challenge paper

CLIMATE CHANGE, ADAPTATION

Francesco Bosello,
Carlo Carraro,
Enrica De Cian,

COPENHAGEN
CONSENSUS 2012
solving the world's challenges

Market and Policy Driven Adaptation to Climate Change

Francesco Bosello, University of Milan and FEEM
Carlo Carraro, University of Venice and FEEM
Enrica De Cian, University of Venice and FEEM

Table of contents

This report has been prepared for the Copenaghen Consensus 2009. This version is a revised and updated version prepared for the Copenaghen Consensus 2012. AD-WITCH, the model used in this study, has been developed by FEEM in cooperation with the OECD. The authors gratefully acknowledge their financial support. They are also grateful to Shardul Agrawala, Rob Dellink, Kelly de Bruin and Richard Tol for helpful comments. Nonetheless, the views expressed in this paper are the authors' sole responsibility. Finally, the contribution of all colleagues who worked to the development of the original WITCH model – in particular Valentina Bosetti, Emanuele Massetti, and Massimo Tavoni – is gratefully acknowledged. Correspondence address: Carlo Carraro, President, University of Venice, Ca' Foscari, 30123 Venice, Italy. E mail: ccarraro@unive.it.

Draft: January 2012; Revised: March 2012

Introduction

The climate talks in Durban, by postponing negotiations on future commitments to 2015, are likely to increase the risk of exceeding the 2°C target and to make the pathway towards 3-3.5°C a likely outcome of global economic development[1]. Already right after the Copenhagen Conference of Parties (COP XV), a number of studies made the point that the outcome of COP XV was inconsistent with the 2°C temperature target re-stated in the Copenhagen Accord[2]. At that time, it was already clear that stabilizing global warming below what is commonly considered a "dangerous" level was a very difficult task. After Durban this is even more true. The unspoken implication is that adaptation to climate change becomes even more necessary. Additional effort and resources should then be devoted to narrow the gap between what needed to be done and what would be done to adapt to future climate change.

However, adaptation should not be considered as a substitute of mitigation. The ultimate question that interests policy makers is how to reduce the climate-change vulnerability of socio-economic systems in the most cost-effective way. This objective need to be achieved with both mitigation and adaptation policies. What is therefore the optimal balance of mitigation and adaptation? What is the regional distribution of this policy mix? How should adaptation and mitigation be allocated over time? To address these questions requires, on the one hand, a thorough knowledge of the size and the regional distribution of climate-related damages and, on the other hand, a precise assessment of the costs and benefits of alternative policy-mixes.

Given its local- and project-specific nature, costs-benefit analysis of adaptation strategies has been treated within a micro-perspective. Although this approach can inform about the economic performance of specific projects, it lacks a broader perspective on the interactions with other economic activities. Adaptation is only one of the possible responses to global warming within a range of possible options. In order to maximize the benefit from a portfolio of alternatives, a joint analysis of different measures is certainly more informative.

If an extended literature has investigated the different dimensions of mitigation strategies and their interactions with economic development, much less can be found on adaptation. Even less attention has been paid to the interactions between adaptation and mitigation. At the same time, the interest to define their strategic complementarity or trade-off in a macroeconomic cost-benefit context has constantly risen. This is witnessed by an increasing number of research efforts and publications. A

---

[1] http://climateactiontracker.org/news/

[2] Carraro, C. and E. Massetti. 2010. "Two Good News from Copenhagen?", http://www.climatescienceandpolicy.eu/2010/01/two-good-news-from-copenhagen/ and "Adding up the Numbers: Mitigation Pledges under the Copenhagen Accord", http://www.pewclimate.org/docUploads/copenhagen-accord-adding-up-mitigation-pledges.pdf

recent survey of these contributions is provided by Agrawala *et al.* (2011a) while Agrawala *et al.* (2011) contains the first comparison of model results on adaptation and mitigation costs.

Nonetheless, many questions concerning the design of an optimal mix of mitigation and adaptation measures, the cost-benefit ratio of different adaptation/mitigation options, and their regional distribution, are still unanswered. Following the outcome of the Copenhagen and Durban Conferences, a renewed interest on how to spend the money that will be disbursed through the Green Climate Fund (this fund, reaching USD billion 100 in 2020, is meant to finance mitigation and adaptation in developing countries) has emerged. Historically, the majority of climate funding (USD 93 billion out of USD 97 billion) has been used for mitigation, with adaptation receiving only USD 4.4 billion. Most of the current adaptation financing comes from bilateral accords between countries, whereas dedicated funds, such as the Adaptation Fund, play only a minor role (Buchner *et al.* 2011). The question arising is whether this uneven allocation of short-term climate funds is justified or whether more resources should be devoted to adaptation, given the low benefit-cost ratio of many mitigation measures and given the complementarity of adaptation expenses with development goals, which increases their benefit-cost ratio.

This paper addresses the question of how resources for climate change should be allocated between adaptation, mitigation, and residual damage from climate change. The study adopts a macro-angle and uses the AD-WITCH model, an Integrated Assessment Model (IAM) that has been developed for the joint analysis of adaptation and mitigation.[3] With respect to the existing studies in the field (de Bruin *et al.*, Hof *et al.*, 2009; Hof *et al.*, 2010; Bosello *et al.*, 2010, Bahn *et al.*, 2010) the proposed modeling framework provides a a novel characterization of the adaptation process, which includes not only anticipatory and reactive adaptation, but also adaptation specific technological change. This enable us to:

- Analyse adaptation to climate change both in isolation and jointly with mitigation strategies
- Provide a comparative cost-benefit analysis of both adaptation and mitigation
- Assess the marginal contribution to the benefit-cost ratio of different adaptation modes
- Emphasise region-specific characteristics of climate policy

The study is organised as follows. First we present a cost-benefit analysis of macro, policy-driven responses to climate change, namely, adaptation, mitigation, and joint adaptation and mitigation. By

---

[3] The model has been developed by FEEM in cooperation with the OECD team led by Shardul Agrawala.

narrowing down the focus on policy-driven adaptation, we will then compute the benefit-cost ratios of three macro adaptation strategies (reactive, anticipatory or proactive, and knowledge adaptation).

A second novel contribution of this work is the assessment of the market potential to adjust to climate change and to reduce the vulnerability of economic systems to climate change. To some extent, adaptation will occur without any policy intervention, as a reactive response to changes in climate, driven by market price signals. Although market-driven adaptation has a strong damage smoothing potential at the global level, we show that damages are likely to remain significant, especially in developing countries. We therefore compute and discuss the benefit-cost ratios of different policy-driven adaptation strategies net of market-driven, autonomous adaptation to climate change.

AD-WITCH, the model used to carry out most of the analysis, is an optimal growth Integrated Assessment model endowed with an adaptation module to compute the costs and benefits of policy-driven mitigation and adaptation strategies. Given the game-theoretic and regional structure of AD-WITCH (see Appendix I), both first best and second best climate policies can be computed. In this study, we focus on a first best world in which all externalities are internalized. The social planner implements the optimal levels of adaptation and mitigation, namely the level that equalizes marginal costs and benefits.

To account for both market-driven and policy-driven adaptation, two different modeling tools have been used. The ICES model, which is a highly disaggregated computable general equilibrium model, has been used to identify the effects of market–driven adaptation. ICES and AD-WITCH have then been integrated to provide a full assessment of both market- and policy-driven adaptation. More precisely, the effects of market-driven adaptation on regional climate damages have been estimated using the ICES model. These estimates have been used to modify all regional climate change damage functions in the WITCH model to compute climate damages net of market-driven adaptation.

The final part of this study describes specific adaptation proposals. These are consistent with the analysis carried out in the first part of the study, and build upon existing estimates of costs and benefits of specific adaptation strategies.

Background concepts

In this study, climate change is defined as a set of alterations in the average weather caused by global warming, which is due to emissions of greenhouse gases (GHGs). Climate change affects not only average surface temperature, but it also involves other physical modifications, such as changes in precipitations, intensity and frequency of storms, and the occurrence of droughts and floods.

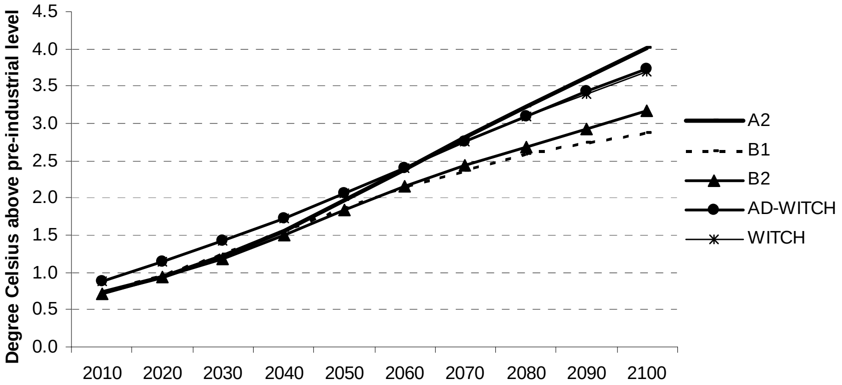
Average temperature is already 0.7 degree above preindustrial level and further warming might be substantial if no immediate global action is undertaken. Even if all radiative forcing agents were held constant at the 2000 level, a further warming would be observed due to the inertia of oceans. According to the main IPCC scenarios,[4] world-average temperature is likely to increase in the business as usual scenarios as shown in Figure 1, which also shows the expected pathways produced by AD-WITCH. Projected global temperature increases above preindustrial levels range between 2.8 and 4 degrees Celsius.

Anthropogenic climate change, accelerating the natural trend, will induce a series of impacts on natural and social ecosystems with potentially both negative and positive consequences on human well being. As highlighted in the IPCC Fourth Assessment Report (Parry *et al.* 2007), already a moderate warming produces negative consequences: increasing number of people exposed to water stresses, extinction of species and ecosystems, decrease in cereal productivity at low latitudes, land loss due to sea level rise in coastal areas, increase in mortality and morbidity associated to change in the incidence of vector borne diseases or to increased frequency and intensity of heath waves; infrastructural disruption and mortality increase due to more frequent and intense extreme weather event occurrence.

---

[4] The SRES scenarios A2, B1 and B2 are from http://www.iiasa.ac.at/Research/GGI/DB/.

Figure 1: Temperature estimates of the IPCC SRES[5] (IIASA) , the WITCH model (Bosetti et. al 2006) and the AD-WITCH baseline scenario used in this study



Source: Our elaboration.

A first classification of climate change impacts distinguishes between market and non-market impacts. Market effects can be valued using prices and observed changes in demand and supply, whereas non-market effects have no observable prices and therefore require other methods such as valuations based on willingness to pay.

The recent literature points to the large potential damages from climate change, especially in developing countries and non-market sectors (Parry *et al.* 2007; Stern 2007). In particular, important non-market impacts are those on health. Current estimates are largely incomplete and most assessments have looked at specific diseases (vector-born diseases, cardiovascular and respiratory diseases) and do not consider other adaptation costs, such as those relating to building the required infrastructure that will be particularly needed in developing countries. Nonetheless, for the US only, Hanemann (2008) estimates large impacts on health, reporting a loss of 1990 $US10 billion per year against the $US 2 billion reported in Nordhaus and Boyer (2000).

Climate change can lead to a significant rise in sea level and catastrophic events with implications on migrations and the stock of capital. Insurance companies are an important source of information regarding estimates of capital losses due to climate change impacts. UNFCCC (2007) reports a cost of protecting infrastructure from climate change in North America between 1990 $US4 and 64 billion already in 2030, when temperature increase is likely to be far below 2 degrees Celsius.

The Munich Re insurance company developed a database which catalogues great natural catastrophes that had severe impacts on the economic system. Such a database underestimates damages from climate, because only large events are included. Yet estimated losses are in the order

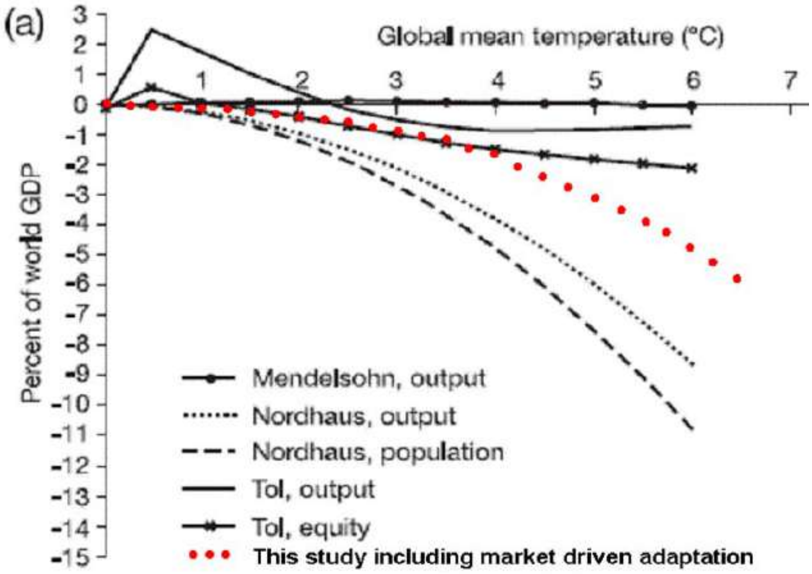
---

[5] Available at: http://www.iiasa.ac.at/Research/GGI/DB/

of 0.5 percent of current world GDP, and damages are increasing at a rate of 6 percent a year in real terms. Using this information and adjusting for the under-reporting of other minor impacts, UNFCCC (2007) extrapolated a cost between 1 and 1.5 percent of world GDP in 2030, which corresponds to 1990 $US850-1 350 billion. Nordhaus and Boyer (2000) reported similar figures for total impacts, and for a temperature increase of 2.5 degrees Celsius, which is likely to occur at least several decades after 2030.

For a temperature increase above 2.5 degrees Celsius, the majority of Impact Assessment (IA) models currently used to evaluate the full cost of climate change, forecast net losses from climatic changes ranging roughly around 2 percent of world GDP (Figure 2).

Figure 2. Climate change damages as a function of global mean temperature increase (above preindustrial levels)



Source: Our adaptation from IPCC AR4 (2007)

Should global warming exceed the 3°C above pre-industrial, climate change impacts are likely to be more drastic and move to higher level of risk. The probability of the so-called climate tipping points increases non-linearly when certain temperature thresholds are crossed. Zickfeld *et al*. (2007) reports probability estimates for the shutdown of Atlantic meridional overturning circulation until 2100. It ranges between 0–0.2% for low temperature increases (2 °C), but it increases significantly (0–0.6%) for medium level of global warming (2–4 °C).

Climate change is not uniform over the world though, moreover impacts are diverse and highly differentiated by regions. Regions themselves differ for their intrinsic adaptive capacity. These dimensions, i.e. exposure, sensitivity and autonomous adaptive capacity determine a highly differentiated regional vulnerability to climate change. Accordingly, the global picture can provide only a very partial and potentially misleading insight on the true economic cost of climate change. Aggregation can indeed conceal vulnerability and climate change costs hot spots as depicted in Table 1. As a general rule, developing countries would be more affected than their developed counterparts.

