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The use of scenarios as the basis for combined assessment of climate change mitigation and adaptation

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ABSTRACT

Scenarios are used to explore the consequences of different adaptation and mitigation strategies under uncertainty. In this paper, two scenarios are used to explore developments with (1) no mitigation leading to an increase of global mean temperature of 4 °C by 2100 and (2) an ambitious mitigation strategy leading to 2 °C increase by 2100. For the second scenario, uncertainties in the climate system imply that a global mean temperature increase of 3 °C or more cannot be ruled out. Our analysis shows that, in many cases, adaptation and mitigation are not trade-offs but supplements. For example, the number of people exposed to increased water resource stress due to climate change can be substantially reduced in the mitigation scenario, but adaptation will still be required for the remaining large numbers of people exposed to increased stress. Another example is sea level rise, for which, from a global and purely monetary perspective, adaptation (up to 2100) seems more effective than mitigation. From the perspective of poorer and small island countries, however, stringent mitigation is necessary to keep risks at manageable levels. For agriculture, only a scenario based on a combination of adaptation and mitigation is able to avoid serious climate change impacts.

1. Introduction

Scenario analysis forms a very important tool in the assessment of climate change and climate change policy, allowing analysts to explore the complex and uncertain future interactions between factors like economic development, greenhouse gas (GHG) emissions, climate and ecosystems. Together these factors determine the need and the possibilities for mitigation and adaptation policy. Scenarios can also act as a means to harmonize assumptions across very different research communities that are involved in the fields of climate research, allowing a better comparison of their results. As such, scenarios have been used extensively in both mitigation and adaptation studies (see Metz et al., 2007; Parry et al., 2007) (especially the scenarios from Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000)).

Moss et al. (2010) point out that since the SRES information requirements from scenario analysis are changing. First, there is an increasing interest in exploring the relationships between adaptation and mitigation. As indicated by Moss et al. (2010), this would require a further integration of information across the different analytical traditions involved in climate research. Secondly, there is also an increased interest in scenarios that explicitly explore the impact of climate policies in addition to the climate policy-free scenarios explored so far. Specifically, there is a strong interest in being able to evaluate the “costs” and “benefits”

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of long-term climate goals vis-à-vis the situation without climate policy.

In this paper, we follow this line of thought and explore how scenario analysis can contribute to a joint assessment of future adaptation and mitigation strategies. Such a joint assessment can be useful for several reasons: (1) the preferred mitigation strategy depends on expected climate impacts and adaptation costs, (2) it takes account of the limitations of adaptation to climate change, (3) some adaptation and mitigation strategies may interact and (4) finally, impacts of climate change may have important feedbacks that need to be taken into account. Such analysis is most useful at a strategic level, and not for individual adaptation (or mitigation) decisions. Given this purpose, we discuss in the paper two main scenarios that include elements of adaptation and mitigation strategies (see further in this paper), resulting in an increase of global mean temperature of 4 °C and 2 °C by the end of this century. These two temperature levels have started to become iconic numbers, representing a potential outcome in the situation without mitigation policy (4 °C) and the temperature target of international climate negotiations (2 °C) (Copenhagen Accord, 2009). Arguably, understanding the implications of these two temperature levels is essential if political leaders are to make informed choices about the balance between mitigation, adaptation and climate impacts (Environmental Change Institute, 2009).

Integrated assessment of mitigation and adaptation strategies is hampered by methodological differences. Integrated assessment models have difficulties describing adaptation processes given the importance of local circumstances (Patt et al., 2010). A practical problem is that to date a considerable part of the impact literature has concentrated on impacts under no-policy scenarios (exceptions include Arnell et al., 2002; Bakkenes et al., 2006; Hayashi et al., 2010; Krol et al., 1997; Nicholls and Lowe, 2004).

This paper therefore presents a generalised scenario assessment based on coupled pieces of information – but without pretending to be complete or to be fully integrated. As a learning-by-doing exercise, the paper intends to show important differences between a 4 °C and a 2 °C world, but also to identify some of the practical issues involved in performing integrated scenario analysis. This implies that the most important advancement compared to existing literature is that we present a multi-sector analysis based on consistent scenarios. Given the state-of-the-art of current integrated assessment models, the experiments have been done using several loosely coupled models. As a result, several important linkages could not be addressed such as between the adaptation responses for agriculture, which may involve irrigation (see Section 5.3) and water demand (Section 5.4). In fact, an important question raised in the paper is whether a fully integrated analysis is needed or whether partial integration is sufficient.

The paper is organized as follows: we first discuss some of the methodological complications in developing scenarios that can provide information for both adaptation and mitigation policy decisions. Next, we discuss the differences between the two main scenarios in terms of socio-economic drivers (Sections 3 and 4). In Section 5 we explore the potential consequences of adaptation and mitigation strategies on various impacts of climate change.

2. Assessment of climate strategies and scenario development (theory and methods)

2.1. Different strategies in response to climate change

Climate change and the responses to it can lead to three forms of costs (not necessarily monetary): (1) the (residual) costs of climate impacts, (2) the costs of adaptation and (3) the costs of mitigation. At least theoretically, this corresponds to three different strategies: (1) "laissez faire" (accept climate change), (2) focus on adaptation and (3) focus on mitigation as illustrated conceptually in Fig. 1 (see also Klein et al., 2007). While Fig. 1 suggests that the costs and benefits of mitigation, adaptation and residual damages can be traded-off against each other, there are conceptual and analytical problems that complicate such an approach. These relate to spatial and temporal scales, and risks and uncertainty (Swart and Raes, 2007).

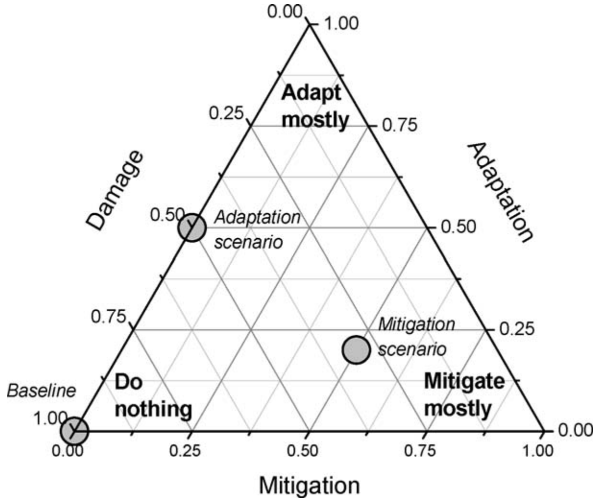

Fig. 1. Climate policy is associated with different combinations of three types of costs: mitigation costs, adaptation costs and residual damage (illustration based on Klein et al., 2007).

Mitigation and adaptation are processes that take place at different *spatial* scales. While mitigation action is often taken at the national or local scale, the benefits are shared globally. As a result, a critical factor in the success and costs of climate policy is the degree of international cooperation (Barker et al., 2009; Clarke et al., 2010; van Vliet et al., 2009; van Vuuren et al., 2009). For adaptation, in contrast, both costs and benefits occur on multiple scales from local to national and even international. An enabling environment at a larger scale can still enhance adaptation at a smaller scale (e.g. local capacity-building funded by international financing mechanisms). For these kinds of reasons, assessment of mitigation tend to concentrate on the global level, while by contrast, adaptation research is mostly focusing at the local scale.

The *dynamics over time* of mitigation and adaptation is also an important factor. Stringent mitigation scenarios typically require strong, early reduction of emissions. Climate change impacts of these scenarios, however, will in the short-term (first decades) hardly differ from those in scenarios without climate change policy due to the large inertia within the climate system. In contrast, some associated impacts (e.g. co-benefits in reduced local air pollution) may be realized at a much faster pace. Adaptation measures are likely to yield private and social benefits over the near-term. For instance, simple adaptation measures such as air conditioning can bring clear short-term benefits. Some important exceptions exist which may require decades to implement, such as changes in spatial planning or large-scale engineering works for flood protection (see Hallegatte, 2009).

Other important factors are *risk and uncertainty*. Our understanding of climate change faces many uncertainties. Key uncertainties to be identified comprise epistemic, data, model, and ontic uncertainties (Schneider and Kuntz-Duriseti, 2002; van Vuuren et al., 2008a). Examples of factors that involve uncertainty are (i) future emissions, (ii) the climate system, (iii) future vulnerability and exposure to climate risks and (iv) mitigation costs. Taking mitigative action reduces some uncertainties, since it reduces the originating sources of climate change and reveals the actual mitigation costs (Barker, 2003; Piani et al., 2005). Mitigation may, however, also add to risks. For example, bio-energy, if implemented unsustainably, may offset one set of risks (climate change) while creating another set of different risks (biodiversity loss and reduced food security). One way of dealing with risks is to include assessments of probabilities. This is often done using past evidence, extrapolated to cover specific future circumstances. Other uncertainties (for instance unknowable shocks and surprises) are more difficult to deal with in quantitative sense, but justify acknowledgement of ignorance. Scenarios can be used to explore the potential for extreme events and the robustness of various policy portfolios but this is not often done (Berkhout et al., 2002).

Traditionally, the disciplines involved in mitigation research and adaptation research have different ways of describing uncertainty. While mitigation research often uses quantitative methods and concentrates on mean estimates, adaptation research often focuses more on qualitative descriptions of uncertainty and concentrates on the risks of hazardous events even if these have a low probability of occurrence. These different perceptions of uncertainty may complicate an integrated assessment of different strategies (Swart et al., 2009).

2.2. *Types of scenarios*

We can characterize scenarios into different classes based on the considerations about mitigation and adaptation. First, we define a baseline scenario, as a trajectory of events assuming no major feedbacks from climate change and no specific policy efforts on either mitigation or adaptation (such a scenario may still include many actions that indirectly influence the ability to mitigate or adapt to climate change; for instance, increasing income levels can be expected to coincide with greater investment in health services reducing the risks of climate-related diseases such as malaria). The main purpose of this type of scenario is analytical, serving as a point of reference for other scenarios. Second, adaptation scenarios describe a world in which societies are responding to climate change impacts. Their purpose is to explore the type of technologies and policies required to adapt to climate change, the avoided damage and the associated costs. Adaptation includes so-called autonomous adaptation (i.e. actions that occur without specific government action) and planned adaptation. Third, mitigation scenarios describe a world including policies aiming to limit climate change. Their purpose is to explore the type of technologies and policies required to minimize climate change and the associated costs. As there will always be remaining impacts, the fourth set, adaptation and mitigation scenarios combine both types of responses to climate change. Possibly, this fourth category of scenarios could re-order policy options according to the synergies that might exists between adaptation and mitigation options, e.g. for some re-afforestation options. Each of these scenarios is connected to a broader social, political and cultural context in which they are assumed to arise.

