criterion for assessing their adaptation needs and for prioritizing international adaptation funding.

An analysis of climate change inequity based on national-level indicators necessarily has several limitations. Most importantly, it cannot consider the vast differences in vulnerability within many countries. Furthermore, a global analysis has to neglect special conditions that make whole countries or population groups particularly vulnerable to climate change. Climate change risks that are not considered in the current analysis due to the lack of appropriate data at the global level include, for example, the risk to water supply in regions supplied from glacier-fed rivers, the risks from glacier-lake outburst floods, and economic risks to countries whose export is strongly dependent on cash crops currently grown near their upper thermal limit. Finally, the selection of vulnerability indicators is constrained by data availability, and it always contains a subjective element. However, application of a common conceptual framework across impact categories, quality control of potential indicators, and the use of multiple indicators whenever feasible suggests that the main results of this analysis are robust to refinements of the indicator selection.

This analysis has confirmed that there is a double inequity between responsibility/capability and outcome vulnerability to climate change for most climate-sensitive sectors, and to establish the causes of this inequity. This finding is not self-evident given that several recently developed national-level vulnerability indices come to different conclusions. In addition, this study has identified numerous indicators that could be applied to allocate the burdens and benefits of global climate policy across countries. However, such an allocation is eventually a political decision.

The results of this study have several implications for the design of global climate policy. First of all, the double inequity between responsibility and (outcome) vulnerability for most climate-sensitive sectors strengthens the moral case for financial and technical assistance from those countries most responsible for climate change (which in general are also those most capable to assist) to those countries most vulnerable to its adverse impacts. Second, the disaggregated analysis stresses that the high (outcome) vulnerability of many poor countries is not only due to their low socio-economic capacity but also due to their higher biophysical sensitivity, which for most climate-sensitive sectors and systems is largely determined by the current climate in a region.[13] Finally, the substantial differences in the distribution of the social impacts of climate change across sectors and the far-reaching normative choices required in aggregating vulnerability indicators across sectors and impact categories suggest that scientists should not heed to the repeated requests from participants in international climate negotiations to develop a generic index of countries' vulnerability to climate change. Science can identify a range of suitable vulnerability indicators, discuss their merits and drawbacks, and analyze the implications of alternative aggregations of these indicators. Decisions on pending policy questions (e.g., the prioritization of recipient countries for the Adaptation Fund established under the Kyoto Protocol), however, require clear political guidance on several inherently normative issues. The expert group report to the Pilot Program for Climate Resilience (Expert Group to the Subcommittee of the PPCR, 2009) has provided a convincing example how national-level indicators of vulnerability to various climate change risks can be used together with information on countries' adaptability and expert judgements on other pertinent issues to make specific recommendations for resource allocations guided by reasonably clear political goals.

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Appendix A. Capital stock

The capital stock of countries was estimated based on data collected by World Bank (2006). This World Bank dataset calculates produced capital by the perpetual inventory method based on national investment data for the period 1960–2000 from 81 countries, and for a shorter period from some other countries. Investments were depreciated at 5% per year over a life time of 20 years, after which their value is set to zero ("One Hoss-Shay retirement"). Large data gaps exist in Eastern Europe and Central Asia (except for Russia) and in Africa. The correlation between capital stock and GDP data in the World Bank dataset is $r = 0.95$ for the full dataset; it increases to $r = 0.98$ if four statistical outliers (Georgia, Congo, Iran, and Syria) are excluded from the analysis. There is no systematic variation in the capital to GDP ratio, except for Russia. World Bank (2006) explicitly mentions that Russia is "*achieving extremely low rates of return on their produced, human, and institutional capital*" (p. 29) because of the resource curse. The very strong correlation between capital stock and GDP allowed estimation of missing capital stock data. The capital stock of successor states of the Soviet Union was estimated based on the capital stock to GDP ratio of Russia whereas the capital stock of other countries was estimated based on the average capital stock to GDP ratio of all other countries.

[13] For example, 46 out of 49 least developed countries but none of the OECD countries and economies in transitions has a population-weighted annual mean temperature above 18 °C.

Appendix B. Climate change projections

Data on future climate change was derived from an ensemble of 19 general circulation models (GCMs) that have contributed to the World Climate Research Program's Coupled Model Intercomparison Project phase 3 (WCRP CMIP3) and the IPCC Fourth Assessment Report (Meehl and Stocker, 2007; Randall and Wood, 2007). These models were forced by the SRES A2 emissions scenario, which is characterized by a world of independently operating nations, regionally oriented economic development, continuously increasing population, and fragmented technological changes and improvements to per capita income, which leads to a substantial increase in greenhouse gas emissions during this century (Nakicenovic and Swart, 2000). The mean response of surface air temperature and precipitation from monthly data of 19 different GCM realizations for the SRES A2 scenario was utilized in order to obtain a best estimate of regional climate change for that scenario. First, all data was interpolated from the original GCM resolution to a regular 0.5° grid using bilinear interpolation. Second, the climate anomalies for each variable and each future period were calculated based on the average anomaly relative to the 1961–1990 mean climate from the GCM simulations and the observed climate for the same period (Mitchell and Jones, 2005) using a modified delta approach (Füssel, 2003). Finally, the resulting data was spatially and temporally aggregated to obtain annually averaged changes in precipitation and temperature at the national level.

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