Table 1: Regional climate change impacts as percentage of GDP. One point estimates for a 2.5 degrees Celsius increase in global temperature above preindustrial levels(negative figures are gains)

	ICES model (Bosello et al. 2009)[a]	***AD-WITCH* model (Bosello et al. 2009)[b]**	**Fankhauser (Fankhauser and Tol 1996)**	**Tol (Fankhauser and Tol, 1996)**	**Nordhaus and Boyer (2000)**	**Mendelsohn et al. (2000)**	**Pearce et al. (1996)**
USA	0.2	0.4	1.3	1.5	0.4	-0.3	1
WEURO	-1.3	1.6	1.4	1.6	2.8	n.a.	1.4
EEURO	0.8	0.5	n.a.	0	0.7	n.a.	-0.3
KOSAU	0.9	0.8	n.a.	0	-0.4	n.a.	1.4
CAJANZ	-0.8	0.5	n.a.	3.8	0.5	0.1	1.4
TE	0.9	0.8	0.4	-0.4	-0.7	-11	0.7
MENA	0.2	2.9	n.a.	5.5	1.9	n.a.	4.1
SSA	2.0	5.1	n.a.	6.9	3.9	n.a.	8.7
SASIA	3.0	5.5	n.a.	0	4.9	2	n.a.
CHINA	1.7	0.5	2.9	-0.1	0.2	-1.8	5
EASIA	2.3	4.2	n.a.	5.3	1.8	n.a.	8.6
LACA	1.8	2.3	n.a.	3.1	2.4	1.4	4.3

Source: our adaptation from the quoted studies
a This study includes market driven adaptation
b This study includes only policy driven adaptation

Notwithstanding the differences in results, - driven by different model specifications, modelling approaches and underlying assumptions - the inspection of Table 1 highlights the following robust messages:

- Even an almost null aggregate loss potentially experienced by the world as a whole, and associated to a moderate climatic change, entails high costs for some regions. It is even more so in the case of moderate to high aggregate economic losses.

- There is a clear equity-adverse effect from the distribution of climate change impacts: higher costs are experienced by developing regions which are already facing serious challenges to their social economic development; moreover, within a country or region, climate change adverse effects hit more severely weaker social groups which are both more exposed and less able to adapt.

What is true at the world level applies at the regional level as well. Even a net gain for a region compounds both positive and negative effects. Some of these negative effects can be particularly concerning also for a developed region. Think for instance to an increase in mortality due to more frequent and intense heat waves, hitting aged population; loss of coastal areas due to sea-level rise; increase in hydro-geological risk due to an increase in frequency and intensity of extreme weather events. Table 2 summarizes the damage estimates for a 2.5 degrees Celsius increase in global temperature above its 1900 level, both for the whole economy (Total) and broken down by sectors, as estimated in Nordhaus and Boyer (2000).

Table 2. Climate change impacts in different world regions. One point estimates for a 2.5 degrees Celsius increase in global temperature above preindustrial levels

Region	TOTAL	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use	Catastrophic	Settlements
United States	0.45	0.06	0	0.11	0.02	-0.28	0.44	0.1
China	0.22	-0.37	0.13	0.07	0.09	-0.26	0.52	0.05
Japan	0.5	-0.46	0	0.56	0.02	-0.31	0.45	0.25
EU	2.83	0.49	0	0.6	0.02	-0.43	1.91	0.25
Russia	-0.65	-0.69	-0.37	0.09	0.02	-0.75	0.99	0.05
India	4.93	1.08	0.4	0.09	0.69	0.3	2.27	0.1
Other high income	-0.39	-0.95	-0.31	0.16	0.02	-0.35	0.94	0.1
High-income OPEC	1.95	0	0.91	0.06	0.23	0.24	0.46	0.05
Eastern Europe	0.71	0.46	0	0.01	0.02	-0.36	0.47	0.1
Middle-income	2.44	1.13	0.41	0.04	0.32	-0.04	0.47	0.1
Lower middle-income	1.81	0.04	0.29	0.09	0.32	-0.04	1.01	0.1
Africa	3.91	0.05	0.09	0.02	3	0.25	0.39	0.1
Low-income	2.64	0.04	0.46	0.09	0.66	0.2	1.09	0.1
Global								
Output-weighted	1.5	0.13	0.05	0.32	0.1	-0.29	0.17	1.02
Population-weighted	2.19	0.17	0.23	0.12	0.56	-0.03	0.1	1.05

Source: Nordhaus and Boyer (2000)

Among rich countries, Europe is estimated to suffer most from climate change, because of the assumption of high vulnerability to catastrophic events. Among developing regions, Africa and India face larger climate impacts due to impacts on health and catastrophic events, respectively. It is worth noticing that sea-level rise constitutes a higher share of damages in developed than in developing countries. However, the aggregated data hides important hot spots for vulnerability to sea floods in developing regions. In these regions, densely populated urban area are often located in river deltas particularly exposed to sea level rise (e.g. the Nile, Gange, Mekong, Niger etc.). Impacts on agriculture vary a lot with the climatic conditions of the regions and become positive for cold or mild regions (e.g. Russia, China). Similar pattern can be identified for impacts on energy use, with cold regions being more positively affected (Russia).

Although policy makers are–still striving for an agreement that will lead to low warming scenarios (a notable example is the European effort aiming at ambitious emission reduction already by 2050, see the Energy Roadmap, European Commission 2011), the world will be anyway exposed to a certain degree of climate change and to its negative consequences for the century to come.

In the light of this, and as stressed by the EU White Paper on Adaptation (European Commission, 2009) and the European strategy on adaptation (EEA 2010), mitigation needs to be coupled with adaptation actions to cope with unavoidable climate change impacts that mitigation cannot eliminate.

Defining adaptation: a multidimensional concept

Adaptation to climate change received a wide set of definitions, both by the scientific and the policy environments (among the first group, see e.g. Burton 1992; Smit 1993; Smithers and Smit 1997; Smit *et al.* 2000; among the second group, see e.g. EEA 2005; Lim and Spanger-Siegfred 2005; UNFCCC 2006). The large number of not always coincident definitions already highlights a specific problem concerning adaptation: it is a process that can take the most diverse forms depending on where and when it occurs and on who is adapting to what.

Indeed, probably the most comprehensive, known and widely accepted definition of adaptation is the one provided by the IPCC Third Assessment Report, which states that **adaptation** is any "*adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli, and their effects or impacts. This term refers to changes in processes, practices or structures to moderate or offset potential damages or to take advantages of opportunities associated with changes in climate*" (McCarthy *et al.* 2001), which is general enough to encompass the widest spectrum of options.

Adaptation can be identified along three dimensions:

- the subject of adaptation (who or what adapts)
- the object of adaptation (what they adapt to)
- the way in which adaptation takes place (how they adapt).

This last dimension includes what resources are used, when and how they are used and with which results (Wheaton and Maciver 1999).

The subject of adaptation: Who or what adapts. Adaptation materialises in changes in ecological, social and/or economic systems. These changes can be the result of natural responses and in this case they usually involve organisms or species, or of socio-economic or institutional reactions in which case they are undertaken by individual or collective actors, private or public agents.

The object of adaptation: What they adapt to. In the case of climate change, adaptive responses can be induced either by changes in average conditions or by changes in variability of extreme events. While in the first case the change is slow and usually falls within the coping range of systems, in the second case changes are abrupt and outside this coping range (Smit and Pilifosova, 2001).

How adaptation occurs: *Modes, resources and results*. The existing literature (see e.g. Klein and Tol 1997; Fankhauser *et al.* 1999; Smit *et al.* 1999; McCarthy *et al.* 2001) proposes several criteria that can be used to identify the different adaptation processes. Table 3 offers a tentative summary of this classification based upon spatial and temporal aspects, forms and evaluation of performances.

Table 3. Adaptation: Possible criteria for classification

Concept or Attribute	
Purposefulness	Autonomous → Planned
Timing	Anticipatory → Reactive, Responsive
Temporal Scope	Short term → Long term
Spatial Scope	Localised → Widespread
Function/Effects	Retreat – accommodate – protect – prevent
Form	Structural – legal – institutional
Valuation of Performance	Effectiveness-efficiency-equity-feasibility

Source: Our adaptation from Smit *et al.* 1999

This study focuses on a different way of classifying adaptation to climate change, by distinguishing between autonomous or market-driven and planned or policy-driven adaptation. Inside policy driven adaptation, we will distinguish between anticipatory or proactive and responsive or reactive adaptation.

The IPCC Third Assessment Report defines **autonomous adaptation** as "*adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems*" and planned adaptation as: "*adaptation that is the result of a deliberate policy decision based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state*" (McCarthy *et al.* 2001).

This apparently clear distinction, may originate some confusion when adaptation involves socio-economic agents. Indeed, climate change may induce market or welfare effect triggering reactions in private agents without the necessity of a planned strategy designed by a public agency, but just as a response to scarcity signals provided by changes in relative prices. A typical example of this is the effect of climate change on crops' productivity. This has both physical effects (changing yields) and economic effects (changing agricultural goods' prices) that can induce farmers to some adaptation (for example changes in the cultivation type or timing). This form of private socio-economic adaptation even though responding to a plan and originated by (rational) economic decisions is considered autonomous or market-driven (see e.g. Smit 1993; Leary 1999). On the contrary, the term planned adaptation is reserved to public interventions by governments or agencies.[6]

Another important distinction is the one based on the timing of adaptation actions which distinguishes between **anticipatory** or proactive adaptation and **reactive** or responsive adaptation. They are defined by the IPCC Third Assessment Report (McCarthy *et al.* 2001) as "*adaptation that takes place before and after impacts of climate change are observed*", respectively. There can be circumstances when an anticipatory intervention is less costly and more effective than a reactive action (typical example is that of flood or coastal protection), and this is particularly relevant for planned adaptation. Reactive adaptation is a major characteristic of unmanaged natural system and of autonomous adaptation reactions of social economic systems.

The temporal scope defines long-term and short- term adaptation. This distinction can also be referred to tactical opposed to strategic, or to instantaneous versus cumulative. In the natural hazards field it is adjustment versus adaptation (Smit *et al.* 2000).

For the sake of completeness, let us mention other classifications of adaptation. Based on spatial scope, adaptation can be localized or widespread, even though it is noted that adaptation has an intrinsic local nature (Fussel and Klein 2006). Several attributes can also characterize the effects of adaptation. According to Smit *et al.* 1993 they can be: accommodate, retreat, protect, prevent, tolerate etc. Based on the form adaptations can take they can be distinguished according to whether they are primarily technological, behavioural, financial, institutional, or informational.

---

[6] The IPCC (McCarthy *et al.*, 2001) provides also the definition of private adaptation: "*adaptation that is initiated and implemented by individuals, households or private companies. Private adaptation is usually in the actors' rational self interest*" and of public adaptation that is: *"adaptation that is initiated and implemented by governments at all levels. Public adaptation is usually directed at collective needs"*.

Finally the performance of adaptation processes can be evaluated according to the generic principles of policy appraisal: cost-efficiency,[7] cost-effectiveness, administrative feasibility and equity. As noted by Adger *et al.* (2005), in such appraisal effectiveness has to be considered *lato sensu*. Indeed, it is important to account for spatial and temporal spillovers of adaptation measures. Basically, a locally effective adaptation policy may negatively affect neighbouring regions, and a temporary successful adaptation policy can weaken vulnerability in the longer term, both constitute examples of maladaptation. By the same token efficiency, effectiveness, equity are not absolute, but context specific, varying between countries, sectors within countries, actors engaged in adaptation processes.

Mitigation and adaptation as a single integrated policy process

Adaptation and mitigation are both viable strategies to combat damages due to climate change. However they tackle the problem from completely different angles.

Mitigation and adaptation work at different spatial and time scales. Mitigation is global and long-term while adaptation is local and short-term (Klein *et al.* 2003; Ingham *et al.* 2005a; Tol 2005; Wilbanks 2005; Fussel and Klein 2006). This has several important implications.

Firstly, mitigation can be considered as a permanent solution to anthropogenic climate change. Indeed, once abated, one ton of say CO2, cannot produce damage anymore (unless its removal is temporary like in the case of carbon capture and sequestration provided by forests or agricultural land). In contrast, adaptation is more temporary as it typically addresses *current* or *expected* damages. It may require adjustments, if climate change damage varies or if it is substantially different from what was originally expected.

Secondly, the effects of mitigation and adaptation occur at different times (Wilbanks 2005; Klein *et al.* 2003; Fussel and Klein 2006). Mitigation is constrained by long-term climatic inertia, while adaptation by a shorter-term, social-economic inertia. In other words, emission reductions today will translate in a lower temperature increase and ultimately lower damage only in the (far) future, whereas adaptation measures, once implemented, are immediately effective in reducing the

---

[7] The concept of cost efficiency implies that resources are used in the best possible way, cost effectiveness that resources to reach a given target - that can be sub-optimal - are used in the best possible way. The practical implementation of both concepts requires that actions respond to some kind of cost benefit criterion.

damage.[8] This differentiation is particularly relevant from the perspective of policy makers. The stronger reason for the scarce appeal of mitigation policies is probably due to their certain and present costs and future and uncertain benefits.[9] This issue is less problematic for adaptation. Moreover the different intertemporal characteristics tend to expose mitigation more than adaptation to subjective assumptions in policy decision making, like the choice of the discount rates. It can be expected that a lower discount rate, putting more weight on future damages, can increases the appeal of mitigation with respect to adaptation.

Thirdly, mitigation provides a global good, whereas adaptation is a local response to anthropogenic climate change. The benefits induced by a ton of carbon abated are experienced irrespectively of where this ton has been abated. Differently, adaptation entails measures implemented locally whose benefits advantage primarily the local communities targeted. The global public good nature of emissions reduction creates the well known incentive to free ride. This is one of the biggest problems in reaching a large and sustainable international mitigation agreement (Carraro and Siniscalco 1998; Bosetti *et al.* 2009). Again this should be less of a problem in the case of adaptation policies.

It is worth mentioning that mitigation involves decision making at the highest level, such as national governments. Mitigation is implemented at the country level (Tol 2005) and it concerns large, highly concentrated sectors, for example energy and energy intensive industries (Klein *et al.* 2003). Adaptation needs to be implemented at an atomistic level involving a much larger number of stakeholders. Thus, at least in principle, the design of an international policy effort could be easier and the related coordination and transaction costs lower.

In the absence of international coordination, substantial unilateral mitigation actions are unlikely to occur. Here the concern is double. On the one hand, the environmental effectiveness of unilateral action is likely to be small. On the other hand, national goods and services of the abating country can loose competitiveness in international markets if their prices incorporate the cost of the tighter emission standards. This is not necessarily true with adaptation. Its smaller scale and the excludability of its benefits can make unilateral effort a viable choice.

---

[8] It has to be stressed that economic inertias can be long as well e.g. implementing coastal protection interventions can take many years (or even decades) and that adaptation may not be immediately effective as it is the case for anticipatory adaptation.

[9] Fussel and Klein (2006) note that monitoring mitigation effectiveness is easier than monitoring adaptation. They refer to the fact that it is easier to measure emission reduction than quantify the avoided climate change damage due to adaptation. They do not refer to the quantification of the avoided future damage due to emission reduction.

The different regional effectiveness of adaptation and mitigation is also relevant in the light of spatial uncertainty of climate change damages (Lecoq and Shalizi 2007). Not knowing exactly where and with which intensity negative climatic impacts are going to hit, policy decision should bias toward mitigation which is globally effective. On the contrary, adaptation should be used to deal with reasonably well understood local phenomena.