In exploring a preferred mix of mitigation, adaptation and residual damage, two main approaches exist: (i) the impact and risk-based approach that describes potential impacts as function of global mean temperature increase (and thus mitigation), and (ii) the cost–benefit analysis, which identifies monetary costs and benefits in order to maximize welfare (see for instance Nordhaus, 2008; Tol, 2002c). In both cases, we believe it to be more useful and reflective of the issue to describe the relationships between different response strategies than to seek to determine an optimum. Given the complexities and uncertainties laid out in Section 2.1, we believe no optimal mitigation, adaptation or combined strategy can be pursued in reality.

2.3. *Integrated analysis*

An integrated analysis of mitigation and adaptation can be achieved in different ways: e.g., by using one single, so-called integrated assessment model, or by exchanging information between different models and disciplines, assessing available literature and making results comparable. Both methods are organized around the cause–effect chain of climate change, i.e. describing the relationship between economic activities (income, energy use, agriculture, etc.), emissions, climate change and impacts – and the related feedbacks (Fig. 2). The scheme in fact also forms the backbone of information flows around scenarios for the IPCC reports (Moss et al., 2010). Scenarios are developed first by integrated assessment and emission modelers (focusing on economic driving forces, energy and land use and GHG emissions (IPCC "Working Group III")). Subsequently, the emission trajectories are used in climate models to assess the impacts of climate change (IPCC "Working Group I"). Finally, the scenarios are used for impact, adaptation and vulnerability analyses (IPCC "Working Group II"). The involvement of different research disciplines and working groups implies that it is difficult to account for feedbacks between the different areas.

Integrated Assessment models capture only a limited number of the possible feedbacks (frequently omitted feedbacks include the impact of food and water security on population and economic drivers; relationships between water scarcity and food production, impact of climate change on energy use, etc.). Ignoring (some of) these feedbacks may be reasonable if they are not substantial enough to significantly influence the system. For analytical reasons, there are major advantages to organizing scenario

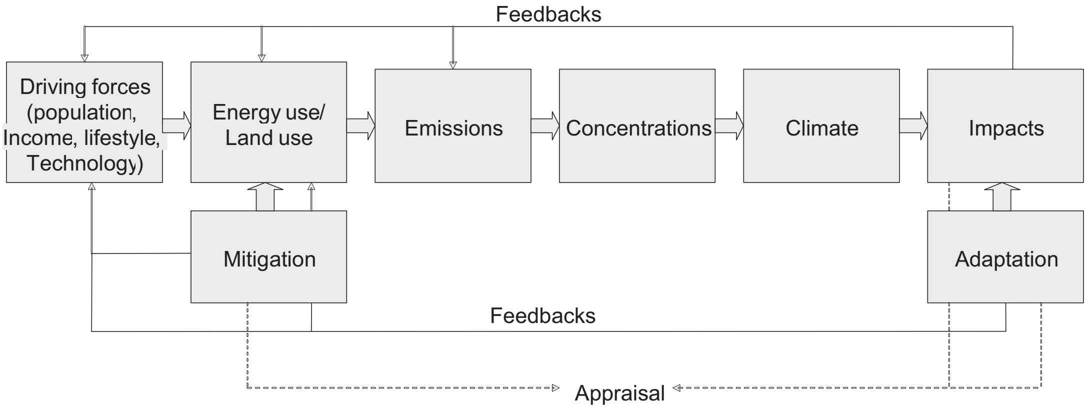

Fig. 2. Driving force–pressure–state–impact–response framework for climate change. Thick lines indicate direct linkages. Solid small lines indicate potentials feedback (many of which are not included in current scenarios). The dashed lines indicate the three costs categories that need to be appraised for climate policy.

development within disciplinary fields and consider a limited number of feedbacks. It allows researchers to focus on elements of the chain that they understand well and to add the required amount of detail, without being confronted with the complications of interlinkages. However, this may change in a situation of increased focus on integrated analysis of mitigation and adaptation strategies. Some examples of why an integrated approach may be necessary are:

i. Climate impacts, such as those triggered by extreme events, may be so severe that they undermine the economic assumptions of the original scenario;
ii. Climate impacts could be substantial in agriculture so that estimates of land-use related emissions not taking impacts into account might be wrong, and the mitigation potential of bio-energy may be affected; and
iii. There may be competing claims for land areas attractive for both mitigation and adaptation purposes.

Thus, an interesting question is whether the need for more integrated analysis is so urgent that more complex modes of integration are needed (interactive coupling of models; one complex model), or whether the impacts can be handled separately simplifying the analysis framework. The time horizon and the decision focus may also be important here, e.g. whether potential tipping points are taken into account (Lenton et al., 2008). The few available studies that have looked into this question seem to suggest that in most sectors the adaptation implications of any mitigation project are small as well as the emissions generated by most adaptation activities (Klein et al., 2007). The most integrated analyses to date come from the cost–benefit oriented integrated assessment models like FUND, DICE and MERGE (Manne and Richels, 2005; Nordhaus, 2008; Tol, 2002c) – but these models typically aggregated climate impacts into a limited amount of rather abstract damage functions.

We believe that over time, with growing intensity of both mitigation and adaptation measures across many sectors, the need for joint assessment with sufficient detail will intensify. The scenarios presented here, based on the current state of the art in modeling and scenario development, take a first step. The same scenarios are used in one assessment for mitigation and impact assessment and we explicitly address mitigation and adaptation strategies (either as part of the scenarios or within the models used for the different impacts). However, many feedbacks are not accounted for. We come back at the end of the paper to the role of more integrated (but also more complex) scenarios.

2.4. Methods used in this paper

As described above, several types of scenarios can be identified: baseline, mitigation, adaptation and adaptation–mitigation scenarios. These scenario types are also presented in this paper. For the baseline/adaptation scenario, we assume intermediate assumptions for most socio-economic drivers. Scenarios assumptions are described in Sections 3 and 4. The scenarios do not include mitigation, leading to a global mean temperature increase of 4 °C above pre-industrial levels by 2100. While we describe possible impacts and adaptation in these scenarios, we do not include feedbacks on the original drivers.

In the mitigation scenarios, stringent mitigation efforts are included leading to a global mean temperature increase of 2 °C. Using the median value for climate sensitivity given by IPCC of 3 °C (Meehl et al., 2007), this translates into a stabilization level of around 450 ppm CO_2-equivalent (CO_2-equiv.). The impacts of climate policy on economic drivers are not accounted for – but several other relationships are coupled (e.g. land use).

In most of the paper, we thus ignore potential impacts of climate change and climate policy on the economic assumptions. In Section 5.8, however, we discuss their impacts within a simple, economic model (FAIR) to provide some insight in the possible size of the economic consequences on the global scale.

Several model tools are used. The scenarios are mainly developed using the IMAGE integrated assessment model (Bouwman et al., 2006). The IMAGE model describes developments in energy and land use in the 21st century based on assumptions for population and the world economy, combined with assumptions for technology development and consumption patterns. The model projects climate change (as indexed by global mean temperature change and sea level rise) at the global scale, and constructs spatial scenarios for change in monthly temperature and rainfall at a $0.5^\circ \times 0.5^\circ$ grid by pattern-scaling downscaled climate model patterns. The output of IMAGE is used in the model DIVA to describe sea-level rise; in the global hydrology model Mac-PDM to estimate consequences for water stress; in the TIMER energy model to estimate implications for heating and cooling demand; in the MARA/ARMA malaria suitability model for impacts on malaria and in the FAIR model for a monetary cost–benefit analysis. Moreover, we discuss more generally the implications for agriculture (based on IPCC AR4) and extreme events. Appendix A provides a brief description of all models used. In our descriptions, we focus on the global level (in view of the limited space). Clearly, this leads to limitations in our discussion of adaptation. The experiments depend on the design each model and thus the number of scenarios that can be presented differs between different impacts. This implies that the study should be interpreted as a first illustration of an integrated assessment, and not as a holistic study on adaptation and its limits.

3. Results: socio-economic trends in the baseline scenario

3.1. Population development and economic growth

We assume that population follows medium-fertility variant of the 2004 revision of the World Population Projections (UN, 2005) up to 2050, and the UN's long-range medium projections up to 2100 (Fig. 3). This implies that the global population steadily increases to almost 9.1 billion people by 2050 and stabilizes at about 9.2 billion people over the subsequent 50 years up to 2100. The scenario takes a middle ground within the range of population forecasting (see Fig. 3). For economic growth up to 2050, the scenario follows projections linked to the Cambridge model E3MG (Barker and Scrieciu, 2010; Barker et al., 2008). The scenario was extended beyond 2050 using the economic growth projections of the SRES-based B2 scenario (IMAGE-team, 2001). Quantitatively, the scenario is a medium to high economic growth scenario, which is mainly the result of optimistic growth assumptions for China and India. The OECD economies are projected to remain the richest in the world in per capita terms, but in terms of total economic activity the importance of developing regions grows rapidly. The growth of GDP per capita is between 0 and 2% per annum in Africa, the Middle East and Latin America. In Asia, it falls from the current high levels to 3% per annum in 2050.

3.2. Energy use and greenhouse gas emissions for the baseline scenario

Energy use in the baseline scenario is made consistent with a baseline published by the European Commission (EC, 2006). Despite a further decrease of energy intensity, world energy consumption more than doubles in the 2000–2050 period and increases by another 25% in the 2050–2100 period (Fig. 4). Over the whole century, energy supply remains dominated by fossil fuels.