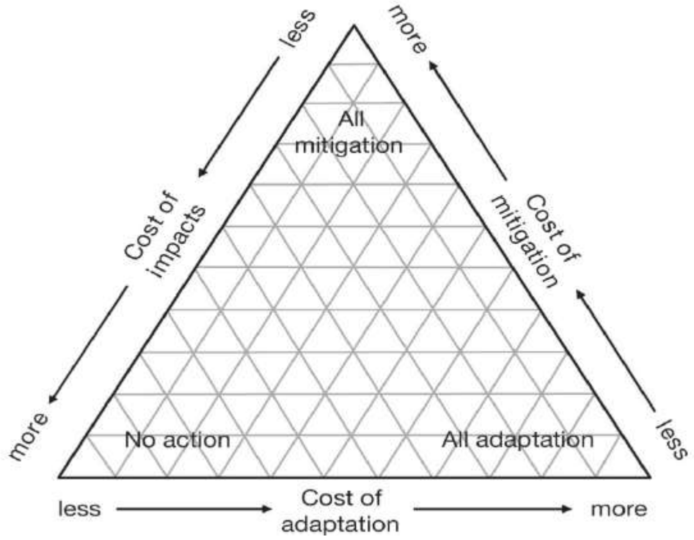
Finally, there is an equity dimension. Mitigation intrinsically endorses the polluter-pays principle. Each one abates her own emissions (directly or indirectly if where flexibility is allowed).[10] This is not necessarily the case with adaptation. It can well alleviate damages which are not directly provoked by the affected community. This is particularly important for international, especially North/South, climate negotiations. Indeed adaptation is particularly needed in developing countries which are either more exposed or vulnerable (higher sensitivity, lower capacity to adapt) to climate change (Watson *et al.* 1995; McCarthy *et al.* 2001; Parry *et al.* 2007), while historically they contributed relatively less to the problem. Adaptation in developing countries thus calls objectively for strong international support.

Following a widely accepted efficiency principle according to which a wider portfolio of options should be preferred to a narrower one, the integration of mitigation and adaptation should increase the cost-effectiveness of a policy aimed at facing climate change (Ingham *et al.* 2005a; Kane and Yohe 2000; Parry *et al.* 2001). This is particularly true in light of the overall uncertainty that still surrounds our understanding of climatic, environmental, social-economic processes, which ultimately determines the uncertainty in the assessment of the costs and benefits of climate change policy. In an uncertain framework, a precautionary policy would avoid both the extremes of total inaction and of drastic immediate mitigation. The optimal strategy would be a combination of mitigation and adaptation measures (Kane and Shogren 2000; McKibbin and Wilcoxen 2004). In other words, the decision maker needs to place herself somewhere inside the decision space represented by the triangle of Figure 3. Vertexes are possible, but unlikely.

---

[10] Again this is not necessarily so in the case of sequestration activities.

Figure 3. Mitigation adaptation and impacts: a schematic "decision space"



Source: IPCC AR4 (2007)

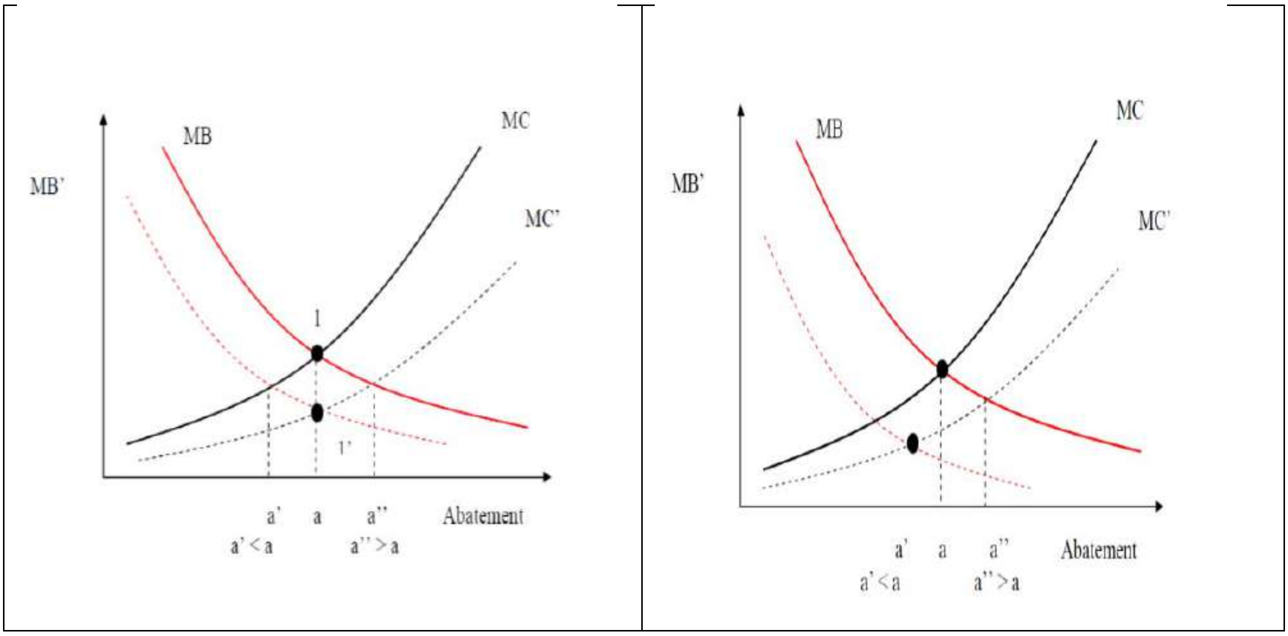
How mitigation and adaptation should be combined? This intuitively depends on their degree of substitutability or complementarity. Kane and Shogren (2000) analyse this issue in the context of the economic theory of endogenous risk. They demonstrate that when both adaptation and mitigation reduce the risk of adverse effects of climate change, they are used by agents until expected marginal benefits and costs are equated across strategies. Corner solutions (adaptation or mitigation only outcomes) are also discussed as theoretical possibilities. They could occur if, for instance, an international mitigation agreement failed to be signed, making agents aware of the practical ineffectiveness of (unilateral) mitigation action or if, conversely, the climate regime is so strict to eliminate the necessity to adapt to any climate change damage. The analysis of agents' response to increased climate change risk is more complex. It depends on two effects: a direct effect of risk on the marginal productivity of a strategy and an indirect effect of risk which is determined by risk impacts on the other strategy and by the relationship between the two strategies. The indirect effect amplifies (dampens) the direct effect if the marginal productivity of one strategy increases (decreases) and the two strategies are complement (substitutes) or if marginal productivity decreases (increases) and the strategies are substitutes (complements). Kane and Shogren (2000) suggest that the actual relationship between adaptation and mitigation strategies is an empirical matter.

Buob and Stephan (2011) found similar results. They investigate the problem in a non-cooperative game-theoretical setting showing that adaptation-only and mitigation-only equilibria are possible only when the two are perfect substitutes. The strategy that exhibits the lower discounted marginal costs will prevail. This reflects the fact that if there are two almost equally effective ways to improve a region's environmental quality, the decision to mitigate or to adapt in the end depends on their intertemporal cost-effectiveness. On the contrary, when the strategies are complements, an equilibrium in which all regions invest in mitigation and adaptation from the outset can exist.

In this vein Antweiler (2011) stresses the role of the shape of mitigation and adaptation costs in driving the final outcome, If they are quasi-linear, mitigation-only and adaptation-only outcomes can be expected. Which of the two prevail depends straightforwardly on the mitigation-adaptation cost ratio. The higher it is the more likely adaptation would prevail and vice versa. With quasi-quadratic costs, mixed strategic outcomes can be observed. An interesting point stressed by the study is that, in the quasi-quadratic case, when the temperature and accordingly damages are increasing more rapidly, both mitigation and adaptation increase, but mitigation relatively more than adaptation. A final insight regards the role of country heterogeneity: a country with a high emission share is shown to have a higher mitigation to adaptation ratio than a country with a small emission share. As small emitters will tend to prefer adaptation over mitigation, which reduces the potential for the efficacy of mitigation, Antweiler (2011) concludes that coordination on mitigation policies is very unlikely.

Finally, Bréchet *et al.* (2010) builds on a Solow Swan growth set-up endowing a central planner with the possibility to decide how much to invest in mitigation ad adaptation. In their comparative static analysis they show that the ratio between adaptation and mitigation crucially depends on the stage of development of the economy. In richer, developed and more productive economic systems, it is worth investing in adaptation, whereas in developing, poorer, weakly efficient economies, opportunity cost of adaptation can be too high, thus inducing zero adaptation. Differently from adaptation, some level of mitigation is always optimal. The consequence is a bell-shaped behaviour of the adaptation-mitigation ratio. Before a given development level is reached, no adaptation is undertaken and only mitigation takes place. With economic growth, adaptation increases to a maximum level after which adaptation investment starts to decline. This is driven by the specific modelling of adaptation: it is a cumulative stock with declining marginal productivity. Therefore, when almost full protection is reached, the value of additional adaptation investment is very small and it becomes more efficient to invest in productive capital.

Figure 4: Technical change and optimal abatement in the presence of adaptation and mitigation



Source: Our elaboration.

Figure 4 provides a neat representation of the trade-off between mitigation and adaptation, taking into account the potential effects of technical change. The role of technical change as a key element to reduce abatement costs and therefore to encourage cheaper abatement effort has long been studied in the climate-economy literature (e.g. Bosetti *et al.* 2009). However, such analyses have neglected potential interactions that may arise in the presence of adaptation responses. Technical change as conceived by most Integrated Assessment models featuring endogenous technical change would reduce marginal abatement cost from *MC* to *MC'* (see Figure 4). In the absence of any adaptation effort, abatement would increase to *a''*. However, adaptation affects the optimal level of mitigation and thus of abatement, because it increases the damage that can be tolerated, thus reducing the marginal benefit from abatement. Should adaptation shift the marginal benefit curve downward (from *MB* to *MB'*), then final abatement could be even lower than the initial level *a* (see the right-hand side panel of Figure 4 where the final equilibrium *a'* is smaller than *a*).

It is thus crucial to assess the exact nature of the relationship between mitigation and adaptation. However, the literature on this topic, either the one focussing on the general characteristics of mitigation and adaptation or the one proposing specific case studies, does not seem to converge on a consistent characterisation of the trade-off between the two climate policy measures.

According to Klein *et al.* (2003) complementarity can be invoked as important synergies can be created between the two strategies when measures that control greenhouse gas concentration also reduce adverse effects of climate change or vice versa. In addition, there is the possibility that many adaptation measures implemented specifically in developing countries may also promote the sustainability of their development (see e.g. Huq *et al.* 2003; Dang *et al.* 2003).

Parry *et al.* (2001) highlight that mitigation delaying climate change impacts can buy more time to reduce vulnerability through adaptation (the converse is more controversial, see Klein *et al.* 2007). Symmetrically, adaptation can rise thresholds which need to be avoided by mitigation (Yohe and Strzepek 2007). Consequently there is an intuitive appeal to exploit and foster synergies by integrating mitigation and adaptation.

An excessive emphasis on synergies can present some risks as well (Klein *et al.* 2003, 2007; Dang *et al.* 2003; Tol 2005). Adaptation measures could pose institutional or coordination difficulties, especially at the international level, and these may be transmitted to the implementation of mitigation measures if the two are conceived as tightly linked. Synergetic interventions can be less cost effective than separate mitigation, adaptation and especially (sustainable) development interventions.

There are finally trade-offs between mitigation and adaptation (Tol 2005; Bosello 2008; de Bruin *et al.* 2009a). Resources are scarce. If some of them are used for mitigation, fewer are available for adaptation, and vice versa. This point is clarified by Ingham *et al.* (2007) who demonstrate that mitigation and adaptation are substitutes in economic terms, implying that if the cost of mitigation falls, agents' optimal response would be to increase mitigation and decrease adaptation.

It is worth noting that substitutability is not in contradiction with the fact that mitigation and adaptation should be both used in climate change policies. Substitutability justifies an integrated approach because either mitigation or adaptation alone cannot optimally deal with climate change (Watson *et al.* 1995; Pielke 1998). The point is that an increase in climate-related damage costs would increase both mitigation and adaptation efforts, which is exactly the typical income effect with normal goods. Finally, as noted by Tol (2005), if adaptation is successful, a lower need to mitigate could be perceived.

The above considerations can be of practical relevance also for the analysis of international environmental negotiations. Even though the literature still in its early stages, recent results show that the joint presence of adaptation and mitigation, depending on their assumed degree of substitutability, can indeed influence participation in an environmental climate agreement. Barrett (2010) for instance demonstrates that if more adaptation implies less mitigation, adaptation can enlarge participation to a mitigation agreement in a non cooperative game theoretical set-up.

Enlargement occurs because adaptation decreases the need to mitigate, thus pushing the environmental effectiveness and costs of the agreement closer to a non-cooperative effort.

Auerswald *et al.*, (2011) show that in a leader follower game, early adaptation commitment from a group of countries can be used as credible signal of low engagement in mitigation. And this would induce other countries to increase their abatement effort. Total abatement effort can then increase or decrease depending on the shape of the respective reaction functions.

An interesting perspective somehow encompassing both Barrett (2010) and Auerswald et al. (2011) is provided by Marrouch and Chauduri (2011). They show that, at given conditions, the presence of adaptation can enlarge the size of a mitigation coalition. Moreover, if the coalition acts as a Stackelberg leader, total emissions can decrease. The intuition behind this is as follows: differently from a no adaptation case, if a country can also adapt it may respond with higher adaptation and lower abatement (thus higher emissions) to higher emissions from another country. On the one hand, this lowers the incentive to free ride on a mitigation agreement and could enlarge participation. On the other hand, if the coalition acts as leader, it may be induced to lower its emissions to lower the emissions in non participatory countries.

More pessimistic results can be found in Buob and Stephan (2008): in a non cooperative setting, they show that in principle rich countries can fund adaptation in poor countries to foster their abatement effort as well as global mitigation when mitigation and adaptation are complements. Nonetheless, they also show that the additional abatement costs in developing countries is typically higher than the adaptation aids. Consequently, developing countries will not be willing to accept such an agreement.

Turning to more case-specific examples, Klein *et al.* (2007) discuss many circumstances in which adaptation and mitigation can complement (facilitate) or substitute (conflict with) each other. In general each time adaptation implies an increased energy use from fossil sources, emissions will increase and mitigation becomes more costly. This is the case, for instance, of adaptation to changing hydrological regimes and water scarcity. This form of adaptation takes place through increasing reuse of wastewater and the associated treatment, deep-well pumping, and especially large-scale desalination. These adaptation measures increase energy use in the water sector, leading to increased emissions and mitigation costs (Boutkan and Stikker, 2004 quoted by Klein *et al.,* 2007). Another example is the case of indoor cooling, which is proposed as a typical adaptation in a warming world (Smith and Tirpak, 1989 quoted by Klein *et al.,* 2007).

However, there are also adaptation practices that decrease energy use and thus facilitate mitigation For instance, the new design principles for commercial and residential buildings could simultaneously reduce vulnerability to extreme weather events and energy needs for heating and/or cooling. Carbon sequestration in agricultural soils as well highlights a positive link from mitigation to adaptation. It creates an economic commodity for farmers (sequestered carbon) and it makes the land more valuable, by improving soil and water conservation. In this way, it enhances both the economic and environmental components of adaptive capacity (Butt and McCarl, 2004; Klein *et al.,* 2007).

There are finally ambiguous cases. For instance, avoided forest degradation implies in most cases an increased adaptive capacity of ecosystems through biodiversity preservation and climate benefits. However, if incentives to sequester carbon by afforestation and reforestation spur an over-plantation of fast-growing alien species, biodiversity can be harmed (Caparros and Jacquemont, 2003) and the natural system can become less adaptable.

These examples demonstrate the intricate inter-relationships between adaptation and mitigation, and also the links with other environmental concerns, such as water resources and biodiversity, with profound policy implications.

Adaptation strategies and macro, policy-driven, integrated measures

Given the multifaceted features of adaptation, and the difficulty to compare the very different adaptation actions or even the same adaptation strategy in different locations, the choice of this study is to aggregate adaptation responses into three main categories: anticipatory adaptation, reactive adaptation and adaptation R&D.

Anticipatory adaptation implies building a stock of defensive capital that must be ready when the damage materializes. It is subject to economic inertia: investment in defensive capital translates into protection capital after some years. Hence, it needs to be undertaken before the damage occurs. By contrast, reactive adaptation is immediately effective and it can be put in place when the damage effectively materializes.

Reactive adaptation is represented by all those actions that need to be undertaken every period in response to those climate change damages that cannot be or were not accommodated by anticipatory adaptation. They usually need to be constantly adjusted to changes in climatic conditions. Examples of these actions are energy expenditures for air conditioning or farmers' yearly changes in seasonal crops' mix.

Investing in R&D and knowledge can be seen as a peculiar form of anticipatory adaptation. Innovation activity in adaptation or simply knowledge adaptation is represented by all those R&D activities and investments that make adaptation responses more effective. These are especially important in sectors such as agriculture and health, where the discovery of new crops and vaccines is crucial to reduce vulnerability to climate change (Barrett, 2008).[11]

These three groups of adaptation measures will be contrasted one against the other and with mitigation in a cost benefit analysis in both a non-cooperative and cooperative (first-best) setting. The analysis will be conducted with the AD-WITCH model (see Appendix I for more information). AD-WITCH is a climate-economic, dynamic-optimization, Integrated Assessment model that can be solved under two alternative game-theoretic scenarios:

- In a non-cooperative scenario, each of the 12 regions in which the world is disaggregated maximises its own private welfare (defined as the present value of the logarithm of per capita consumption), taking other regions' choices as given. This yields a Nash equilibrium, which is also chosen as the baseline. In this context, externalities are not internalized.

- In a cooperative scenario, a social planner maximizes global welfare and it takes into account the full social cost of climate change. In this scenario, the first best cooperative outcome in which all externalities are internalized can be achieved.

The climate change damage function used by the AD-WITCH model includes a reduced-form relationship between temperature and gross world product which follows closely Nordhaus and Boyer (2000), both in the functional form and in the parameter values. The resulting patterns of regional damages are thus in line with what depicted in Tables 1 and 2. Higher losses are estimated in developing countries: in South Asia (including India) and Sub-Saharan Africa, especially because of higher damages in agriculture, from vector-borne diseases and because of catastrophic climate impacts.

Damage estimates in agriculture, coastal settlements and catastrophic climate impacts are significant in Western Europe, resulting in higher damages than in other developed regions. In China, Eastern EU countries, non-EU Eastern European countries (including Russia), Japan-Korea,

---

[11] To test the generality of results, Appendix III proposes an alternative specification in which R&D contributes to build adaptive capacity that improves the effectiveness of all adaptation actions be they proactive or reactive.

climate change up to 2.5 degrees Celsius would bring small benefits, essentially because of a reduction in energy demand for heating purposes (non-EU Eastern European countries including Russia) or positive effects on agricultural productivity (China).

Nonetheless recent evidence - an important contribution on this is the 2007 Stern Review (Stern 2007), but also UNFCCC (2007) and the IPCC Fourth Assessment Report (Parry *et al.* 2007) - suggests that climate change damages may probably be higher than the values proposed in the RICE model by Nordhaus and Boyer (2000). Probably, the most important reason is that RICE, as well as AD-WITCH and many other IA models), only partially captures non-market impacts, which are confined to the recreational value of leisure. Important climate related impacts on biodiversity and ecosystem losses or on cultural heritage are not part of the damage assessment.

Secondly the model abstracts from very rapid warming and large-scale changes of the climate system (system surprises). As a consequence, AD-WITCH yields climate related impacts that, on average, are smaller than those described in studies like the 2007 Stern Review or the UNFCCC (2007) report, which do consider the possibility of abrupt climate changes.

Thirdly, the time horizon considered in this report also plays also a role. The longer it is, the larger the observed damages from climate change, as temperature is projected to keep an increasing trend. Like most IAMs, AD-WITCH considers the dynamics of economic and climatic variables up to 2150, while, for instance, the Stern Review reaches the year 2200.

Finally, the AD-WITCH model was partly based on out-of-date evidence, as many regional estimates contained in Nordhaus and Boyer (2000) are extrapolations from studies that have been carried out for one or two regions, typically the United States.

In order to account for new evidence on climate-related damages and economic impacts, the cost-benefit analysis of adaptation has been performed under two different specifications of the damage functions. The standard one, based on the assessments contained in Nordhaus and Boyer (2000). And a new one, characterised by a much higher damage from climate change, about twice the standard one. This new specification of the damage function yields values of damages larger than those contained in UNFCCC (2007) and closer to those in Stern (2007).

As suggested by Stern (2007), we have also assessed the benefit cost ratios of adaptation under two possible values of the pure rate of time preference. The standard one, again based on Nordhaus and Boyer (2000), is equal to 3 percent declining. The new one is much lower and equal to 0.1 percent, as in Stern (2007). Still the AD-WITCH model does not perform a risk assessment on threshold effects or on discontinuous low probability high damage impacts, which go beyond the scope of this report.[12]

Summing up, four cases will be considered when analyzing the costs and benefits of mitigation, adaptation and of different types of adaptation:

1. **LDAM_HDR** : low damage – high discount rate. This is the baseline scenario with a discount rate set initially at 3 percent and then declining over time as in WITCH, DICE and RICE (see Nordhaus and Boyer, 2000).

2. **LDAM_LDR**: low damage – low discount rate**.** The damage is the same as in the baseline; the discount rate is 0.1 percent and then declining, as in Stern (2007).

3. **HDAM_LDR**: high damage – low high discount. The damage is about twice the damage in baseline; the discount rare is 0.1 percent and then declining, as in the Stern Review.

4. **HDAM_HDR**: high damage – high discount rate. The damage is about twice the damage in baseline; the discount rate is 3 percent and then declining over time as in WITCH, DICE and RICE.

Optimal integrated climate-change strategy in a non cooperative setting.

The main strategic difference between mitigation and adaptation responses to global warming can be summarized as follows. Mitigation provides a public good that can be enjoyed globally, while adaptation provides private or club goods. Mitigation is thus affected by the well known free riding curse, while this is much less of an issue for adaptation.

In the absence of climate change international cooperation, climate change policies at the regional level are chosen to equalize marginal private benefits and marginal private costs, without

---

[12] However, it is likely that the general conclusions of the present study would not change. What can change is the relative weight of adaptation and mitigation in the optimal policy mix. As adaptation to catastrophic events can only be partial, and given that the probability of their occurrence can be lowered only by reducing temperature increase, mitigation could become more appealing than adaptation when the occurrence of catastrophic events is accounted for.

internalizing negative externalities imposed globally. Because of the free-riding incentive, little mitigation effort is thus undertaken.

In practice, in a non-cooperative scenario, when both adaptation and mitigation are chosen optimally, equilibrium abatement (mitigation) is so low that emissions almost coincide with the no policy case (Figure 5, left). Optimal (non-cooperative) adaptation reduces climate change damages and therefore provides an incentive to increase emissions compared to the no policy case (non-cooperative no policy scenario). By contrast, the full appropriability of benefits from adaptation induces regional planners to implement adaptation measures even in the non-cooperative equilibrium. Expenditures for adaptation reach 3.2 US$ trillion or 0.8 percent of world GDP in 2100 (Figure 5, right). Cumulated over the century and discounted at the 3 percent discount rate, they total about 9 US$ trillion, 77 percent of which taking place in developing countries, and the remaining in developed countries.

Figure 5: Equilibrium adaptation and mitigation in the non-cooperative scenario

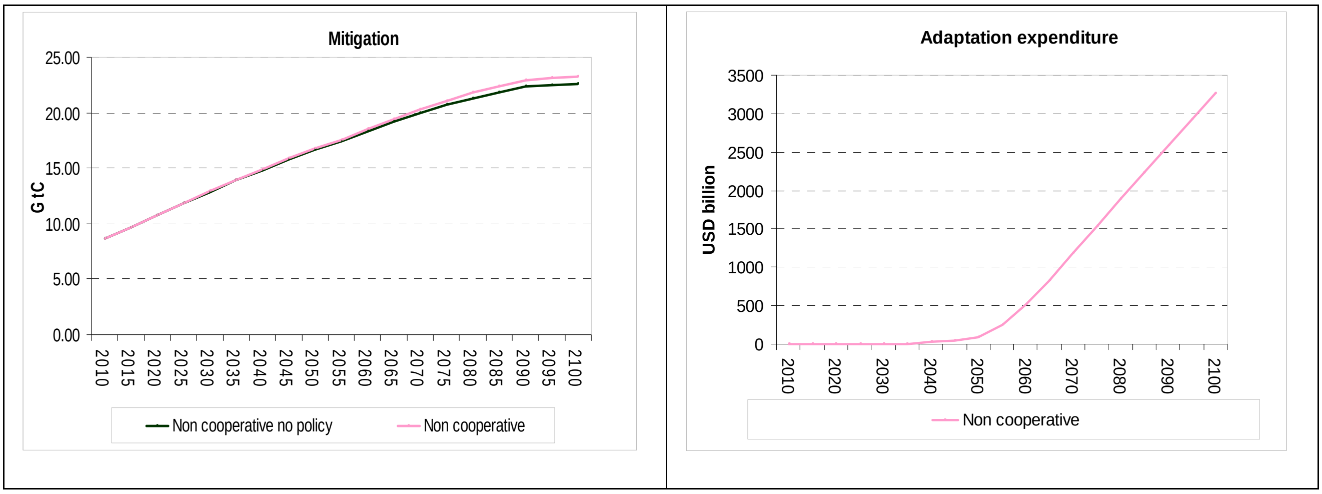


Figure 6 shows total climate change damage (residual damages + adaptation expenditure) in the absence of any policy. It amounts to an annual average of 584 US$ billion already in 2035, and increases exponentially over time. Adaptation reduces substantively residual damages (see again Figure 6), up to 55 percent in 2100. Adaptation starts slowly in the first two decades. Consistently with the AD-WITCH damage function, damages from climate change are indeed low in the first two decades. Hence, adaptation, typically addressing current and near-term damages, is only marginally needed. This applies also to anticipatory adaptation. Economic inertia in the model is about five years. As a consequence, adaptation investments do not need to start too in advance. When considering higher damages and higher preferences for the future (the high damage and low discount rate case), adaptation starts earlier - already in 2020 60 US$ billion are allocated to the reduction of damage. Hence, total damage reduction increases – it amounts to more than 70 percent in 2100 (see Figure 7).

Figure 6: Residual damage and adaptation expenditure in the non-cooperative scenario - Low damage High discount rate. On the lowerpanel, discounted values at 3% discount rate, 2005USD Trillion.

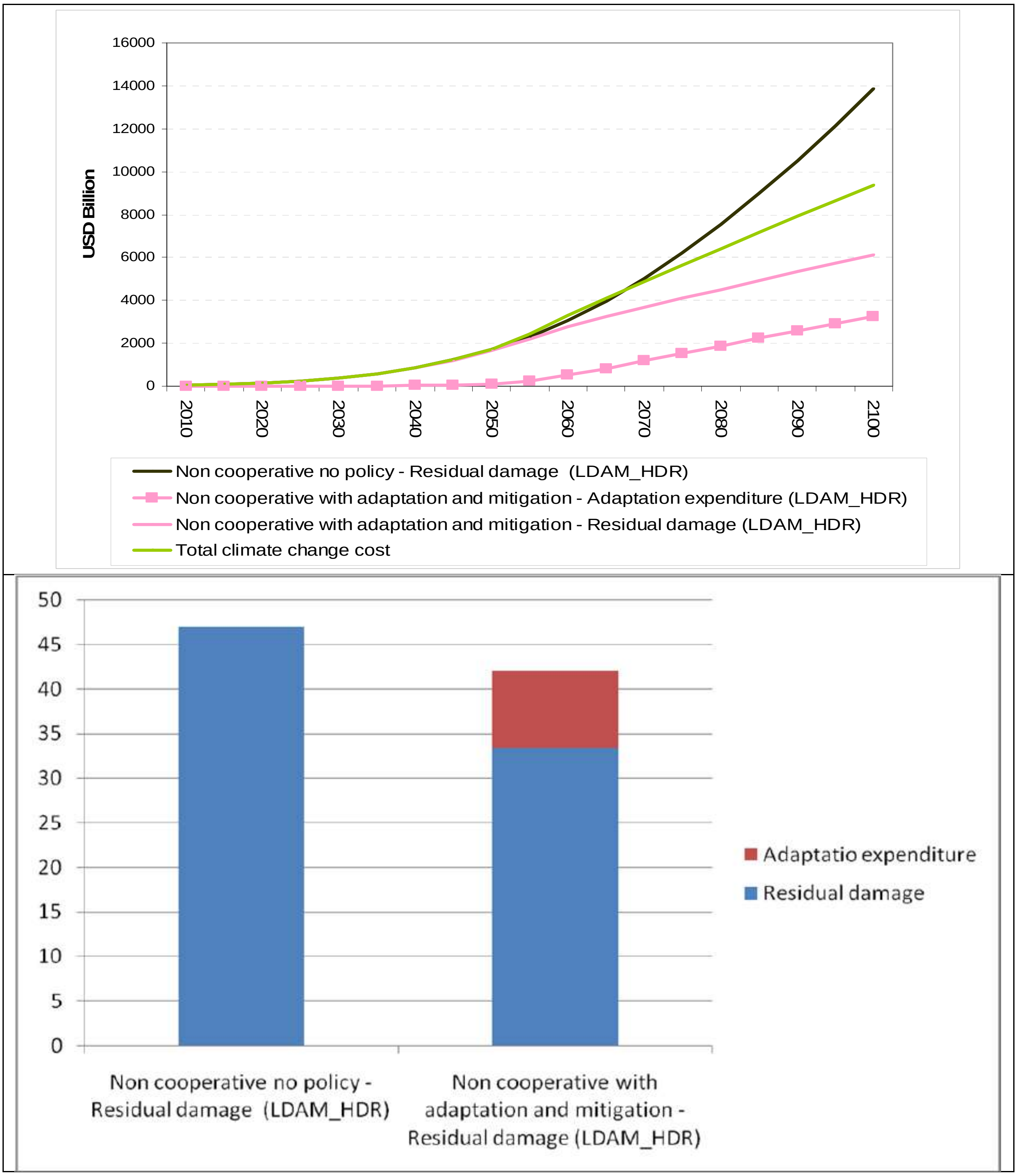
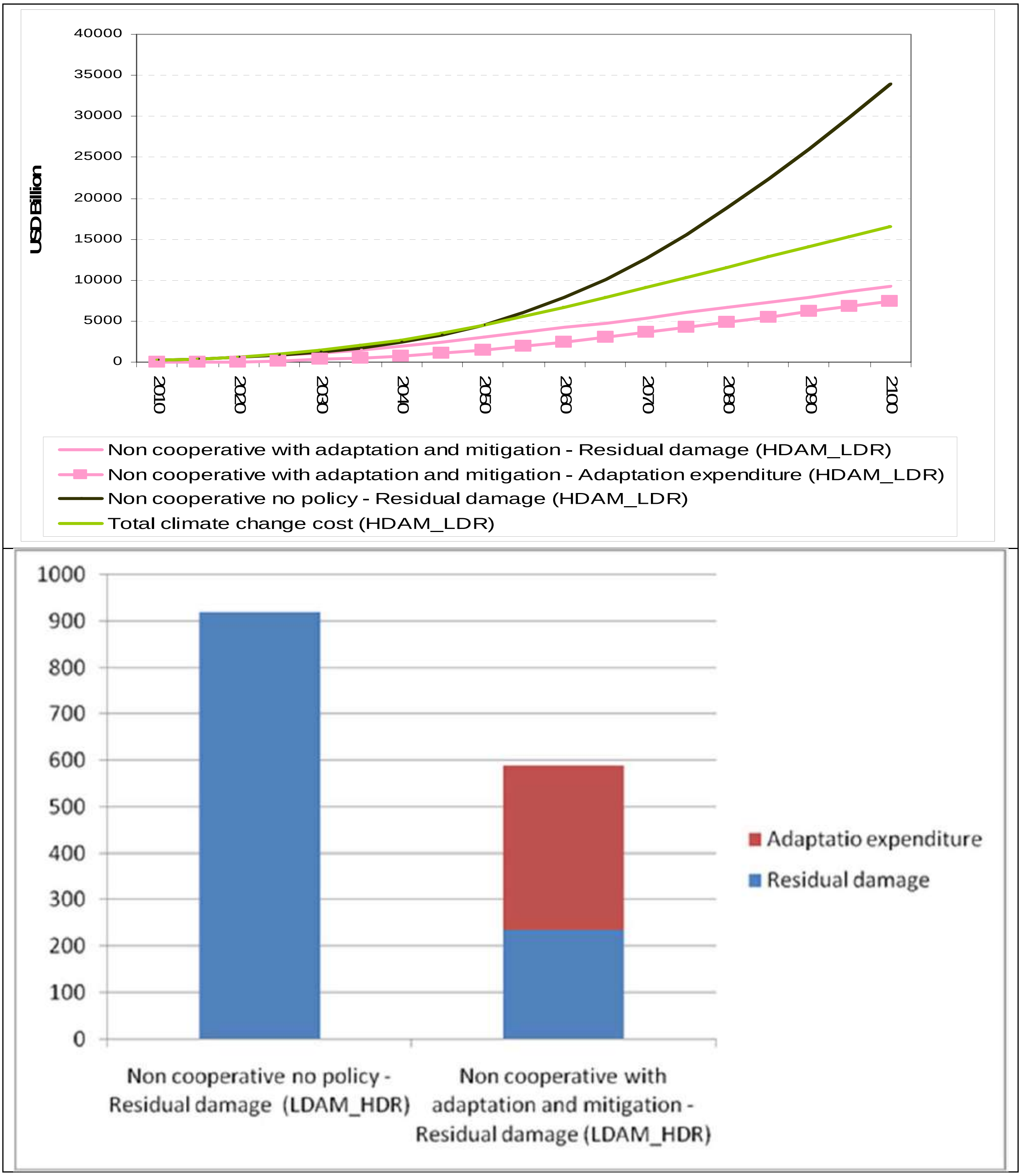


Figure 7: Residual damage and adaptation expenditure in the non-cooperative scenario - High damage Low discount rate. On the right panel, discounted values at 0.1% discount rate, 2005USD Trillion.