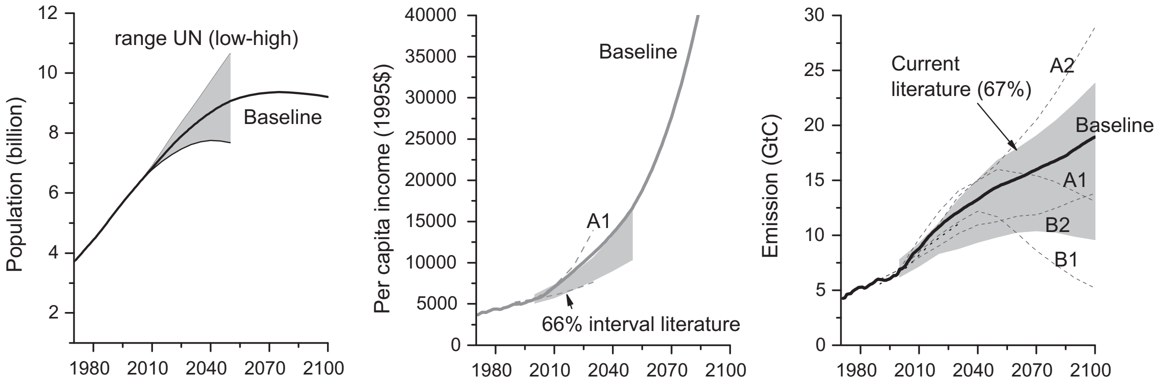

Fig. 3. Population development, economic growth and CO_2 emissions from energy use in the baseline scenario vis-à-vis recently published scenarios in the literature (grey area, for economic growth and CO_2 emissions the scenario database compiled for AR4 was used (see Fisher et al., 2007; Nakicenovic et al., 2006).

While oil and natural gas production peak and decline during the century, the use of coal increases during the whole scenario period. Also non-fossil energy production increases rapidly. Nuclear energy use increases by a factor of two to three to 76 EJ over the period until 2100, the use of biomass increases strongly, while hydro-electricity production increases by about 60–80%. The largest relative increase is that of wind and solar energy; this rises from less than 1% of all non-fossil energy to between 10 and 14% in 2050. Total renewable energy use in 2050 is 120–140 EJ, and 190 EJ in 2100.

The trends described above imply that emissions of CO_2 from energy activities more than double in the period to 2050, and rise by another third between 2050 and 2100 (see Fig. 3). As such, the scenario forms an intermediate baseline scenario within the literature range (Fisher et al., 2007). Non-CO_2 GHGs (in particular methane) increase steadily in the period 2000–2050, but at a slower rate than CO_2 (as their driver, agriculture, is expected to grow more slowly than the energy sector). CO_2 emissions from land-use fall back to zero during the first half of the century. The area of agricultural land lies within the range of similar scenarios that have recently been published, although at the low end of the range (Rose et al., 2007).

4. Results for the mitigation scenario and climate scenarios

4.1. Energy use and greenhouse gas emissions

The mitigation scenario aims at stabilising GHGs at around 450 ppm CO_2-equiv. (see also van Vuuren et al., 2007, 2010). The scenario allows for an initial overshoot of concentration to about 510 ppm CO_2-equiv. Den Elzen and van Vuuren (2007) have shown earlier that a limited overshoot of concentration allows for meeting

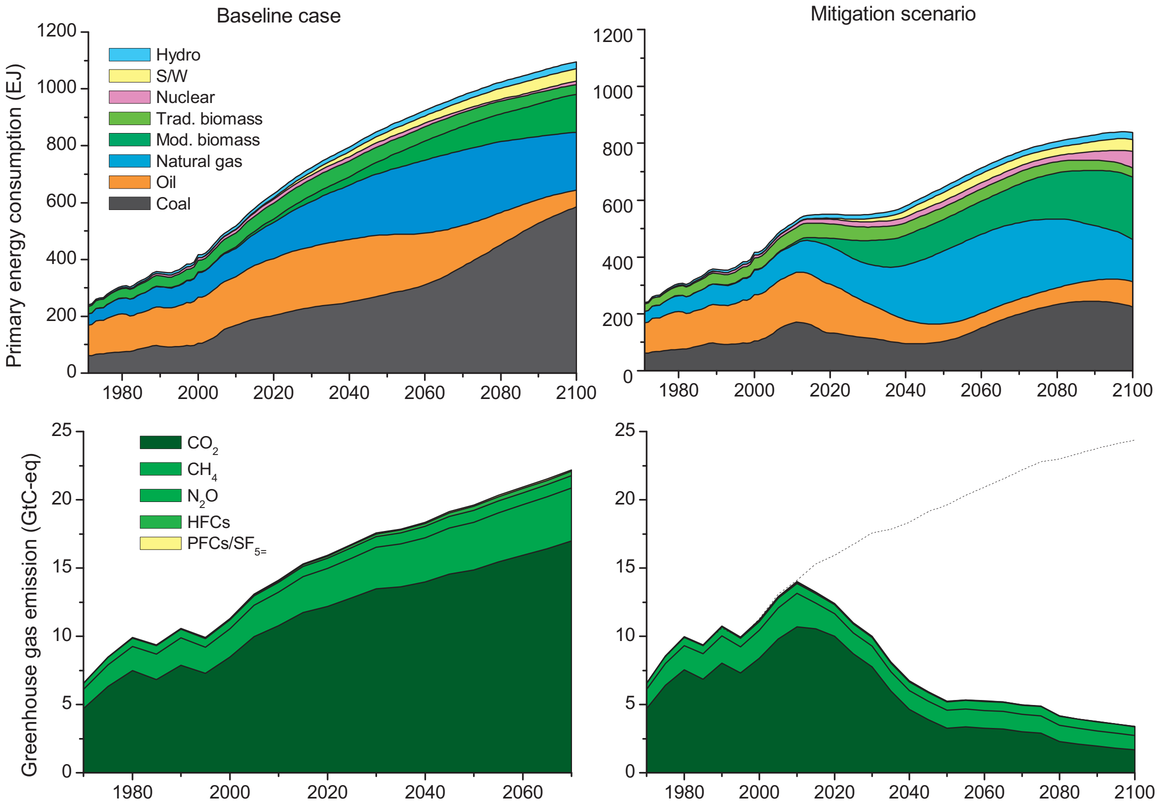

Fig. 4. *Upper panels*: Global primary energy use for the baseline scenario (left) and the 450 ppm scenario (right) (TIMER model). *Lower panels*: Global CO_2-equiv. emissions for the baseline scenario (left) and the 450 ppm scenario (right) (dotted line in lower right graph indicate baseline emissions).

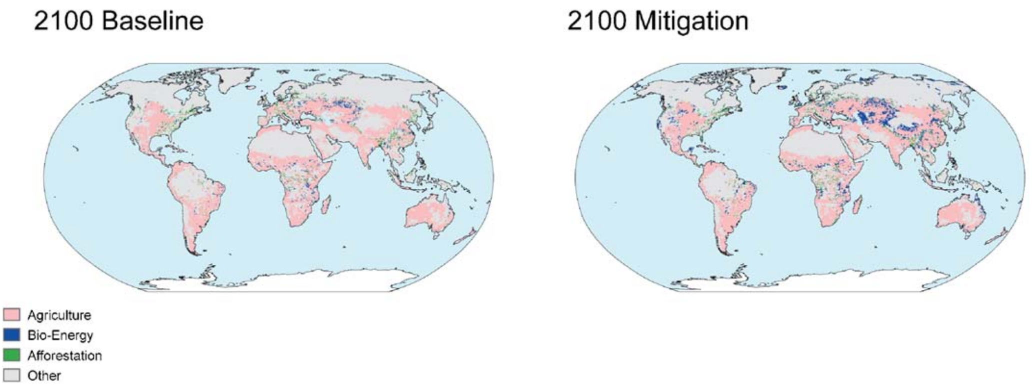

Fig. 5. Land use in the different scenarios. Geographic details are for illustration only. The figure shows the visible impact of land-use related mitigation options on future global land use.

similar climate targets at lower costs. Emission reductions are achieved in various ways. One element is to increase energy efficiency, which reduces the total amount of energy use (a 20% reduction in 2050 compared to baseline) (see Fig. 4). The scenario also shows an increasing use of energy from non-fossil sources, which account for most of the growth in total energy use. Non-fossil energy use increases from about 15% of total primary energy use in 2010 to more than 30% in 2050 and is over 40% of the total by the end of the century. Most of this growth is due to an increase in bio-energy use. Carbon capture and storage is applied in most remaining stationary uses of fossil fuels. Finally, also non-carbon dioxide greenhouse gas emissions are reduced. As a result, global emissions peak around 2020, and reduce further with time. Emissions are reduced by more than 70% compared to the baseline in 2050 and more than 80% by 2100. The consequences of mitigation policies affect not only the energy sector, but also land use. Substantial additional land areas are used for afforestation and bio-energy (see Fig. 5).

Model comparison studies show that the mitigation scenarios presented here are consistent with the current literature, although models show significant differences in the contribution of various reduction measures (Clarke et al., 2010; Edenhofer et al., 2010). According to the IMAGE model calculations, the abatement costs of the emission reductions are in the order of 1–2% of GDP (i.e. the annual additional expenditures which can be compared to the current expenditure of around 1.5% of GDP on environmental policy in OECD countries) (Fig. 6). The literature range of comparable scenarios is in the order 0.5–5.5% in 2100. Most studies agree that these additional expenditures would lead to a reduction of GDP. We discuss this further in Section 5.8.

4.2. Climate change under the baseline and mitigation scenario

The atmospheric GHG concentration and associated mean global temperature change resulting from the emissions of the two scenarios is shown in Fig. 7 (solid lines indicate best-guess values), based on the IMAGE model calculations. The IMAGE model uses the MAGICC model to calculate changes in global mean temperature. The MAGICC model was used earlier for similar IMAGE scenarios by van Vuuren et al. (2008b) to calculate trajectories for greenhouse gas concentration and temperature including uncertainty ranges. Here, the uncertainty ranges used for the MAGICC calculations were based on existing runs of more complex carbon cycle and climate models. We have used the implications for ranges in greenhouse gas concentration and temperature outcomes to also depict the uncertainty ranges here as is indicated by the shaded areas in this graph. For temperature, the wider shaded area indicates the uncertainty as result of uncertainty in the carbon cycle and climate sensitivity. For the baseline scenario, global mean temperature increases almost linearly to 2.1 °C above the pre-industrial levels in 2050 and to 3.7 °C in 2100 (uncertainty range 3–5 °C). In the mitigation scenario, the global mean temperature increase by 2100 is limited to 1.9 °C. Again, there is considerable uncertainty. Fig. 7 indicates that by the end of the century the mitigation case could also lead to a temperature increase of 2.6 °C compared to pre-industrial levels. As the mitigation scenario presented here is among the most stringent in the scientific literature (cf. Clarke et al., 2010; Edenhofer et al., 2010; Fisher et al., 2007), two important conclusions can be drawn. First, the analysis indicates that global warming can be moderated but not halted. Second, the observation that a stringent scenario could also lead to considerably greater climate change than 2 °C may imply that hedging adaptation policies against more warming might have considerable value. For example, such policies may be to '... aim for 2 °C, but prepare for 3 °C'. In the assessment of impacts below, we focus on the central climate change projections.