The benefit-cost ratios (BCRs) of adaptation, measured as the discounted sum of avoided damages over the discounted sum of total adaptation expenditures, are reported in Table 4. On a sufficiently long-term perspective, they are larger than one. Had we chosen a longer time period they could have been even higher, as in the model benefits increase more than costs, due to the stronger convexity of the damage function with respect to the adaptation cost function.[13]

Figure 4 also shows adaptation BCRs increase more when climate damage increases than when the discount rate decreases. When damages become more relevant all along the simulation period and not only at its later stages, adaptation becomes relatively more useful.

Table 4. Benefit-cost ratios of adaptation in four scenarios (non-cooperative scenario with adaptation and mitigation)

US$ 2005 Trillion ***Discounted values over the period 2010-2105***	LDAM_HDR	HDAM_HDR	LDAM_LDR	HDAM_LDR
Benefits	16	62	227	695
Costs	10	25	134	270
BCR	**1.67**	**2.41**	**1.69**	**2.57**

Benefits are measured as total discounted avoided damages compared to the non cooperative no policy case
Costs are measured as total discounted expenditures on adaptation. Values are discounted using a 3% discount rate the LDAM_HDR and HDAM_HDR cases and 0.1% discount rate in the LDAM_LDR and HDAM_LDR cases.

Our results confirm the theoretical insight[14] that, in a non-cooperative setting, adaptation is the main climate policy tool. Mitigation is negligible at the non-cooperative equilibrium. As a consequence, adaptation investments are high and increasing over time. Most importantly, the benefit-cost ratio is larger than one. Higher emissions in the presence of adaptation, and the relatively higher sensitivity of adaptation to the level of climate damages, already highlight the potential strategic complementarity between mitigation and adaptation. This issue will be addressed more deeply in the next sections.

An optimal integrated climate-change strategy in a cooperative scenario.

In a cooperative scenario, all externalities originated by emissions are internalized. Accordingly, emission abatement (mitigation) is considerably higher than in the non-cooperative scenario (Figure 8, left). Adaptation is still undertaken, but slightly less than in the non cooperative case (Figure 8, right). Higher cooperative mitigation efforts reduce the need to adapt with respect to the non cooperative scenario. This result is robust to different discount factors and damage levels (see Figure 9). When discounting expenditure flows with a high discount rate (3%), net present value

---

[13] This result is driven by our model assumptions, which are anchored on calibration data.

[14] There is an extensive literature on international environmental agreements showing the non cooperative abatement level is negligible at the equilibrium. Therefore, adaptation remains the only option to reduce climate damages.

adaptation expenditure is reduced from 8.7 to 7.2 2005US$ Trillion. When a lower discount rate is used (0.1%), net present value adaptation expenditure is reduced from 80 to 67 2005US$ Trillion.

As expected, abatement is further increased when the discount rate decreases or the damage from climate change increases. Adaptation is reduced accordingly. This effect is not proportional to emission reduction though. The discounting effect, which tends to favor mitigation by increasing the weight of future damages, is partly offset by the damage effect, which increases future and present damages and calls for both mitigation and adaptation.

Figure 8: Optimal adaptation and mitigation in a cooperative scenario - Low damage High discount rate

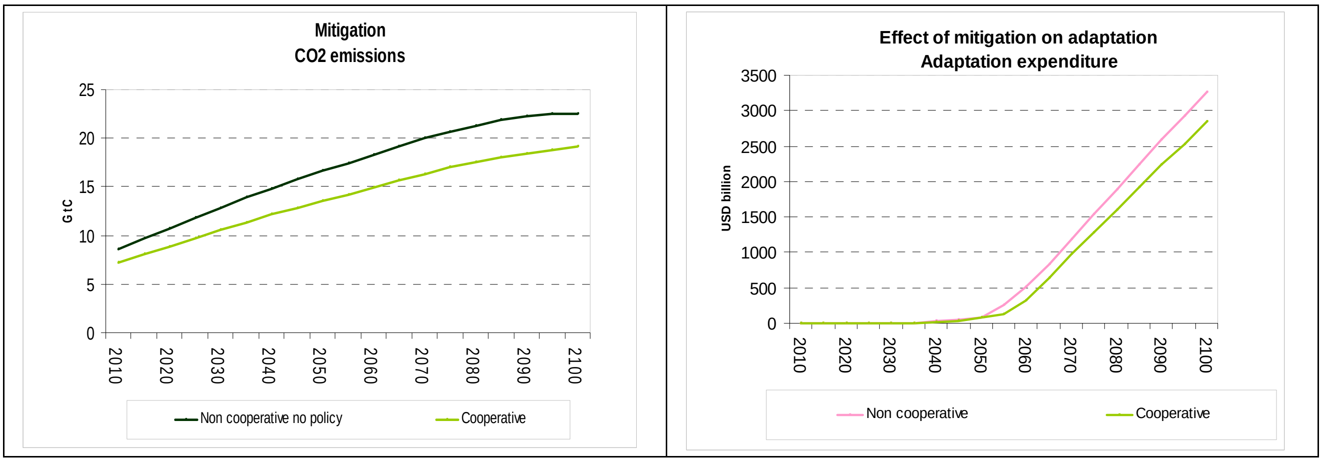
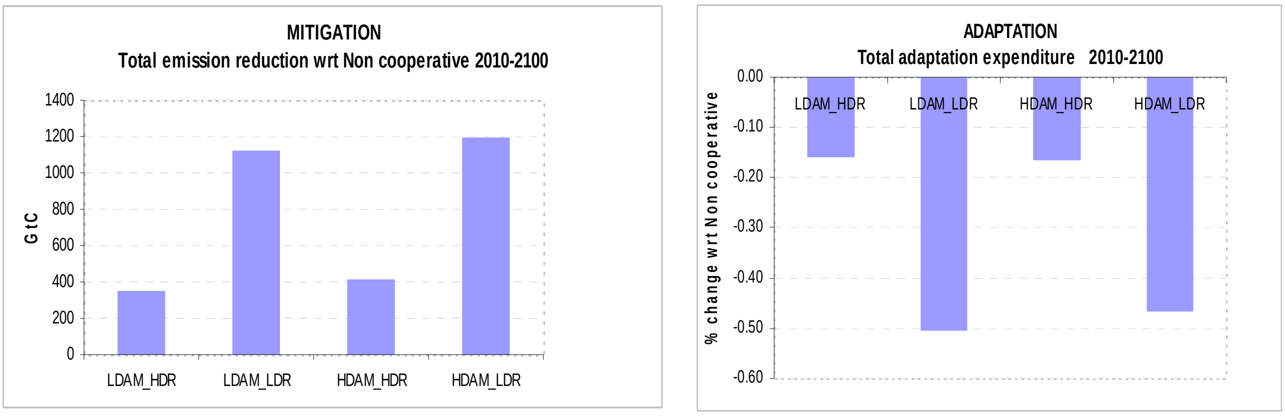


Figure 9: Effects of mitigation on adaptation



The trade-off between optimal mitigation and adaptation emerges also when analyzing cooperative mitigation with and without adaptation. As shown by Figure 10, adaptation reduces the need to mitigate, i.e. cooperative emissions in the presence of adaptation are higher. Nonetheless, even in the presence of adaptation, which can potentially reduce by 50 percent climate change damage, mitigation remains an important and far from negligible component of the optimal response to climate change.

After 2050, on a 5-year average, optimal emission reduction is approximately 17 percent compared to the no policy case. This stresses again the strategic complementarity between mitigation and adaptation. Both reduce climate-related damages. Therefore their integration can increase total welfare (proxied by cumulated discounted consumption) as shown by Figure 11. Notice also that cumulated consumption decreases less by giving up adaptation than mitigation. Indeed, investments in (proactive) adaptation crowd out consumption. This effect is amplified by the discounting process in earlier periods.

Figure 10: CO2 emissions- Low damage High discount rate

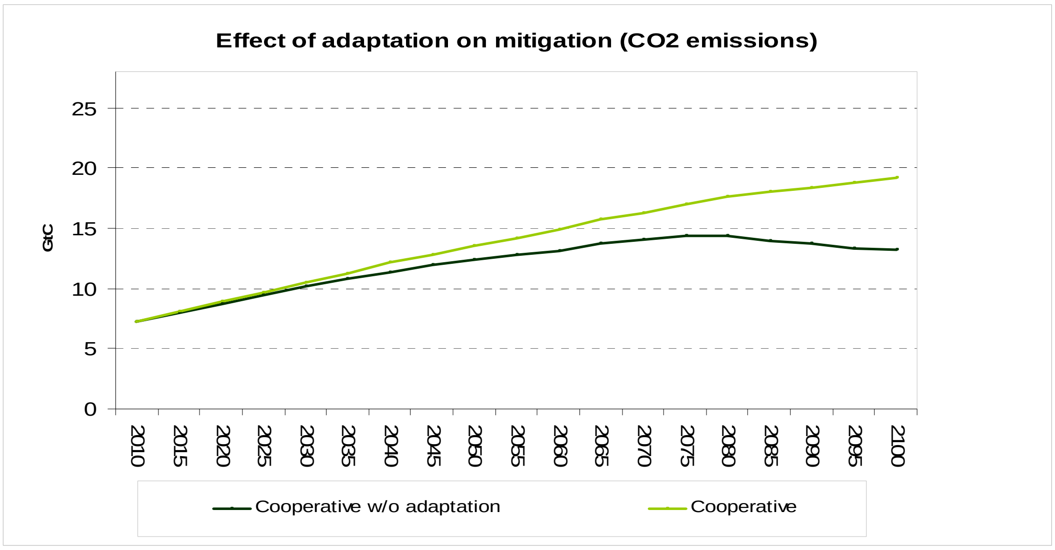
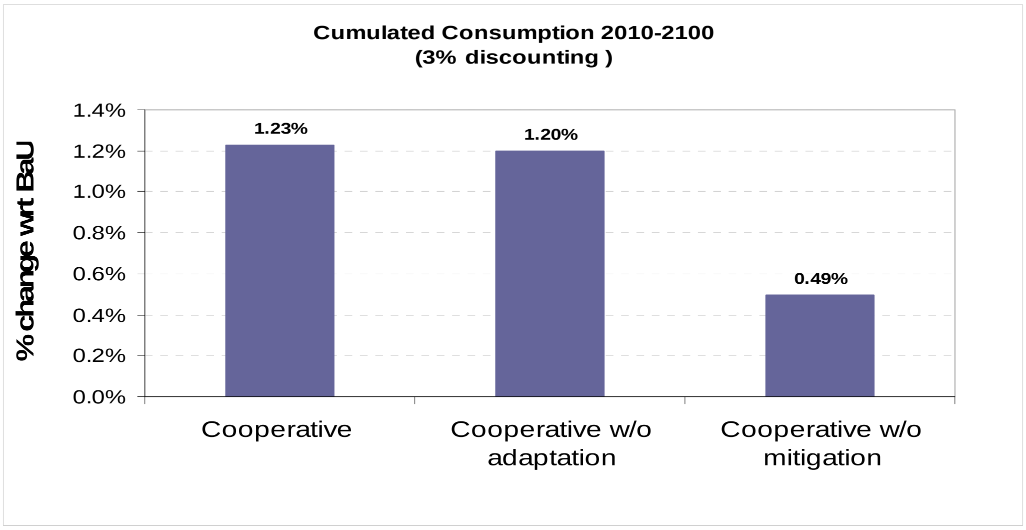


Figure 11: Global welfare



Further information on the relation between mitigation and adaptation is provided by Table 5. In 2100, mitigation cuts the potential climatic damage by roughly 3 US$ trillion, whereas adaptation by nearly 8 US$ trillion. Interestingly, the two strategies, when jointly chosen, reduce climate change damages by 8.2 US$ trillion, which is less than the sum of what the two strategies could accomplish if adopted separately. Mitigation and adaptation remain indeed competing strategies. On the benefit side, because adaptation reduces the marginal benefit of mitigation. And on the cost side, because both compete for scarce resources. Accordingly, when they are used jointly, there is a lower incentive to use each of the two.

Table 5. Strategic complementarity between adaptation and mitigation

Damage reduction in the cooperative case wrt baseline (2005 US$ trillion)					
	Mitigation only	Adaptation only	Sum	Adaptation & Mitigation	Interaction effect
2035	0.04	0.00	0.05	0.04	0.00
2050	0.20	0.10	0.30	0.23	-0.06
2075	0.99	2.24	3.23	2.43	-0.80
2100	3.05	7.92	10.97	8.23	-2.74

Table 6. Timing of adaptation and mitigation in a cooperative scenario

	2035	**2050**	**2100**
Adaptation (Total protection costs – Billion US$ 2005)	2	78	2838
Mitigation	-18.8%	-18.7%	-15.1%

(emission % wrt BAU)

Table 6 highlights another important difference between adaptation and mitigation: their timing. Mitigation starts well in advance with respect to adaptation. Abatement is substantial when adaptation expenditure is still low. Mitigation needs to be implemented earlier than adaptation. It works through carbon cycle inertia. Accordingly action needs to start soon to grasp some benefits in the future. By contrast, adaptation measures work through the much shorter economic inertia, and can thus be implemented when relevant damages occur, which is from the third decade of the century.

Table 7 disentangles the effectiveness of mitigation and adaptation when they are chosen optimally. It shows clearly that mitigation is preferred when the discount rate is low, whereas adaptation prevails when damages are high.