Changes in mean monthly temperature and precipitation across the globe at the 0.5° × 0.5° scale, associated with the global average temperature changes, have been constructed by rescaling patterns derived from the HadCM2 climate model (Fig. 8). These patterns show that the change in annual mean temperature is larger at high latitudes than at low latitudes, and show considerable spatial variation in change in rainfall. Considerable disagreement about the expected patterns of climate change exists, especially for precipitation: the impact results presented in this paper therefore represent only one possible outcome.

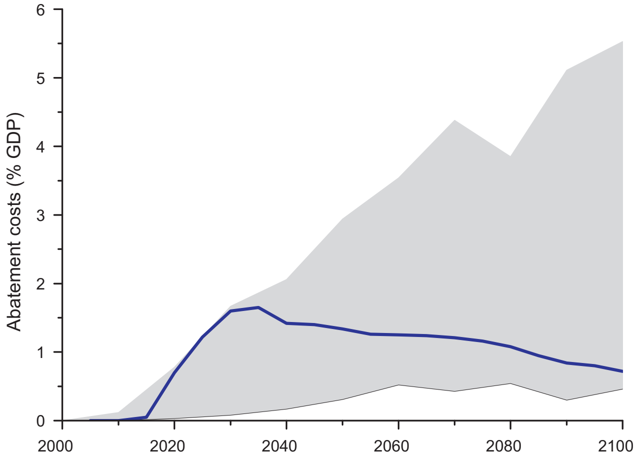

Fig. 6. Annual abatement costs as percentage of GDP (grey area depicts literature range 70% interval for category I scenarios based on IPCC AR4 definition (Fisher et al., 2007) – data based on (Clarke et al., 2010; Nakicenovic et al., 2006); solid line this study).

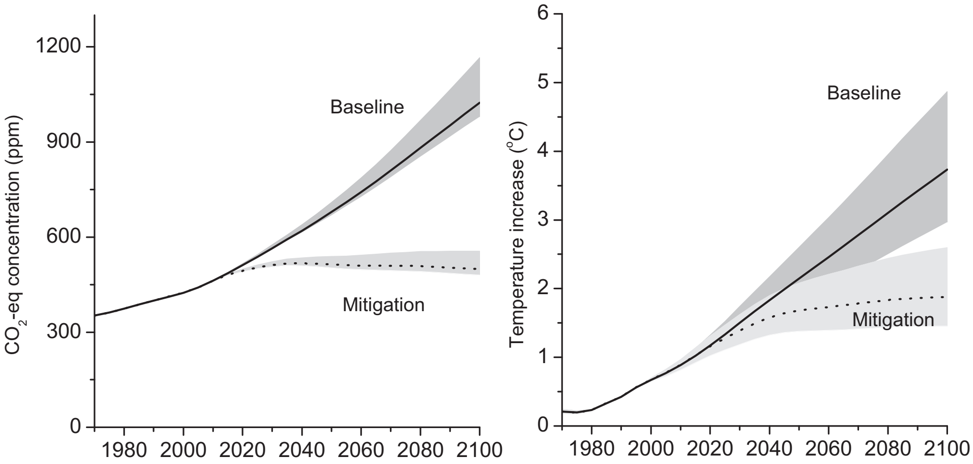

Fig. 7. Atmospheric CO_2 equivalent concentration (taking into account the Kyoto gases) for the baseline scenario (4 °C, no climate policy) and mitigation scenario (2 °C) (left) and global temperature change (since the pre-industrial age) for the same two scenarios (right). Uncertainty ranges (grey area) are based on van Vuuren et al. (2008b).

5. Results: impacts and adaptation in the different scenarios

5.1. Introduction

IPCC's Fourth Assessment Report (IPCC, 2007) gives an overview of climate impacts. Some of these impacts result from changes in average climate, but other impacts may result from changes in extreme events. Table 1 summarizes some of the impacts, for health, agriculture, water availability, coastal flooding, urban areas and energy system, and large-scale disruptions of the climate system (in contrast, biodiversity and ecosystem services have not been included). As noted earlier, most of the literature has treated climate change as "a gradual phenomena" (Agrawala and Fankhauser, 2008). This is problematic for impacts characterized by low probabilities coupled with high impacts (see below).

In this exploratory analysis, we sketch some of the impacts and adaptation requirements. We aimed to cover several key impacts mentioned in Table 1, but the assessment was limited by the availability of models that could easily be coupled. Therefore, rather than intending to be exhaustive, the descriptions provide some indication of the magnitude of some impacts and key adaptation challenges. In presenting our results, we have used several new model runs based on the scenario discussed above (e.g. for malaria, water resources, sea-level rise, heating and cooling demand). We have, however, also assessed existing information from IPCC 4th Assessment Report in the context of the two

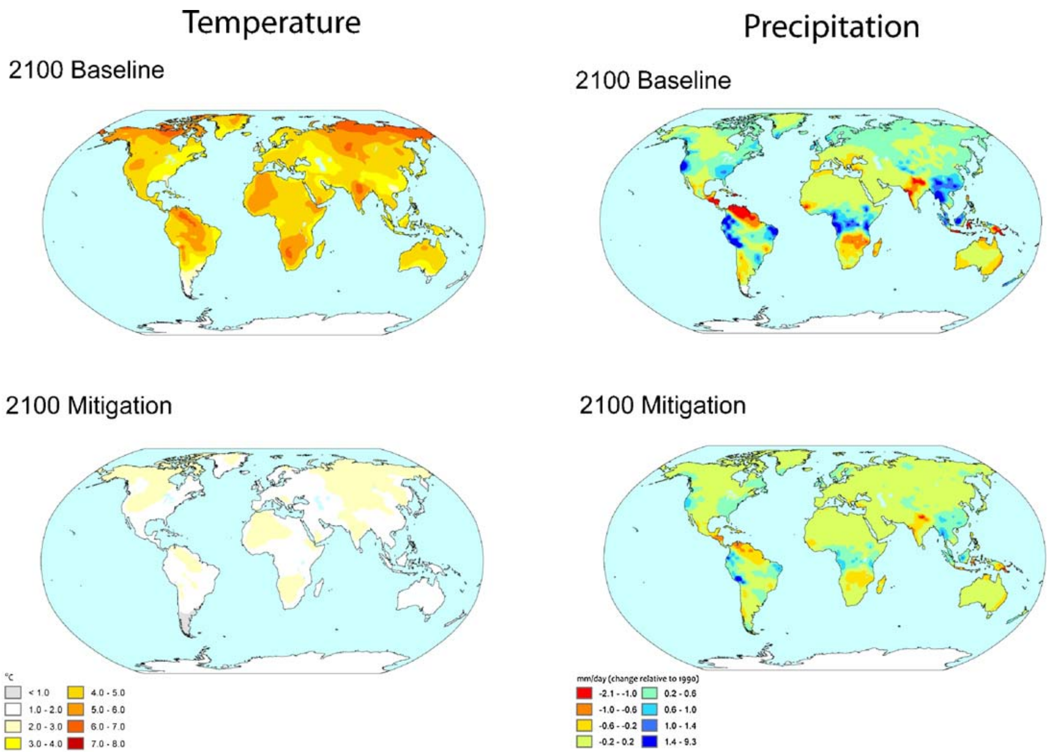

Fig. 8. Maps of the change of annual mean temperature (left) and precipitation (right) in 2100 relative to 1990 for the baseline (top) and mitigation (bottom) scenarios.

Table 1
Possible impacts of climate change (based on IPCC AR4).

	Impacts associated with global average temperature change	Impacts due to changes in extreme events
Health	Increasing burden from malnutrition, diarrhoeal, cardio-respiratory and infectious diseases. This will affect particularly populations with low adaptive capacity	1. Reduced mortality from cold exposure, increased risk of heat related morbidity and mortality (heat waves) 2. Risks related to heavy precipitation events (deaths, injuries and diseases) 3. Food and water shortage and increased risk of water- and food-borne diseases as a result of drought 4. Risks related to floods 5. Population migration with associated health risks due to droughts, floods, increased incidence of extreme high sea level
Food	Negative impacts on vulnerable groups. Region specific changes (both positive and negative) in cereal crop productivity	1. Changed yields in agriculture (due to extreme temperatures, droughts, heavy precipitation) 2. Land erosion and degradation (due to heavy precipitation events, droughts) Increased livestock deaths (due to drought)
Water	Increased availability in some areas, decreased availability and increasing drought and water stress in other areas. Effects are both through changes in rainfall + evapotranspiration and through changes in snow and ice melt. This will affect agriculture	1. Effects on water resources relying on snowmelt and glaciers (due to changed extreme temperatures) 2. Effects on water supplies (due to changed extreme temperatures, changed seasonality, droughts, heavy precipitation events) 3. Increased water demand (due to heat waves, droughts) 4. Changed (reduced or increased) hydropower generation potentials due to changing droughts
Coasts	Increased damage from floods and storms due to sea level rise. This will affect low-lying coastal systems	Increased risk and costs of coastal protection from extreme weather events.
Industry, settlements and society	Affected by impacts in all of the above categories, compounding pressures associated with rapid urbanisation, industrialisation and aging in some societies The most vulnerable are generally those in flood plains, those whose economies are closely linked with climate-sensitive resources and the poor	Affected by impacts in all of the above categories. Specific impacts include: 1. Changes in energy demand for space conditioning 2. Reduced quality of life due to heat waves for people without appropriate housing 3. Disruption due to flooding caused by heavy precipitation 4. Water shortages due to drought 5. Disruption due to cyclones 6. Increased costs of coastal protection from extreme high sea level
Large scale disruption	1. Partial loss of ice sheets on polar land implies metres of sea level rise. Rapid sea level rise on century time scales cannot be excluded 2. Large-scale and persistent changes in the meridional overturning circulation (MOC) of the Atlantic Ocean could cause various changes to ocean behavior	

scenarios presented here (temperature-related mortality, agriculture and extreme events).

5.2. Human health: temperature-related mortality and malaria

Health impacts of climate change need to be seen in the context of other, more important drivers of human health, including lifestyle-related factors (Hilderink et al., 2008). We focus here on temperature-related mortality and malaria.