Table 7: Damage reduction due to different strategies

LDAM_LDR	**Mitigation&Adaptation**	**Mitigation**	**Adaptation**
2050	34%	31%	3%
2075	56%	39%	17%
2100	72%	45%	27%
LDAM_HDR	**Mitigation&Adaptation**	**Mitigation**	**Adaptation**
2050	14%	11%	3%
2075	39%	11%	28%
2100	59%	9%	50%
HDAM_LDR	**Mitigation&Adaptation**	**Mitigation**	**Adaptation**
2050	49%	32%	17%
2075	72%	43%	29%
2100	82%	47%	35%
HDAM_HDR	**Mitigation&Adaptation**	**Mitigation**	**Adaptation**
2050	33%	12%	21%
2075	61%	10%	51%
2100	74%	8%	66%

Table 8 shows the benefit-cost ratio of adaptation in the non cooperative and in the cooperative scenarios. The benefit-cost ratio of adaptation improves when it is optimally complemented by mitigation.[15] This is another way of expressing the rule that two instruments are better than one instrument at the first best, i.e. (net) welfare can be enhanced by increasing the degrees of freedom

---

[15] This happens also to mitigation, not shown.

of the policymaker. When combined, both adaptation and mitigation can better be used than in isolation, i.e. with a higher BCR.

Table 8: Benefit-Cost Ratio (BCR) of adaptation and of joint adaptation mitigation

	BCR adaptation		**BCR joint adaptation and mitigation**
Discounted values over the period 2010-2105	Non cooperative	Cooperative	Cooperative
Benefits	16	14	19
Costs	10	8	9
BCR	**1.67**	**1.73**	**2.11**

Benefits are measured as discounted avoided damages compared to non-cooperative no policy case
Adaptation costs are measured as discounted expenditures on adaptation
Mitigation costs are measured as additional investments in carbon-free technologies and energy efficiency compared to the non-cooperative no policy case

The sensitivity analysis reported in Table 9 highlights that adaptation becomes more profitable when climate related damages increase. Indeed, compared to mitigation which reduces mainly future damages, adaptation is more rapidly effective on contrasting future and present damages. Accordingly, in a high damage world (but without climate catastrophes), adaptation becomes the preferred strategy and this is reflected in an increasing benefit-cost ratio. When the discount rate declines, the opposite occurs: future damages become more relevant; mitigation is thus preferred; the benefit-cost ratio of adaptation declines accordingly. As shown in Table 7, with low discounting a larger share of damage reduction is achieved with mitigation. Similar results hold also when adaptation and mitigation are implemented jointly.

Table 9: Sensitivity analysis. Benefit-Cost Ratio (BCR)
of adaptation and of joint adaptation and mitigation in the cooperative scenario

	Adaptation			
Discounted values over the period 2010-2105	LDAM_HDR	HDAM_HDR	LDAM_LDR	HDAM_LDR
Benefits	14	55	99	337
Costs	8	21	65	144
BCR	**1.73**	**2.63**	**1.52**	**2.33**
	Joint adaptation and mitigation			
Discounted values over the period 2010-2105	LDAM_HDR	HDAM_HDR	LDAM_LDR	HDAM_LDR
Benefits	19	67	294	811
Costs	10	24	266	347
BCR	**1.93**	**2.82**	**1.10**	**2.34**

Values are discounted using a 3% discount rate the LDAM_HDR and HDAM_HDR cases and 0.1% discount rate in the LDAM_LDR and HDAM_LDR cases.

Summing up, mitigation and adaptation are strategic complements. Therefore, they should be integrated in a welfare maximizing climate policy. It is worth stressing again that the possibility to mitigate (adapt) reduces, but does not eliminate, the need to adapt (mitigate). The optimal climate policy mix is composed by both mitigation and adaptation measures. The benefit cost ratio of a policy mix where adaptation and mitigation are optimally integrated is larger that the one in which mitigation and adaptation are implemented alone.

Unraveling the optimal adaptation strategy mix

The analysis performed so far does not disentangle the role of different adaptation strategies. This is the aim of this section. Let us consider first the relationship between proactive (anticipatory) and reactive adaptation. As shown by Figure 12 and Table 10, the non cooperative and the cooperative scenarios highlight the same qualitative behavior: not surprisingly anticipatory adaptation is undertaken in advance with respect to reactive adaptation.

Consequently, until 2085 the bulk of adaptation expenditure is devoted to anticipatory measures; reactive adaptation becomes the major budget item afterwards. This is the optimal response to climate damage dynamics. When it is sufficiently low, it is worth preparing to face future damages. When eventually it becomes high and increasing, larger amount of resources need to be invested in reactive interventions, coping with what cannot be accommodated *ex ante*.

Figure 12: Scale and timing of adaptation investments

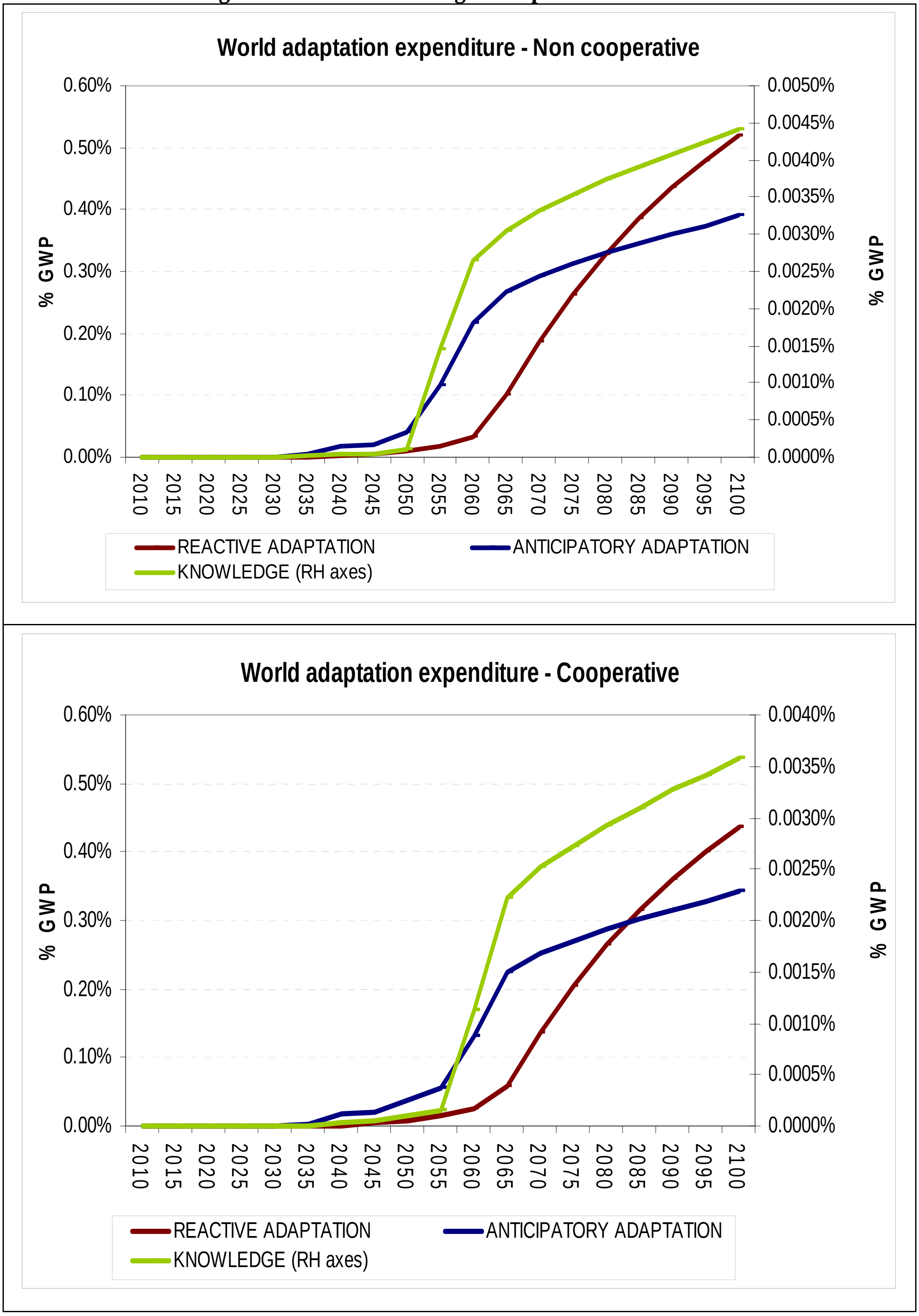


Table 10. Expenditure composition of the adaptation mix

2035	Non-cooperative setting	Cooperative setting
Reactive Adaptation	0.2%	0.6%
Anticipatory Adaptation	99.6%	99.1%
Knowledge Adaptation	0.2%	0.2%
2050	**Non-cooperative setting**	**Cooperative setting**
Reactive Adaptation	19.5%	17.2%
Anticipatory Adaptation	80.3%	82.6%
Knowledge Adaptation	0.2%	0.2%
2100	**Non-cooperative setting**	**Cooperative setting**
Reactive Adaptation	56.8%	55.8%
Anticipatory Adaptation	42.7%	43.8%
Knowledge Adaptation	0.5%	0.5%

Notice that investments in adaptation R&D show a behavior similar to anticipatory adaptation, but the scale of dedicated resources is much smaller. This result depends on the calibration data: we relied on quantitative estimates provided by UNFCCC (2007) on the aggregate amount of money that could be spent on R&D in agriculture, which is estimated to be around 7 US$ Billion in 2060, a very tiny amount compared to world GDP.[16]

The results shown in Figure 12 and Table 10 are based on the full availability of resources and political consensus to implement the optimal policy mix. What happens when first best options are not available? In other words, what kind of adaptation strategy should a decision maker prefer were he/she forced to make a choice between different adaptation measures because of resource scarcity? The answer to this question is summarized by Table 11. It reports the benefit-cost ratio when either one of the three options is foregone.

Table 11: Benefit-Cost Ratio (BCR) of adaptation strategy mix in the cooperative scenario

Option excluded from the optimal mix ***Discounted values over the period 2010-2105***	**Reactive adaptation**	**Anticipatory Adaptation**	**Knowledge Adaptation**
Benefits	789	7.4	13657
Costs	771	5.7	7938
BCR	**1.02**	**1.30**	**1.72**

---

[16] UNFCCC (2007) provides estimates for 2030. We scale this number up proportionally to the temperature gap between 2030 and our reference 2.5°C, which is our calibration point.

If just only one adaptation strategy were to be chosen, reactive adaptation should be privileged. Indeed, the non implementation of reactive adaptation would induce a worsening of the benefit cost ratio of the whole climate change strategy by 41 percent (and by 45 percent in welfare terms). By contrast, the impossibility to use anticipatory adaptation would decrease the benefit cost ratio by 24 percent (33 percent in welfare term).

R&D adaptation appears to be the less crucial adaptation option. But this depends on the way it is modeled. R&D adaptation improves the productivity of reactive adaptation. Hence, its elimination does not impair excessively reactive adaptation itself. Appendix III illustrates an alternative formulation in which R&D augments the productivity of both proactive and reactive adaptation and in which adaptation R&D investments are therefore much larger. Nonetheless, all other conclusions are robust to changes in the model specification as described in Appendix III.

Regional analysis

In order to provide insights on regional specificities, this section disaggregates the above results between developed and developing countries. Even this broad disaggregation is sufficient to highlight substantial differences.

Figure 13 and Table 12 stress the higher vulnerability and the higher need to adapt of developing countries. Not surprisingly, NON-OECD countries spend a higher share of their GDP on adaptation than OECD countries. This is driven by their higher damages – by the end of the century, also in absolute terms, optimal adaptation expenditure is nearly 5 times higher in NON-OECD than in OECD countries – and by their lower GDP.

Figure 13. Adaptation expenditures in NON OECD and OECD countries

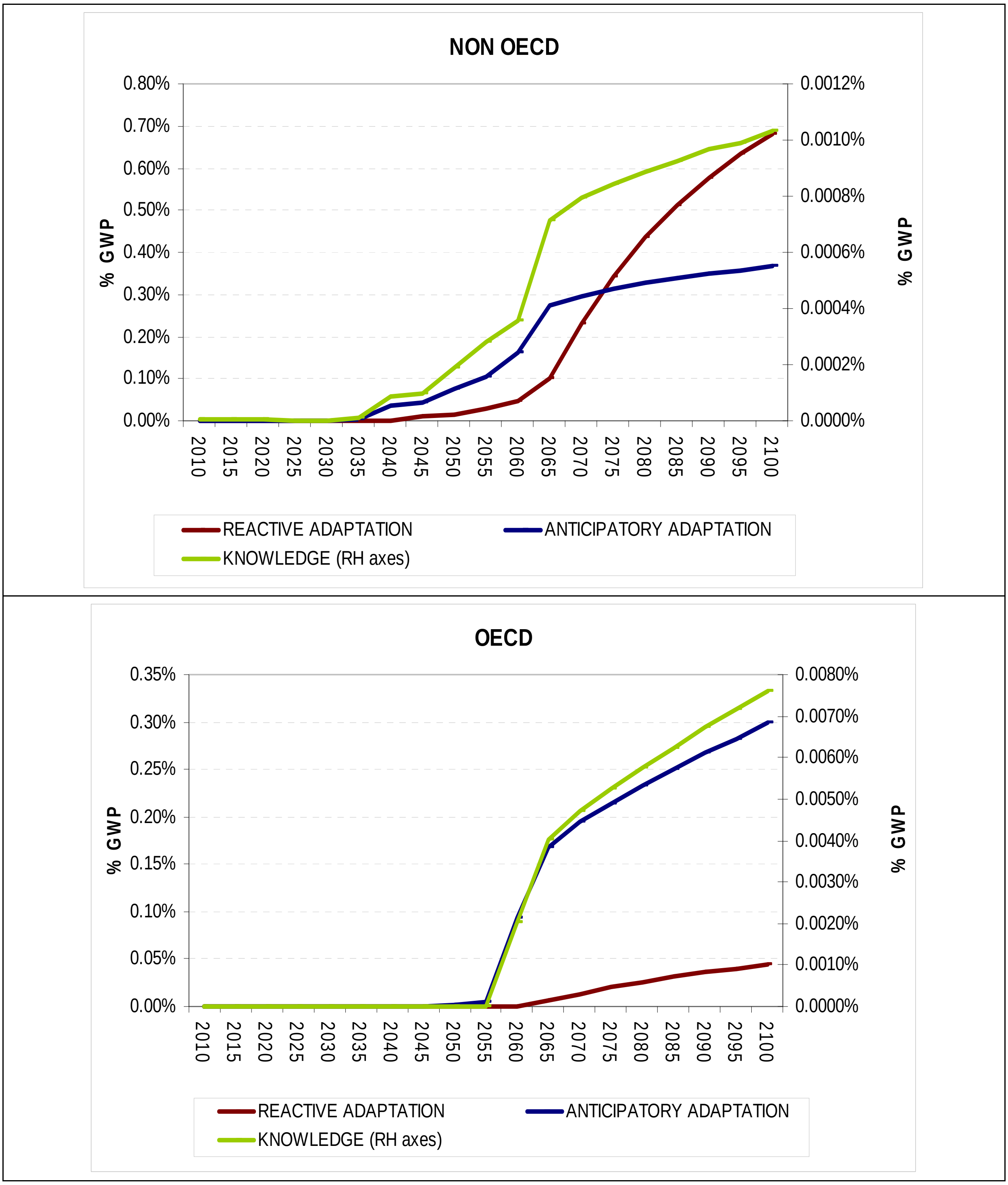


Table 12: Adaptation and mitigation in OECD and NON-OECD regions in the cooperative scenario

	OECD	**NON OECD**
	2035	
Reactive Adaptation (US$ Billion)	0	0
Anticipatory Adaptation (US$ Billion)	0	2
Knowledge Adaptation (US$ Billion)	0	0
Total Adaptation expenditure (US$ Billion)	0	2
Mitigation (emission reduction %)	-24%	-15%
	2050	
Reactive Adaptation (US$ Billion)	0	13
Anticipatory Adaptation (US$ Billion)	2	62
Knowledge Adaptation (US$ Billion)	0	0
Total Adaptation expenditure (US$ Billion)	2	76
Mitigation (emission reduction %)	-24%	-16%
	2100	
Reactive Adaptation (US$ Billion)	62	1520
Anticipatory Adaptation (US$ Billion)	421	821
Knowledge Adaptation (US$ Billion)	11	2
Total Adaptation expenditure (US$ Billion)	494	2344
Mitigation (emission reduction %)	-18%	-14%

It is also worth noting the different composition and timing of the optimal adaptation mix between the two regions. NON-OECD countries rely mainly on reactive measures, which in 2100 contribute to 65 percent of total adaptation expenditure, whereas OECD countries focus on anticipatory measures, which constitute 85 percent of their total expenditure on adaptation. As for the timing, adaptation in NON-OECD is undertaken much earlier than in OECD regions.

The different composition of adaptation responses depends upon two facts:[17] firstly, the regional characteristics of climate vulnerability. In OECD countries, the higher share of climate change damages originates from loss of infrastructures and coastal areas, whose protection requires a form of adaptation that is largely anticipatory. In NON-OECD countries, a higher share of damages originates from agriculture, health, and the energy sectors (space heating and cooling). These damages can be accommodated more effectively through reactive measures.

Secondly, OECD countries are richer. Thus, they can give up relatively more easily their present consumption to invest in adaptation measures that will become productive in the future. By contrast, NON-OECD countries are compelled by resource scarcity to act in emergency.

---

[17] More on the calibration procedure can be found in Appendix I and in another Annex available upon request.

Only the expenditure on adaptation R&D is higher in OECD countries than in NON-OECD countries. Data on R&D and innovation aimed at improving the effectiveness of adaptation are very scarce. Starting from UNFCCC (2007), we decided to distribute adaptation R&D to different regions on the basis of current expenditure on total R&D, which is concentrated in OECD countries. This explains why adaptation R&D investments in developing countries in 2100 are roughly 1/10 and 1/5 of that of developed regions – as a share of their GDP and in absolute terms, respectively.

Table 13: Sensitivity analysis. Benefit-Cost Ratio of adaptation and of joint adaptation and mitigation in the cooperative scenario – OECD regions

	Adaptation			
Discounted values over the period 2010-2105	LDAM_HDR	HDAM_HDR	LDAM_LDR	HDAM_LDR
Benefits	2.2	16	14	93
Costs	1.5	5.9	12	39
BCR	**1.45**	**2.64**	**1.12**	**2.38**
	Joint adaptation and mitigation			
Discounted values over the period 2010-2105	LDAM_HDR	HDAM_HDR	LDAM_LDR	HDAM_LDR
Benefits	4.2	21	68	238
Costs	1.8	6.6	146	164
BCR	**2.23**	**3.17**	**0.46**	**1.45**

Values are discounted using a 3% discount rate the LDAM_HDR and HDAM_HDR cases and 0.1% discount rate in the LDAM_LDR and HDAM_LDR cases.

Table 14: Sensitivity analysis. Benefit-Cost Ratio of adaptation and of joint adaptation and mitigation in the cooperative scenario – NON-OECD regions

	Adaptation			
Discounted values over the period 2010-2105	LDAM_HDR	HDAM_HDR	LDAM_LDR	HDAM_LDR
Benefits	11	40	86	243
Costs	6	15	53	105
BCR	**1.79**	**2.63**	**1.61**	**2.31**
	Joint adaptation and mitigation			
Discounted values over the period 2010-2105	LDAM_HDR	HDAM_HDR	LDAM_LDR	HDAM_LDR
Benefits	15	46	226	573
Costs	6.9	16	128	183
BCR	**2.11**	**2.85**	**1.77**	**3.13**

Values are discounted using a 3% discount rate the LDAM_HDR and HDAM_HDR cases and 0.1% discount rate in the LDAM_LDR and HDAM_LDR cases.

Table 13 and 14 show the benefit-cost ratio of adaptation, and of adaptation and mitigation jointly. In NON-OECD countries, the combination of the two strategies always shows a higher benefit-cost ratio than adaptation alone (Table 14). By contrast, in OECD regions (Table 13) this remains true only with a high discount rate. With a lower discounting, mitigation increases its weight in the policy mix. The additional effort undertaken by OECD countries, which is the group of countries investing more on low carbon technologies, benefits mostly NON-OECD regions. In other words, in a cooperative setting OECD countries are called to abate partly on behalf of NON-OECD countries. For example, consider the low damage, low discount case (LDAM_LDR). Global benefits of joint adaptation and mitigation amount at 294 US$ trillion (see Table 9). 75 percent of these benefits occurs in NON-OECD countries, for a total benefit of 226 US$ trillion, whereas OECD countries receive the remaining 25 percent (68 US$ trillion), though they bear slightly higher costs.

Again, what happens if first best options were not fully available? If just only one adaptation strategy were to be chosen, anticipatory adaptation should be privileged by OECD countries, whereas NON-OECD should prioritize expenditure on reactive adaptation (see Table 15).

Indeed, the elimination of anticipatory adaptation from the adaptation option basket of OECD countries induces a worsening of the benefit-cost ratio of the whole climate change strategy equal to 72 percent. The impossibility to use reactive adaptation in NON-OECD countries reduces the overall benefit-cost ratio by 48 percent (Table 15).

The difference between developing and developed regions is notable. Foregoing reactive adaptation is much more damaging for developing than for developed countries, consistently with what observed about the regional structure of damages and the adaptation expenditure, whereas the opposite holds for anticipatory adaptation. Again, R&D adaptation appears to be the adaptation option one can give up less regretfully.

Table 15: Marginal contribution of specific policy-driven strategies

	WORLD	OECD	NONOECD
Reactive adaptation	-41%	-29%	-48%
Anticipatory adaptation	-24%	-72%	-24%
Knowledge adaptation	-0.36%	-2%	-0.1%

These results, although driven by our model specification and calibration, contain some preliminary policy implications:

- OECD countries invest heavily in anticipatory adaptation measures. This depends on their damage structure. Planned anticipatory adaptation is particularly suited to cope with sea-level rise, but also with hydro geological risks induced by more frequent and intense extreme events, which are a major source of negative impacts in the developed economies. Thus, it is more convenient to act ex ante rather than ex post in OECD countries.

- In NON-OECD countries, climate change adaptation needs are presently relatively low, but will rise dramatically after the mid-century, as long as climate change damages will increase. In 2050, they could amount to 78 US$ Billion, in 2065 they will be above 500 US$ billion to peak to more than 2 US$ trillion by the end of the century. It is sufficient to recall that in 2007 total ODA were slightly above 100 US$ Billion to understand by how much climate change can stress adaptive capacity in the developing world. NON-OECD countries are unlikely to have the resources to meet their adaptation need, which calls for international aid and cooperation on adaptation to climate change.
- At the equilibrium, NON-OECD countries place little effort on adaptation R&D and rely primarily on reactive adaptation. This outcome however depends on the particular structure of NON-OECD economic systems. Being poor, other forms of adaptation expenditures, more rapidly effective, mainly of the reactive type, are to be preferred. This suggests that richer countries can help developing countries also by supporting their adaptation R&D (e.g. by technology transfers) and their adaptation planning.

A comparison with the existing modelling literature

The modelling literature that analyses the optimal investments in adaptation, their time profile and the trade-off between adaptation and mitigation is rapidly increasing, but still in its infancy and for its larger part confined in the grey area (see Agrawala *et al.*, 2011a for a review).

It started with the pioneering PAGE model (Hope 1993, then updated in Hope 2007, 2009) where adaptive policies operate in three ways: they increase the slope of the tolerable temperature profile, its plateau, and finally they can decrease the adverse impact of climate change when the temperature eventually exceeds the tolerable threshold. The default adaptation strategy has a cost in the EU of 3, 12 and 25 US billion US$/year (minimum, mode and maximum respectively) to achieve an increase of 1 degree Celsius of temperature tolerability and of additional 0.4, 1.6, 3.2 US billion US$/year to achieve a 1% reduction in climate change impacts. At the world level, this implies, at a discount rate of 3% declining, a cost of nearly 3 trillion of US$ to achieve a damage reduction of roughly US$ 35 trillion within the period 2000-2200. Impact reduction ranges from 90% in the OECD to 50% elsewhere.

With the given assumptions, the PAGE model could easily justify aggressive adaptation policies (see e.g. Hope et al. 1993), implicitly decreasing the appeal of mitigation. However, in all its versions the PAGE model treats adaptation as exogenous or scenario variable decided at the outset. As a consequence, the model cannot endogenously determine the optimal characteristics of a mitigation and adaptation policy portfolio.

Adaptation is treated as an explicit control variable by a more recently developed group of models - FEEM-RICE (Bosello, 2010), AD-DICE (De Bruin *et al*., 2009a; Agrawala *et al*. 2011), AD-RICE (De Bruin, *et al*., 2009b; Agrawala *et al*. 2011), AD-FAIR (Hof e*t al*. 2009, Hof *et al*. 2010), Ada-BaHaMa (Bahn, *et al*. 2010).

All these models build on the economic core offered by the RICE-DICE model family (Nordhaus 1994, 1996, 2000) where a single world or multiple regional social planners choose between current consumption, investment in productive capital, and emissions reduction balancing a climatic damage component. This is represented by global or regional damage functions that depend on the temperature increase compared to 1900 levels.

In de Bruin *et al*. (2009a) adaptation is a flow variable: it needs to be adjusted period by period, but also, once adopted in one period, it does not affect damages in the next period. They show that adaptation and mitigation are strategic complements: optimal policy consists of a mix of adaptation measures and investments in mitigation. Adaptation is the main climate change cost reducer until 2100, whereas mitigation prevails afterwards. In addition, it is shown that benefits of adaptation are higher than those of mitigation until 2130.

The authors highlight the trade-off between the two strategies: the introduction of mitigation decreases the need to adapt and vice versa. However, the second effect is notably stronger than the first one. Indeed, mitigation lowers only slightly climate related damages, especially in the short-medium term. Therefore, it does little to decrease the need to adapt, particularly during the first decades.

Sensitivity over the discount rate points out that mitigation becomes relatively more preferable as the discount rate becomes lower. Intuitively, mitigation reduces long-term climatic damages: thus, it becomes the preferred policy instrument as these damages become more relevant.

All these results are consolidated in de Bruin *et al.* (2009b), which repeat the analysis with an updated calibration of adaptation costs and benefits and propose also regional results. They show that in terms of utility for low level of damages adapting only is preferable than mitigating only. However, the relationship is reversed when climate damages increase.

Stock adaptation is introduced by Bosello (2010) in the FEEM-RICE model (Buonanno *et al.* 2000), a modified version of Nordahus' RICE 1996 with endogenous technical progress, and by Bahn *et al.* (2010) in a DICE-type model which distinguishes a fossil-fuel-based and a carbon-free sector. Modelling adaptation as a stock of defensive capital cumulating with a periodical protection investment instead of a flow has two main consequences. Both studies show that mitigation should be optimally implemented in early periods, whereas adaptation should be postponed to later stages. Accordingly, and this is the first key qualitative difference with studies modelling adaptation as a flow, the main damage reducer is mitigation and not adaptation at least in the first decades. Secondly, while "stock and flow" approaches agree that a lower discount rate tends to favour mitigation, when adaptation is a stock, both mitigation and adaptation increase, but mitigation is used more intensively in relative terms; when adaptation is only a flow expenditure, it is substituted by mitigation. Other findings are robust across the two approaches, especially the trade-off between the two strategies. Bahn et al. (2010) also demonstrate that a particularly effective adaptation, by shielding the economy from climate change damages, can delay the transition towards a cleaner economy, leading to very high GHG concentrations at the end of the century.

All the aforementioned papers adopt a cost benefit perspective: they aim at determining the first-best balance between adaptation and mitigation, given the respective costs and benefits. Three studies – Hof *et al.* (2009, 2010), Agrawala *et al.* (2011) and Bosello *et al.* (2011) – propose instead a cost effectiveness approach: having set a mitigation policy target, they investigate the optimal adaptation effort and its feedback on the mitigation policy. In Hof *et al.* (2009) mitigation lowers baseline adaptation costs in 2100 from 1% to 0.4% in the case of a 3°C target, and to approximately 0.1% in the case of a 2°C target.

In Agrawala *et al.*, (2011) and Bosello *et al.* (2011) mitigation to stabilize CO2 concentration at 550 ppm lowers the need to adapt and crowds out adaptation expenditure. The crowding-out is particularly prominent after mid-century, when it reaches about 50%. Nonetheless, adaptation remains substantial and it still exceeds US$ 1 Trillion in 2100. Interestingly, differently from Hof *et al.* (2009), adaptation slightly increases mitigation costs. Indeed, the possibility to adapt increases the amount of damage that can be endured, and thus the level of tolerable emissions. Therefore, reaching the GHG concentrations target requires a slightly higher abatement effort. According to both studies, adaptation efforts remain far from negligible anyway and particularly so in developing countries.

In Hof *et al*., (2010) the cost effectiveness analysis of the 2°C and 3°C targets is enriched by the regional picture and by the implications of different allocation schemes for emission rights. The study flags the high distributional implications triggered by both the stringency of the policies and the allocation rules. In term of total discounted climate change costs, the 3°C policy costs half of the 2°C policy (1% vs 2% of global GDP). The lower residual damages and adaptation costs are more than compensated by the higher mitigation costs. Nonetheless at the regional level a 2°C policy implies lower costs for Western Africa and South Asia with the policy burden sustained by all the other regions. It is also shown that, the differences between the regimes are considerable in the short-medium term, but they all move in the same direction in the long term. A contraction and convergence regime would provide the higher benefits for the poorer regions in the short term, but the highest in the long term. A multistage approach is exactly the opposite. Finally, and in accordance with our results, with both policies, but especially with the 3°C one, adaptation costs are higher in the developing countries and concentrated in the second half of the century. Therefore, financing adaptation in developing countries will become a more and more pressing issue over time.

In their critical review of modeling climate change adaptation, Fisher-Vanden *et al.* (2011) identify five characteristics that an ideal Integrated Assessment Model of adaptation should possess. It should combine regional and sectoral resolution for impacts and adaptation strategies. It should represent the different types of adaptation—market-driven adjustments, proactive and reactive adaptation. It should allow for intertemporal decision making under uncertainty. And finally, it should account for induced innovation in adaptation-related technologies; and connection with empirical work on impacts and adaptation. The model used for the present analysis includes all the characteristics just mentioned. What is missing is an explicit treatment of uncertainty with a probabilistic representation of different states of the world. This would make intertemporal optimization computationally difficult and would require some new techniques to keep the problem tractable.

Finally, the quantitative results of the modelling exercise proposed in this report crucially hinge on the empirical estimates of climate change impacts and adaptation costs. Two types of issues arise.

First, there can be a lack of sound empirical evidence. This is the main obstacle in modelling adaptation knowledge and R&D. The lack of empirical studies restricts our ability to calibrate changes in adaptation technology. Second, although some empirical evidence does exist, the linkage between bottom-up, impact-specific studies and the top-down framework adopted in this paper is not always straightforward. Judgements and assumptions are needed in order to translate the empirical information and data into calibrated impacts and adaptation cost curves.

Assessing the role of market driven adaptation

The analysis conducted so far abstracted from any role potentially played by market-driven adaptation. In other words, either the economic impact assessment or the design of the optimal mix between mitigation and adaptation strategies are based on damage functions not accounting for behavioural changes induced by market or welfare changes in human systems.