5.2.1. Temperature-related mortality

Temperature-related mortality impacts may occur via changes in extreme temperatures, changes in average temperatures, or in seasonal variation of temperatures, with the literature showing varying results. McMichael et al. (1996) made an estimation of temperature-related mortality using relative risk ratios, showing that there is an optimum temperature at which the death rate is lowest (also know as the U-shaped dose–response relation). If temperature increases, heat stress-related mortality increases, but cold-related mortality decreases. Tol (2002a) concluded that in monetary terms the reduction in cold-related mortality due to climate change outnumbers the increase in heat-related mortality. This conclusion is however, influenced by the approach used to value a life and also subject to the large uncertainties with respect to the relationships between average and regional temperatures and temperature and health. Adaptation may occur both by the adjustment of the human physiology to higher temperatures (McMichael et al., 1996), changes in behavior and an increase of air conditioning use (Kinney et al., 2008). Given the complexities in using dose–response relationships between temperature and mortality, we have not attempted to quantify these here.

5.2.2. Malaria

Considerable attention has been paid to the relationship between malaria and climate change. In this paper, we also focus on climate-induced changes in malaria risks. Annually more than one million people, mostly African children, die from malaria, a vector-born infectious disease. The anopheles mosquitoes (the vector which spreads the malaria infection) can only survive in climates with high average temperatures, no frost and sufficient precipitation. The MARA/ARMA malaria suitability model (Craig et al., 1999) incorporates these factors to determine climatically suitable areas. Mortality due to malaria is, however, also heavily influenced by factors such as access to preventative measures (including indoor spraying and insecticide-treated bed nets) and access to health care. In the MARA/ARMA model these factors are linked to income and urbanization. Fig. 9 shows the results of this model for the scenarios of this paper. The impact of autonomous

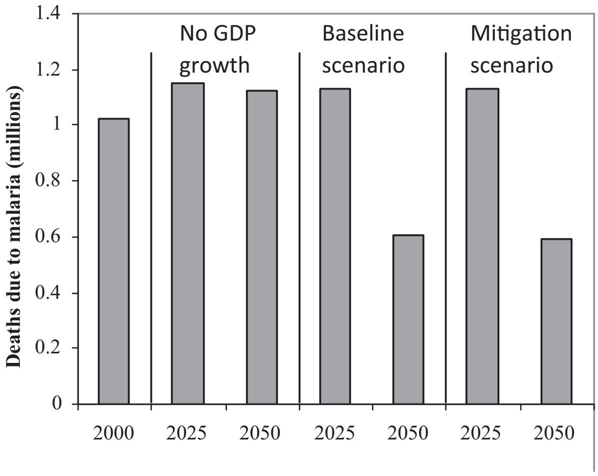

Fig. 9. Death due to malaria in the baseline scenario and in the mitigation scenario. The ‘no GDP growth’ scenario has been added to illustrate the importance of socio-economic development on malaria deaths.

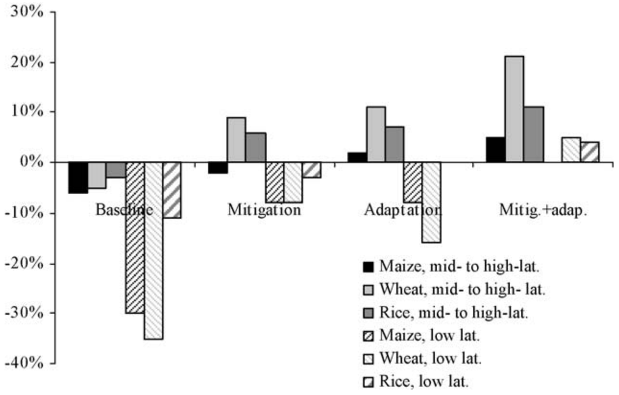

Fig. 10. Indicative results for the sensitivity of maize, wheat and rice yield change at low and mid- to high-latitudes to climate change for each of four scenarios (following Easterling et al. (2007)).

adaptation (as function of rising income) reduces malaria deaths by around 50%, especially in Africa (mainly due to better provision of health care). In contrast, the impacts of climate – and especially the difference between the mitigation scenario and the baseline case are much smaller. Mitigation reduces malaria health risks by about 2% (2050). Adaptation, therefore, has a much more decisive influence on malaria control than mitigation (this finding seems to be robust with available literature).

5.3. Agriculture: impacts on yields

Easterling et al. (2007) have synthesized a large amount of research on the impacts of climate change on crop growth, with and without adaptation. The results were summarized as a function of global mean temperature increase, although in reality changes in temperature and precipitation patterns and CO_2 fertilisation all play a role. For instance, the impacts of CO_2 fertilisation partly offset the impact of climate change. The results can be used to assess the climate impacts for our scenarios by using the best-fit polynomials from Easterling et al. (2007), that indicate the impact on yield as a function of mean temperature change.[1] We looked at the impacts for the baseline (4 °C) and mitigation (2 °C) scenario, with and without adaptation, for maize, wheat and rice (see Fig. 10; results are presented for tropical and temperate zones in 2100; these impacts are additional to the yield increases as a result of other factors than climate change). Although the results are very uncertain, some conclusions seem to be possible. First, the baseline scenario (no adaptation) causes a very substantial decrease in yields (relative to the situation without climate change) for all cases shown: Climate change impacts may reduce yields for the aggregated regions shown by 10–35% for the crops studied (2050). Second, engaging in either mitigation or adaptation limits the decrease in yields. In the tropics, however, impacts remain negative and typically in the order of a 10% loss. Third, the combination of mitigation and adaptation may result in an improvement from today's situation. Agricultural impacts may be more positive for temperate regions, but only if the advantages of higher temperature are not offset by impacts of extreme weather. These results underline the need to look at both mitigation and adaptation. The results presented are based on the IPCC assessment and represent a wide range of models.

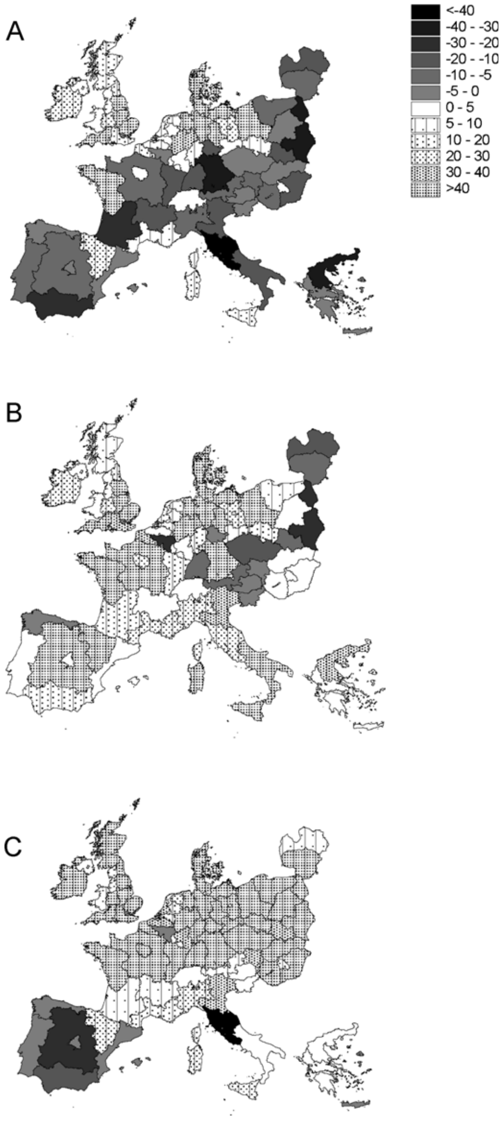

Fig. 11. Changes in annualised drought and heat wave risks to spring wheat over the 2030–2060 period compared to today, without adaptation (A) and with adaptation in terms of advanced sowing (B) and longer cycle variety (C) (in € millions).Mechler et al. (2010) and Moriondo et al. (2010).

The results can also be illustrated by individual studies. Tubiello and Fischer (2007), for instance, found that a mitigation scenario could reduce the global costs of climate change in agriculture significantly. Similarly, Fischer et al. (2007) illustrated the importance of adaptation for water irrigation requirements. They found that mitigation reduced agricultural water requirements by about 40%, leaving 60% of the impacts requiring adaptation.

When dealing with impacts on agriculture both drought and heat wave stress play important roles. Fig. 11 shows, for Europe, the impact of drought and heat wave stress on crop yields for a 2 °C warming scenario, assuming various forms of adaptation (Mechler et al., 2010; Moriondo et al., 2010).[2] Winter and summer crop yields were simulated for spring wheat with today's and future crop management practices. Adaptation options considered comprised shifting the sowing date by a few days and using cultivars with a longer/shorter growth cycle. Results show that Southern Europe and parts of France are today already particularly exposed to drought and heat stress, and this situation is expected

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[1] We have in each case taken the global mean temperature change for a scenario and used that as an indication of the average local temperature change to be expected. This means that our impact estimates are likely to be conservative, as temperature increase is likely to be stronger the global average over many land areas.

[2] Calculations were done using the Cropsyst model on the basis of the HADCM3 climate model for the 2030–2060 time slice.

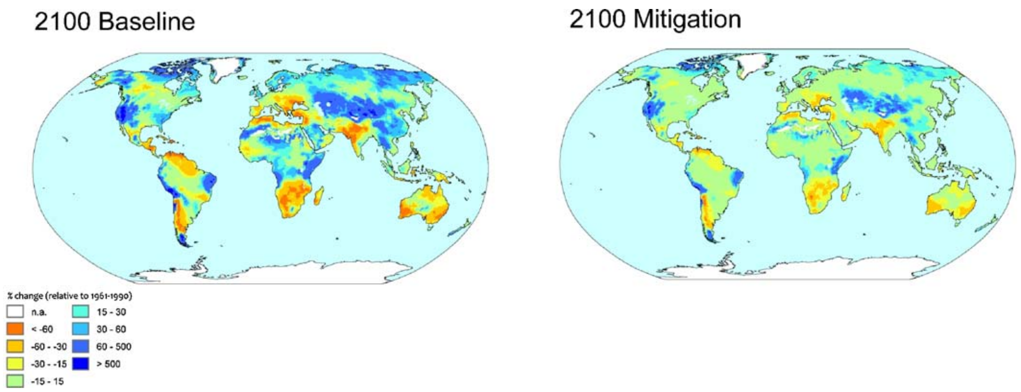

Fig. 12. Change in runoff by 2100. The figure shows the percentage change in average annual runoff, relative to 1961–1990, under the baseline and mitigation scenarios.

to worsen even under the 2 °C (mitigation) scenario (Fig. 11 panel A). When considering the two adaptation strategies in combination with mitigation (Fig. 11 panels B and C), many regions in Europe may actually benefit. Northern Europe, in particular, could exploit the advantage of higher precipitation by using crop varieties with a longer growing cycle. In contrast, in Southern Europe the same adaptation options would result in an added negative impact, since crop development would shift towards summer when longer dry spells and heat waves may significantly affect crop growth. Also, the results show that while there are some region-specific limits to adaptation, overall adaptation would effectively reduce impacts on the agricultural sector in Europe.

5.4. *Water resources: potential water availability*

The effects of the two scenarios on exposure to changes in water resources stress are assessed using a global-scale water resources impact model (Arnell, 2003). Fig. 12 shows the percentage change in average annual runoff by 2100 (relative to the 1961–1990 mean) under the baseline scenario and the mitigation scenario (with the HadCM2 climate model pattern). We define watersheds to be in a water-stressed condition if average annual runoff is less than 1000 m^3/capita/year (other definitions are also used in the literature). The effect of climate change is indexed by summing (i) the populations living in water-stressed watersheds where runoff decreases (increases) significantly (typically by more than 5–10%) and (ii) the population living in watersheds that become water-stressed (cease to be water-stressed) due to climate change. The number of people exposed to an increase or decrease in water stress due to climate change have not been summed for two reasons: (i) the adverse effects of having less water are greater than the beneficial effects of having more water in a water-stressed catchment, and (ii) the regions with an increase and decrease in exposure to water resources stress are widely separated, and "surpluses" in one area do not offset "deficits" in another. The results show substantial differences in exposure to increased water resource stress in 2050, 2080 and 2100 between the mitigation and baseline scenarios. In 2020, there is little difference in runoff between the two scenarios. Fig. 13 shows the numbers of people exposed to an increase or decrease in water resource stress due to climate change under the two scenarios. In both the baseline and the mitigation scenario, the numbers of people living in water-stressed watersheds who apparently benefit from increased water availability is larger than the numbers exposed to a reduction in runoff, but – as outlined above – we do not focus on the net effect. The numbers of people exposed to change in water resources stresses are sensitive to the assumed pattern of climate change. Compared to the baseline, the mitigation scenario reduces the numbers exposed to an increase in water resources stress by 135 million (reducing impacts by 12%), 281 million (20% reduction) and 457 (30% reduction) million in 2050, 2080 and 2100 respectively. At the same time, however, there are also people benefiting from climate change. The relative size of the groups with positive and negative impacts depends on the climate model used (here only the Hadley pattern has been used). Clearly, mitigation also decreases the number of people benefiting from climate change. It is also clear that mitigation does not eliminate water supply impacts of climate change, and adaptation will be required for the remaining billion people exposed to increased water resource stress due to climate change. Adaptation may include measures to increase water storage, transport of water, or reduction of water demand by increasing efficiency. Underlying results show that the effects of mitigation vary significantly by region. In fact, in some regions mitigation may even increase the numbers of people

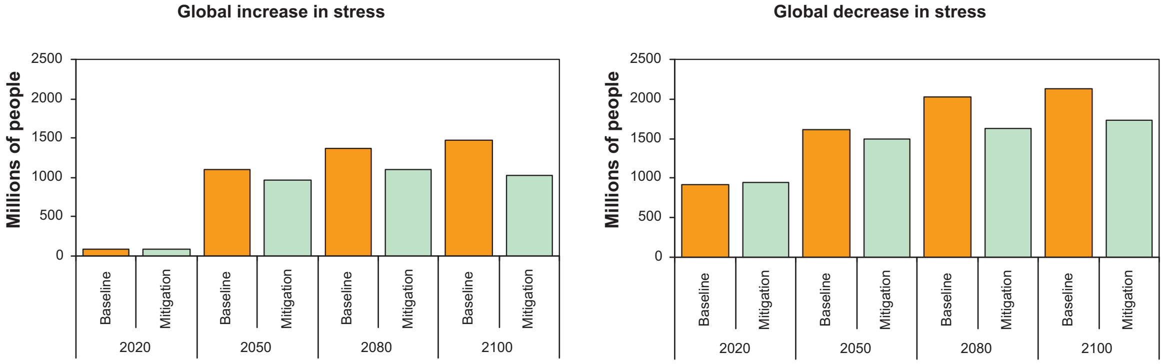

Fig. 13. Numbers of people exposed to increase or decrease in water resources stress due to climate change, under the baseline and mitigation scenarios. The simulations are based on the HadCM2 climate model pattern.

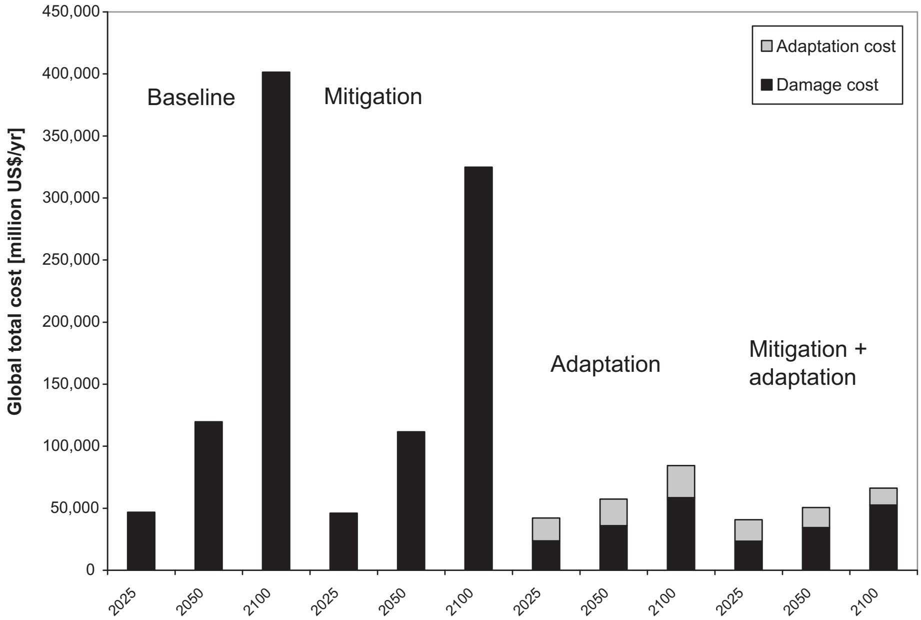

Fig. 14. Global total annual adaptation costs and damages up to 2100 as a result of sea level rise, as modeled in the DIVA model using the scenarios.

exposed to increased stress. Specific uncertainty analysis shows that results are highly dependent on the uncertainty in the changes in the precipitation pattern due to climate change.

5.5. Sea level rise

Another important impact of climate change is rising sea levels. Global mean sea-level rise has been projected for both scenarios using the MAGICC component of the IMAGE model. Due to the delayed response of sea-level to global warming, the projections mainly diverge in the second part of the century: sea level rise is 35 and 31 cm in 2050 in the 4 °C and 2 °C scenario, respectively and 71 and 49 cm in 2100. These projections do not include a potential accelerated contribution of the ice sheets of Greenland and Antarctica, which could lead to higher sea-level rises but the underlying processes are insufficiently understood and are currently not included in climate models (Meehl et al., 2007; Nicholls et al., 2010; Vermeer and Rahmstorf, 2009).

We use the DIVA model to assess both damage and adaptation costs of sea-level rise, associated storm surges and socio-economic development under the two scenarios taking into account coastal erosion (both direct and indirect), forced migration, coastal flooding (including rivers) and salinity intrusion into deltas and estuaries. For each scenario the model is run first without and then with adaptation in terms of raising dikes and nourishing beaches (DINAS-COAST Consortium, 2006; Hinkel and Klein, 2009). Further impacts such as salinity intrusion in coastal aquifers, loss of coastal wetlands and biodiversity as well as further adaptation options such as salinity intrusion barriers, port upgrade, set-back zones and ecosystem-based protection could not be included due to the unavailability of global data and general models of these processes.

Fig. 14 shows that independent of the level of mitigation, adaptation reduces global overall costs rather effectively, which illustrates the necessity for engaging in adaptation even under ambitious mitigation. At the aggregated scale more damages can be avoided through an adaptation-only strategy than through a mitigation-only strategy, although a combination of the two has the strongest positive impact. From the perspective of poorer and small island countries, however, stringent mitigation is necessary to keep risks at manageable levels. Even without sea-level rise, adaptation would be cost-effective in order to protect the assets situated in the floodplain, which increase due to socio-economic development alone. While this would involve substantial investment flows (tens of billions of US$ worldwide), they are a relatively small fraction of global GDP, even for sea level rise at the level of the baseline scenario. However, for individual countries or regions (particularly small island states) these costs can be a much larger fraction of GDP, including the risk of a complete loss.

5.6. Heating and cooling demand (settlements and society)

Climate change is likely to influence the demand for space cooling and heating. Therefore, we have developed a set of simple relationships to describe heating and air conditioning demand in the residential sector and explored the impacts of climate change on this simulated energy demand (Isaac and van Vuuren, 2009). Clearly, changes in population and income are projected to lead to a considerable growth in the energy demand for heating and air conditioning in the coming century (see Fig. 15, no climate change case). Driven by climate, changes in cooling and heating practices are examples of autonomous adaptation (i.e. without policy intervention). Adaptation is not universal, however, since the

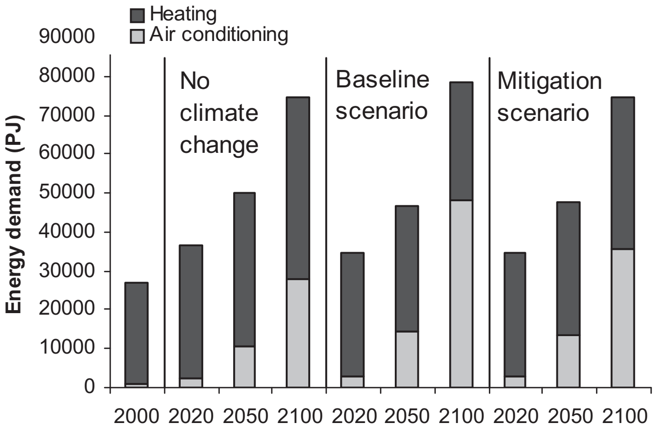

Fig. 15. Global annual energy demand for heating and air conditioning in the residential sector in the year 2000 and during the coming century for two scenarios (baseline and mitigation) and if no climate change at all is assumed (TIMER model).

population will not always be able to respond. Unfulfilled demand for heating and cooling can lead to health impacts (as described in Section 5.2) and to loss of labour productivity. In addition to these effects, there is reduced comfort when indoor temperatures rise above a given level.

Fig. 15 shows that, globally, the autonomous increase in energy demand without taking climate change into account due to increasing income and wealth is much larger than the difference between the energy demand in the baseline scenario and the mitigation scenario (Isaac and van Vuuren (2009) show this a robust result also for other baselines). The effect of climate change on combined energy demand is also smaller than the effect on heating and air conditioning separately, since increases in air conditioning compensate decreases in heating. On the regional and country level, impacts can be far more significant: for example, in India we project a large increase in energy demand due to increased cooling, while in Western Europe and the USA, we project a substantial decrease due to reduced heating.

5.7. Extreme events

Climate change is expected to lead to changes in the frequency and intensity of some weather-related extreme events (Parry et al., 2007). Extremes like floods, droughts, heat waves and storm surges could become more frequent and intense, while cold-extremes, such as cold spells, are likely to become less frequent and weaker. Assessing risks of climate change based on changes in average conditions-only runs the risk that changes in extreme event risks are averaged out. A more risk-based, geographically explicit method is therefore preferable. However, knowledge on disaster impacts is complex and contested. To date, there are only a limited number of national level studies taking a probabilistic approach to projecting future risk in the presence of climate change, mostly focusing on flood risk (Mechler et al., 2010). One such study on the pan-European scale by Feyen et al. (2009) computed that expected annual damages would triple under a baseline scenario.

A key constraint to quantitative risk approaches is the uncertainty in the climate projections. For precipitation, for instance, models often disagree on the sign of changes at the local scale. This is especially important for studies looking for instance flood risk. While the Mechler et al. (2010) study aimed to project future risk, they found future projection to be so uncertain that the authors refrained from projecting future flood risk based on an estimate of today's flood impacts. Current models and data, however, seem to be sufficient to assess the combined risk of drought and heat wave stress on agriculture with a relatively high level of certainty (slower phenomena).

Some examples of work in the context of the 2 °C and 4 °C scenarios are provided here. Several studies looked into flood-affected people at the global scale (Hirabayashi and Kanae, 2009; Kundzewicz et al., 2010). Regression of samples shows that the average global number of people affected by 100-year floods per year for the mitigation scenario (2 °C) is projected to be 211 million compared to 544 million for the baseline (4 °C). Mirza et al. (2003) showed that for Bangladesh, a flood-vulnerable country, even the 2 °C scenario is expected to increase the projected flooded area by at least 23–29%. It should be noted, however, that the uncertainties about exposure, vulnerability and adaptation still lead to a wide range of estimates for the costs of future flood damage. With respect to drought, the projections for the 2090s made by Burke et al. (2006) show that the number of extreme drought events per 100 years and mean drought duration are likely to increase by factors of two and six, respectively, for the baseline scenario by the 2090s.

Evidence suggests that damage of weather and climate related impacts has already increased in the present-day, but these are mainly due to the wealth and population increases (Bouwer, 2010). However, climate change is expected to increase over time, and is likely to become a more significant contributor to rising damages in the future. The most recent IPCC report indicates that the costs of major events are expected to range from several percent of annual regional GDP and income in very large regions with very strong economies, to more than 25% in smaller areas (Parry et al., 2007). Disaster losses for highly exposed small island states in the past have in fact exceeded annual GDP (Cummins and Mahul, 2009).

5.8. Economic evaluation of impacts

Cost–benefit analysis (CBA) is used to express the costs and benefits of climate change of different strategies in terms of a common monetary unit. We use the CBA module of the FAIR model (see model Appendix A) here to obtain some idea of impacts at a more aggregated scale. For mitigation costs, the FAIR model uses the information of the IMAGE model presented earlier. The climate damage and adaptation cost functions used in FAIR are derived from the AD-DICE model (De Bruin et al., 2009a; Hof et al., 2009a). In short, AD-DICE estimates adaptation costs based on the damage function of the DICE model (Nordhaus and Boyer, 2000). The AD-DICE separates these functions into a damage cost function and residual damage function based on an assessment of each impact category described in the DICE model – agriculture, coastal zones, health, settlements, non-market time use, other vulnerable markets and catastrophic impacts. For this study, we assumed an optimal adaptation response to climate change (i.e. given a level of temperature change the model minimizes the sum of adaptation costs and residual impacts).

The impact estimates used in DICE (and thus FAIR) include: (i) real, measurable, economic costs (so-called market costs); and (ii) other, intangible losses (non-market losses), which are monetized using the willingness-to-pay concept. The damage functions are not directly related to the physical or economic damages described earlier in this section, as they are derived from a separate source. It has been shown earlier that the FAIR results of adaptation costs are consistent with the range of values reported in the literature (Hof et al., 2009a).

Under default settings of the FAIR model and a discount rate of 2.5%, the discounted costs as a share of global GDP due to climate change impacts for the period 2005–2200 amount to nearly 4.5% in the baseline (Fig. 16). These costs may seem higher than suggested by the limited set of sectoral analyses presented above, but include more sectors and also the impacts of possible catastrophic events

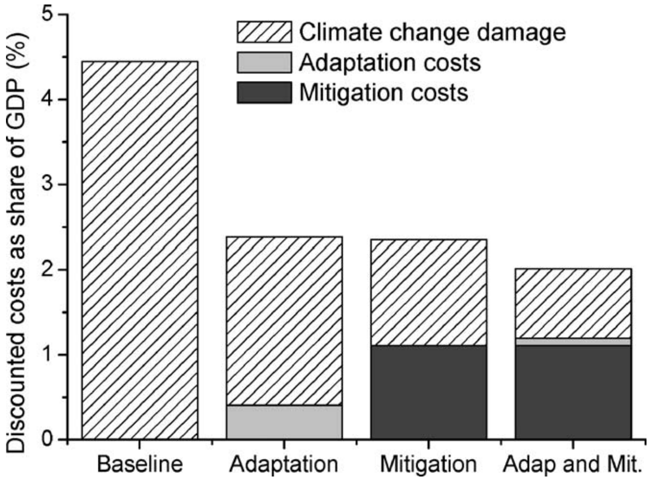

Fig. 16. Mitigation costs, adaptation costs, and residual damages due to climate change as share of GDP according to the FAIR model (Hof et al., 2009b).

(Nordhaus and Boyer, 2000). Annual costs rise sharply over time, reaching 17% in 2200 (note that impact estimates are very uncertain and both higher and lower values can be found in the literature (Parry et al., 2007; Stern, 2006; Tol, 2002b)). Scenarios with only adaptation or mitigation reduce discounted costs substantially to around 2.5% (Fig. 16). Hof et al. (2008) have shown that the results of CBA of climate change are very sensitive to model assumptions, with the discount rate playing the most important role. The discount rate is especially important due to the different costs function over time related to the adaptation only and mitigation only scenarios.[3] With our discount rate of 2.5%, the combination of mitigation and adaptation leads to the lowest discounted costs, namely 2% of GDP. Consistent with literature, the adaptation investments are assessed to be smaller than mitigation investments and residual damages. However, they are very important in limiting residual damages.

Some important caveats need to be mentioned. First, calculations cannot be regarded as reliable for the extreme tails of risks (i.e. low probability, high impact events). As a subjective assessment on how to handle such risks is involved, Weitzman (2008) questioned the usefulness of CBA for policymakers. Secondly, the value of the discount rate to account for time preference and risk is currently heavily debated, with arguments relating to subjective time preference and risk perception (Nordhaus, 2008; Price, 2005; Stern, 2006). As mentioned above, the value of the discount rate can have a large effect on the results. Finally, non-market impacts need subjective quantification of damages; while it is difficult to monetize these impacts, in general, it is even more difficult for irreversible changes, for example a warming of the oceans leading to the loss of coral reefs (Ackerman and Heinzerling, 2004).

5.9. Uncertainties in climate change, impacts and adaptation

There are many sources of uncertainty in projections of future climate change and its impacts. Uncertainties are associated with every step in the causal chain: emissions, climatic drivers (e.g. the carbon cycle), climate (mainly climate sensitivity and pattern of climate change), and impacts (including adaptive capacity). As a result, different studies might give very different results for the same emission scenario. In fact, these differences are often larger than those arising in a particular model under different emission scenarios. For example, for precipitation changes at the end of the century, the multi-model ensemble mean exceeds the inter-model standard deviation only at high latitudes (Kundzewicz et al., 2007). Uncertainties in climate change projections increase with the length of the time horizon. In the near term (e.g., the 2020s), climate model uncertainties play the most important role; while over longer time horizons (e.g. the 2090s), uncertainties due to the selection of emissions scenario become increasingly significant (Jenkins and Lowe, 2003). The impact of future climate change on extreme events is particularly uncertain. This is partly due to a mismatch between the larger spatial and temporal scale of coarse-resolution climate models, and the local occurrence and short life of some weather extremes (e.g. cloudburst precipitation and flash floods). As impacts and adaptation take place at the local scale, detailed information is needed – which implies an increase in uncertainty. The large uncertainty ranges suggests that planning for adaptation should not be based on a single scenarios, but that a large range of projections need to be account for.

6. Conclusions

In this paper, we have discussed how scenario analysis may contribute to the assessment of mitigation and adaptation strategies. We have also presented two integrated scenarios as a starting point for analysis. The scenarios have explicitly treated mitigation and adaptation action for several indicators – and cover several important linkages and feedbacks between socio-economic development and impacts (e.g. the impacts of climate change on land use and mitigation are accounted for). We specified impacts in those scenarios for a selected number of indicators, focusing mainly on mean climate changes. Based on our work, we draw the following conclusions:

- By describing two contrasting sets of possible climate change trajectories for the world, we have created the basis for a more integrated analysis of the interaction between mitigation, adaptation and climate impacts.

  The first scenario (no mitigation) is expected to lead to a global mean temperature increase by the end of the century of around 4 °C (for the most likely values for climate parameters, and current economic trends). This scenario has high adaptation needs as has been shown in some of our analyses. The second scenario assumes stringent mitigation and limits global mean temperature change to 2 °C, with a probability of 50%. Even under this scenario, substantial adaptation measures will be needed.
- Integrated scenario analysis as presented here can form a good basis for exploring the different consequences of policy choices (including uncertainties); it is not feasible, given uncertainties to determine an optimal mix between mitigation, adaptation and residual damages.

  As discussed in this paper, the weighing of the consequences of climate change and the various policy responses is complicated by large differences in scale, space and time; large uncertainties; and clear differences in interest between actors (whether they are perpetrators or victims of climate change, for instance). As a result, subjective interpretation of risks will always play an important role. Still, scenario analysis can provide a description of possible consequences and risks. At this stage, the monetary assessment of cost and benefits (Section 5.8) could not be linked to the description of physical change in the preceding sections.
- Effective climate policy includes both adaptation and mitigation.

  Model calculations show that mitigation scenarios can be designed that lead to an increase of global mean temperature increase 2 °C for a best-guess climate sensitivity. However, even these stringent scenarios can still also result in a global mean temperature increase of more than 2.5 °C (and at best a temperature increase of 1.5 °C) and regional temperature change which is far greater. The need for a combination of mitigation and adaptation has been shown for most of the impacts explored in this paper. For example, adaptation can be more effective than mitigation in dealing with sea-level rise (at least during the 21st century), but mitigation still has a role to play in reducing damages and costs of adaptation. Agriculture presents an example where adaptation and mitigation are both clearly necessary. Crop yields in agriculture are projected to suffer negative impacts in many regions due to climate change in the absence of both adaptation and mitigation action. Without stringent mitigation, adaptation could limit negative impacts, but not remove them. An advantage of mitigation is that it affects all impact categories, while adaptation needs to be tailored to impacts and contexts.
- While impacts of climate change can be severe and, depending on subjective choices, may warrant stringent climate policy, the impacts assessed in this study (given the state of the art) are likely

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[3] A discount rate of 5% leads to discounted costs of 0.8% and 1.9% for the adaptation-only scenario and mitigation-only scenario, respectively. If a discount rate of 1.4% is used (equal to the discount rate used by Stern (2006)), the discounted costs are 3.2% and 2.5% for the adaptation-only scenario and mitigation-only scenario, respectively.

to remain secondary influences of population change and economic growth at a global scale. Yet important caveats apply (see below).

While climate change may have an impact on millions of people, other challenges are likely to influence people and governance more significantly. It should be noted, however, that we have covered only a limited set of impacts and focused mostly on mean estimates of gradual climate change and, for instance, not on catastrophic, very high-impact, extremely low-probability events (Weitzman, 2008). Such events in fact may be so severe that the conclusion above no longer holds. If costs at a global scale remain relatively low, there is less need for global analysis to include all feedbacks on main drivers based on the consistency of the storylines. Clearly, at the local scale the situation is likely to be very different; impacts for individual countries can be far more substantial than at the global scale. For example, sea level rise is very important for some low-lying island states and countries that could be significantly affected by either large adaptation costs and/or damages (up to complete destruction). For agriculture, positive and negative impacts are projected to occur in different places and at different times – with low-income countries often experiencing relatively more negative impacts. Agriculture in temperate regions, where it is currently temperature-limited, could benefit. All in all, we believe that it useful to pursue further the development of integrated scenarios specifying these further on a regional scale. While this paper presents a useful first step, it also has left many feedbacks still unaccounted for.

- The overall mitigation costs in this study are estimated to be in the order of 1–2% of GDP for the 2 °C scenario. The mitigation scenario reduces the risks of climate change.

  There are several types of benefits of investments in mitigation. First, climate-related damages and the costs of adaptation are reduced. Second, also uncertainty is reduced, which is important given the risks involved. While we argue there can be no optimal trade-off between mitigation and adaptation at a global level, we have shown that over the longer-run the costs and benefits of mitigation and adaptation are of an equivalent magnitude.
- Important foci for further analysis include the linkages between assessment of physical changes and monetary impact analysis, variability and changes in extreme events, the potential role of large scale disruptions and governance.

  In our and other assessments, the focus has mostly been on changes in mean values, yet there is considerable concern about extreme events (resulting in natural disasters) associated with climate variability, but also in large scale disruptions (such as the disintegration of the West Antarctic Ice Shield), which are not accurately described by average values. Projections of changes in climate variability have been highly uncertain, and to date often hinder analyses from robustly predicting future extreme event risk. The role of different actors is another issue; some forms of adaptation require active governmental involvement; other forms are likely to be implemented by private investors, such as installation of space cooling systems. The differences between these two adaptation protagonists are relevant for future scenario development.

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Appendix A. Model descriptions

A.1. IMAGE 2.4

The IMAGE 2.4 Integrated Assessment model (Bouwman et al., 2006) consists of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as air pollution, climate change, and land-use change. As part of IMAGE, the global energy model TIMER (van Vuuren et al., 2006) describes the long-term dynamics of demand and production of primary and secondary energy and the related emissions of greenhouse gases and regional air pollutants. The model behavior is mainly determined by substitution processes of various technologies on the basis of long-term prices and fuel-preferences. The agricultural model of IMAGE models the productivity of 7 crop groups and 5 animal categories (Leemans and Born, 1994). The regional production of agricultural goods is distributed spatially (at $0.5^\circ \times 0.5^\circ$) on the basis of a set of allocation rules (Alcamo et al., 1998). Both the land use change maps and the agricultural activity data are used to model emissions from land use (change). The emissions of GHGs are used by the MAGICC model to calculate global mean temperature change (Wigley and Raper, 2001). Patterns of temperature change are obtained by making a link to climate change patterns generated by a general circulation models (GCM).

Limitations: IMAGE is provides a physically oriented description of human activities (use of tons of oil, production of tons of cereals, etc.). A fuller macro-economic description only emerges from cooperation with other models. The broad coverage of IMAGE as Integrated Assessment Model implies that many critical uncertainties influence the model outcomes. In this context, use of a single baseline (as in the ADAM project) does not do fully justice to the fundament uncertainties involved.

A.2. FAIR

The climate policy model FAIR (Den Elzen et al., 2008) is used in conjunction with the IMAGE model to determine the reduction rates across different emission sources. Global climate calculations make use of the simple climate model, MAGICC 4.1 (Wigley, 2003; Wigley and Raper, 2001). Required global emission reductions are derived by taking the difference between the baseline and a global emission pathway. The FAIR cost model distributes these between the regions following a least-cost approach using regional marginal abatement costs curves (MACs) for the different emissions sources. Recently, the FAIR model has been extended with damage and adaptation costs curves (based on the AD-DICE model (De Bruin et al., 2009b) and the ability to estimate macro-economic impacts on GDP growth (Hof et al., 2008)). This allows the model to explore the economic impacts of combined mitigation and adaptation strategies.

Limitations: In its aim to be flexible, the FAIR model does not include a sectoral macro-economic model or an energy model. The model thus works from a partial equilibrium approach – and more underlying consequences of climate policy can only be studied by forwarding the FAIR results to other (linked) models.

A.3. DIVA

DIVA (Dynamic and Interactive Vulnerability Assessment) is an integrated model of coastal systems that was developed, together with its proper coastal database, within the EU-funded project

DINAS-COAST[4] (DINAS-COAST Consortium, 2006; Hinkel and Klein, 2009). DIVA produces quantitative information on a range of ecological, social and economic coastal vulnerability indicators from sub-national to global scales, covering all coastal nations. The model consists of a number of modules developed by experts from various engineering, natural and social science disciplines. Based on climatic and socio-economic scenarios, the model assesses coastal erosion (both direct and indirect), coastal flooding (including rivers), wetland change and salinity intrusion into deltas and estuaries. DIVA also considers coastal adaptation in terms of raising dikes and nourishing beaches and includes several predefined adaption strategies such as no protection, full protection or optimal protection.

Limitations: DIVA excludes the following processes that are likely to affect coastal impacts, but can currently not be modeled with confidence: changes in storm frequency and intensity, local distribution of GDP and population growth due to rapid coastal development and urbanization, and salinity intrusion into coastal aquifers. Further important uncertainties arise due to the coarse resolution and accuracy of elevation data.

A.4. TIMER-cooling/heating energy demand

The TIMER cooling/heating energy demand model (Isaac and van Vuuren, 2009) describes the energy use for cooling and heating as a function of several factors, including population levels, changing income levels and climate. For both heating and cooling, empirical data is used to calibrate a set of system-dynamic demand functions. Climate (cooling and heating degree days) plays an important role. The model is able to account for the impacts of climate change.

Limitations: The empirical basis on which the model is calibrated is relatively poor for developing countries. The model does not contain a description of different ways cooling and heating demand can be supplied and the costs involved in substituting one technology for the other.

A.5. Water resources impact model

The water resources impact model (Arnell, 2003, 2004) has two components. The first simulates river runoff across the entire global land surface (at $0.5^\circ \times 0.5^\circ$) using the macro-scale hydrological model Mac-PDM, and the second determines indicators of water resources stress at the watershed level by calculating *per capita* water resource availability. A watershed is assumed to be exposed to water resources stress if it has an annual average runoff equivalent to less than 1000 m^3/capita/year, a semi-arbitrary threshold widely used to identify water-stressed regions. Climate change leads to an increase in exposure to water resources stress if it causes runoff in a water-stressed watershed to decrease significantly, or causes the watershed to fall below the threshold. Climate change leads to an apparent reduction in exposure for the opposite trends. These changes cannot be directly compared; whilst a reduction in runoff (and an increase in exposure) is highly likely to be adverse, an increase in runoff (and apparent decrease in exposure) may not be beneficial if the additional water cannot be stored or if it occurs during high flow seasons as increased flooding. The number of people living in watersheds exposed to an increase in water resources stress can be used as an indicator of *exposure* to climate change. The actual impacts (in terms of real water shortages) will depend on water management structures in place.

Limitations: The hydrological model does not simulate perfectly the volume of river runoff, and in particular tends to overestimate runoff in semi-arid regions. The water resources indicator is a measure of exposure to impact, not actual impact; it can be seen as a surrogate for the demand for adaptation.

A.6. Malaria risks

Table A.1
Malaria suitability indices for climatic determinants.

	Suitability = 0	Suitability = 1
Monthly temperature (°C)	<18	>22
	>40	<32
Annual minimum monthly temperature (°C)	<0	>4
Precipitation (mm/month)	0	>80

Malaria vectors, the mosquitoes spreading the infection, can only survive in suitable climates with high average temperatures, no frost and enough precipitation. The MARA/ARMA malaria suitability model (Craig et al., 1999) incorporates these climatic factors to determine climatic suitable areas. The climatic levels required for the maximum suitability of 1, and for the minimum suitability of 0, are shown in Table A.1. For indicators with levels between those required for 0 or 1 suitability a level is calculated using s simple function (Craig et al., 1999). All these factors are calculated at half by half degree grid level, making use of the output from the IMAGE-model (Bouwman et al., 2006). Total climatic malaria suitability for each grid cell is determined by the lowest of these three indices.

Limitations: The MARA/ARMA model describes suitability for malaria vectors. It does not provide a process description of the spread of mosquitos, nor does it explicitly describe how people may react to increased risk levels.

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