Modelling and then quantifying market-driven adaptation is extremely challenging. In economic terms, this means representing supply and demand reactions to scarcity signals conveyed by prices and triggered by climate-related impacts. Even assuming a satisfactory knowledge of these impacts, this requires to assessing substitution elasticities in consumers preferences and transformation elasticities in production functions for all goods and services. This needs then to be coupled with a realistic picture of inter-sectoral and international trade flows. Some seminal studies in this field exist, which try to capture the autonomous reactions of demand and supply to climate-induced changes in relative prices and/or in the availability of resources. Most studies use applied or computable general equilibrium models (see, for example, Bosello *et al.* 2006; Darwin and Tol 2001; Deke *et al.* 2001, Ciscar et al., 2009, Aaheim et al., 2010, Eboli et al.,).

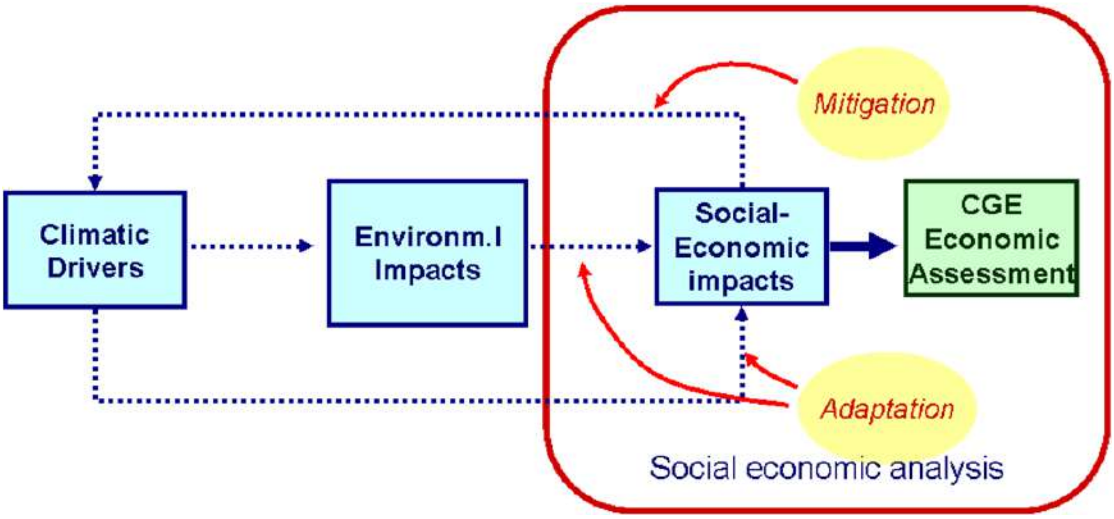
Initially, computable general equilibrium (CGE) models were developed mainly to analyze international trade policies and, partially, public sector economic issues (e.g. fiscal policies). Soon, because of their great flexibility, they became a common tool for economists to investigate the consequences of the most diverse economic perturbations, including those provoked by climate change. Indeed, notwithstanding its complexity, as long as climate-related physical impacts can be translated into a change in productivity, production or demand for the different inputs and outputs of the model, their GDP implications can be determined by a CGE model.[18]

---

[18] In principle CGE model offer also the possibility to measure welfare changes captured by changes in indicators other than GDP, like the Hicksian equivalent variation or consumers' surplus from a pre- to a post-perturbation state.

The structure of an integrated climate impact assessment exercise within a general equilibrium framework is presented in Figure 14. Economics is not independent from other disciplines, in particular it comes into play only after climatic changes have been translated into physical consequences (impacts) and then into changes of activities relevant for human welfare.

Figure 14. The structure of a integrated impact assessment exercise



Using a CGE approach for the economic evaluation of climate impacts implies an explicit modelling of sectors and of trade of production factors, goods and services. Changes in relative prices induce sectoral adjustments and changes in trade flows, thus triggering autonomous adaptation all over the world economic system.

Studies in this field however share one or both of the following shortcomings: they analyse climate change impacts in a static framework; and they consider only one or very limited number of impacts. A static approach fails to capture important cumulative effects - think e.g. to a loss of productive capital that need to be compensated by an increased investment rate – thus it is severely limited especially to analyse long-term climate impacts. As to the second issue, albeit some market-driven adaptation mechanisms can be described even in a single-impact case, interactions among impacts and the full potential of market-driven adaptation are neglected by focusing on one or few impacts.

However, great care should be placed on their interpretation. Here it is sufficient to mention that CGE models only partially capture changes in stock values (like property), and that they usually miss non market aspects to understand the important limitation of these assessments. Nevertheless a CGE approach has the merit to depict explicitly resource re-location, a crucial aspect of which is international trade, which is not captured by traditional direct costing methodologies.

A recent research effort conducted at FEEM tackled these two limitations. ICES, a recursive-dynamic CGE model, has been developed and then used as investigation tool to analyse the higher order costs of an extended set of climate-related impacts (see Table 16) considered one at a time, but also jointly. The study is still in a preliminary phase (many relevant impacts have still to be included, moreover the methodological approach can be improved by a more realistic representation of many features of market functioning) however it can already offer an interesting glimpse of the possible role played by market-driven adaptation.

In this study, the ICES model replicates the same geographical disaggregation of the WITCH and AD-WITCH models. The only difference is that in WITCH WEURO (Western Europe) is now divided into Mediterranean and Northern Europe, while MENA (Middle East and North Africa) is split into Middle East and North Africa. Seventeen production sectors are considered in our analysis (see Table 17).

Table 16. Impacts analyzed with the ICES model

Supply- side impacts
Impact on labour quantity (change in mortality – health effect of climate change)
Impacts on labour productivity (change in morbidity – health effect of climate change)
Impacts on land quantity (land loss due to sea level rise)
Impacts on land productivity (Yield changes due to temperature and CO2 concentration changes)
Demand-side impacts
Impacts on energy demand (change in households energy consumption patterns for heating and cooling)
Impacts on recreational services demand (change in tourism flows induced by climate change)
Impacts on health care expenditure

Table 17. Regional and sectoral disaggregation of the ICES model

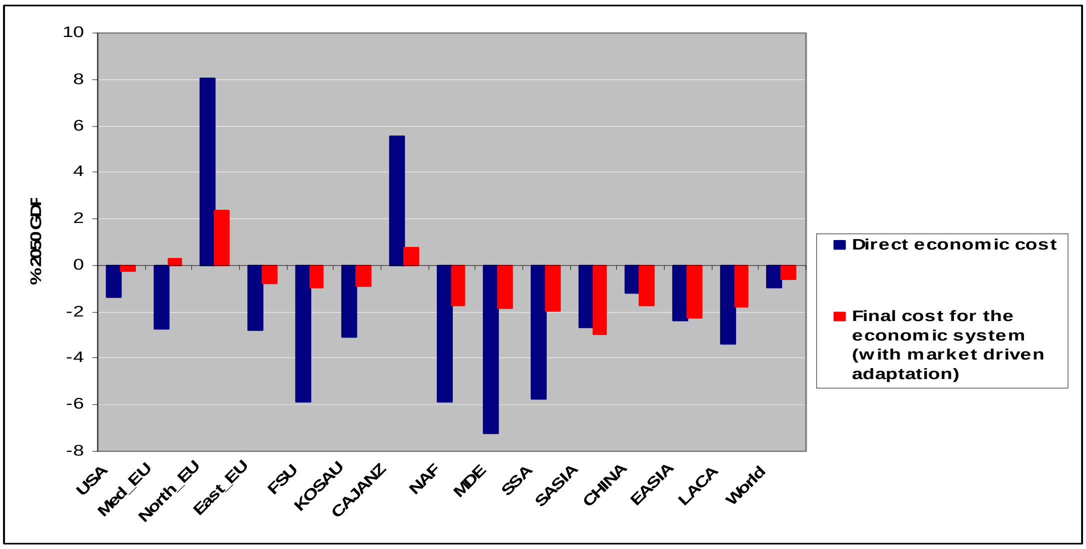
REGIONAL DISAGGREGATION OF THE ICES MODEL (this study)	
USA:	United States
Med_Europe:	Mediterranean Europe
North_Europe:	Northern Europe
East_Europe:	Eastern Europe
FSU:	Former Soviet Union
KOSAU:	Korea, S. Africa, Australia
CAJANZ:	Canada, Japan, New Zealand
NAF:	North Africa
MDE:	Middle East
SSA:	Sub Saharan Africa
SASIA:	India and South Asia
CHINA:	China
EASIA:	East Asia
LACA:	Latin and Central America
SECTORAL DISAGGREGATION OF THE ICES MODEL (this study)	
Rice	Gas
Wheat	Oil Products
Other Cereal Crops	Electricity
Vegetable Fruits	Water
Animals	Energy Intensive industries
Forestry	Other industries
Fishing	Market Services
Coal	Non-Market Services
Oil	

The model, running from 2001-2050, has been calibrated to replicate regional GDP growth paths consistent with the A2 IPCC scenario, and has then been used to assess climate change economic impacts for 1.2 and 3.1 degrees Celsius increase in 2050 with respect to 2000, which is the likely temperature range associated to that scenario. The difference between these values and initial direct costs provides an indication of the possible role of autonomous adaptation. This information then allowed to calibrate world and macro-regional climate change damage functions by explicitly considering market driven adaptation (Appendix II provides further information).

Our main results can be summarised as follows.

Socio-economic systems share a great potential to adapt to climate change. Figure 15 shows the difference between the direct cost of climate change impacts (all jointly considered) and the final impact on regional GDP after sectoral and international adjustments took place. Resource re-allocation smoothes, in some cases turns them into gains, initial direct costs. Nevertheless, it is worth highlighting that in some regions (SASIA, EASIA and CHINA) final costs are very close to direct costs and that in China they are *higher*. This means that some market adjustment mechanisms, primarily international capital flows and terms of trade effect, can exacerbate initial impacts[19].

Figure 15. Direct versus final climate change costs as percentage of regional GDP (in 2050 for a temperature increase of 3°degrees Celsius wrt 2000)



Interactions among impacts are also relevant (see Figure 16). In general, costs of impacts together are higher than the sum of the cost associated to each single impact. This also provides an important justification to performing a joint impact analysis instead of collecting the results provided by a set of single impact studies.

Finally, as clearly shown by Figure 17, climate change impacts at the world level induce costs, even when market-driven adaptation is accounted for. Impacts and adaptive capacity are highly differentiated though, i.e. a relatively small loss at the world level may hide large regional losses. In particular, developing countries remain the most vulnerable to climate change especially because of adverse impacts on the agricultural sector and food production.

---

[19] In principle, some adverse market effects could be controlled by a clairvoyant decision maker. Some restrictions could be for instance imposed on trade or international capital movement to offset negative terms of trade effects. In practice, this is extremely difficult: on the one hand, these controls are hardly accepted by the international community, on the other hand, and most importantly, this would require to isolate the climate change influence on world trade, by country and commodity, which is an almost impossible task.

Figure 16. Role of Impact interaction: percentage difference between GDP costs of all climatic impacts implemented jointly and the sum of GDP costs associated to each impact implemented individually

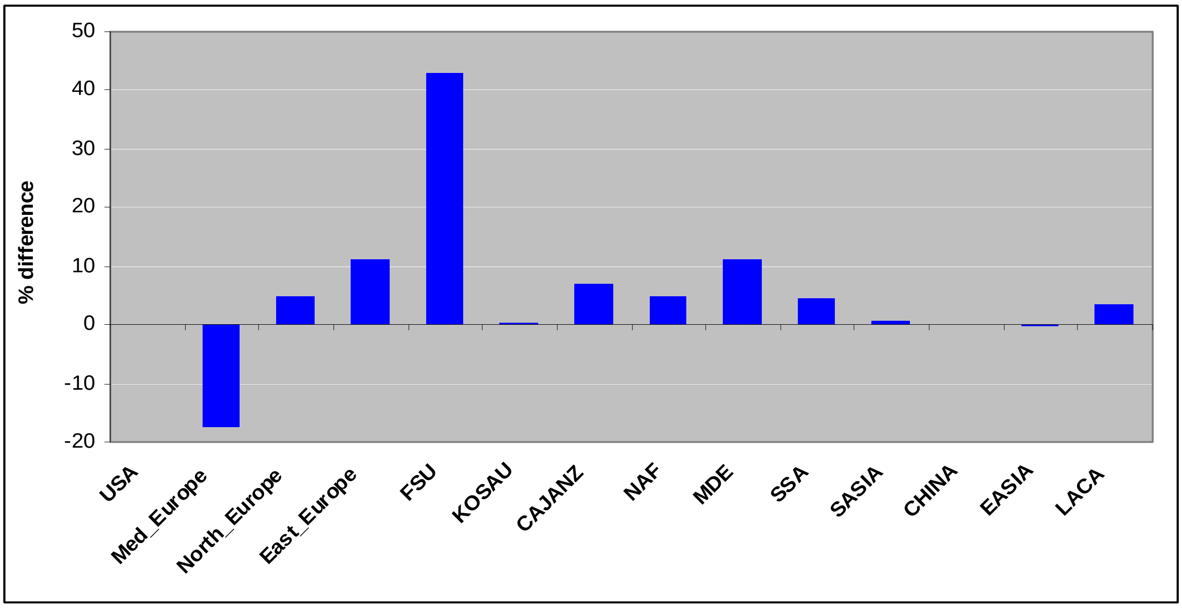
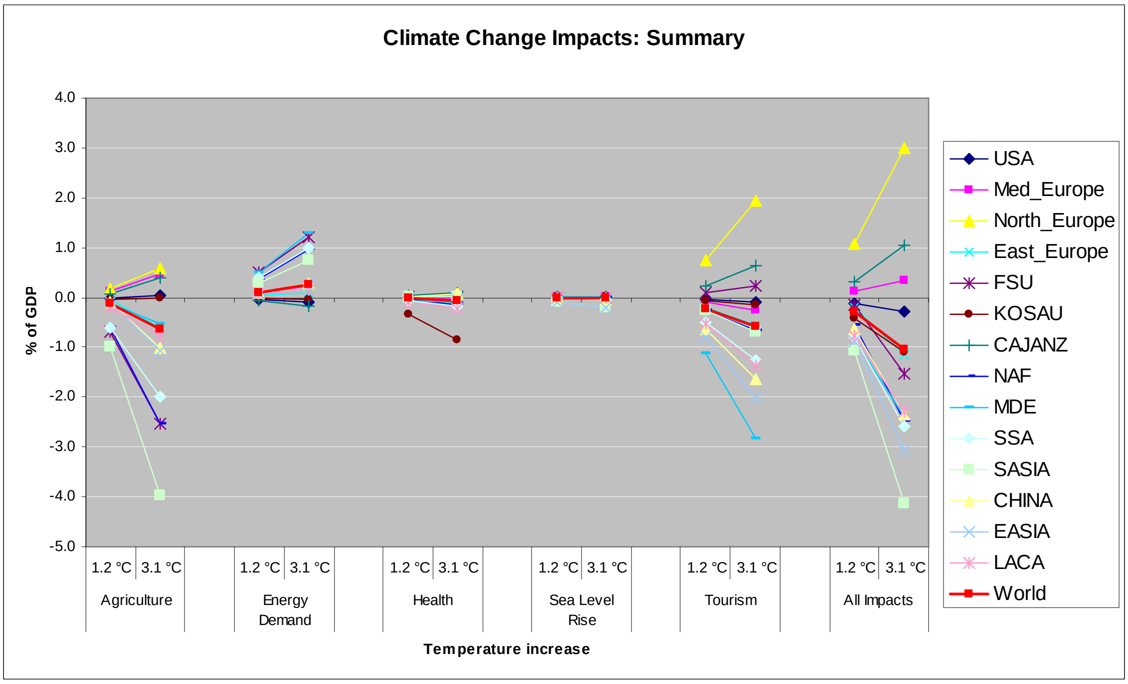


Figure 17. Final climate change impact as percentage of regional 2050 Gross Domestic Product



Insert

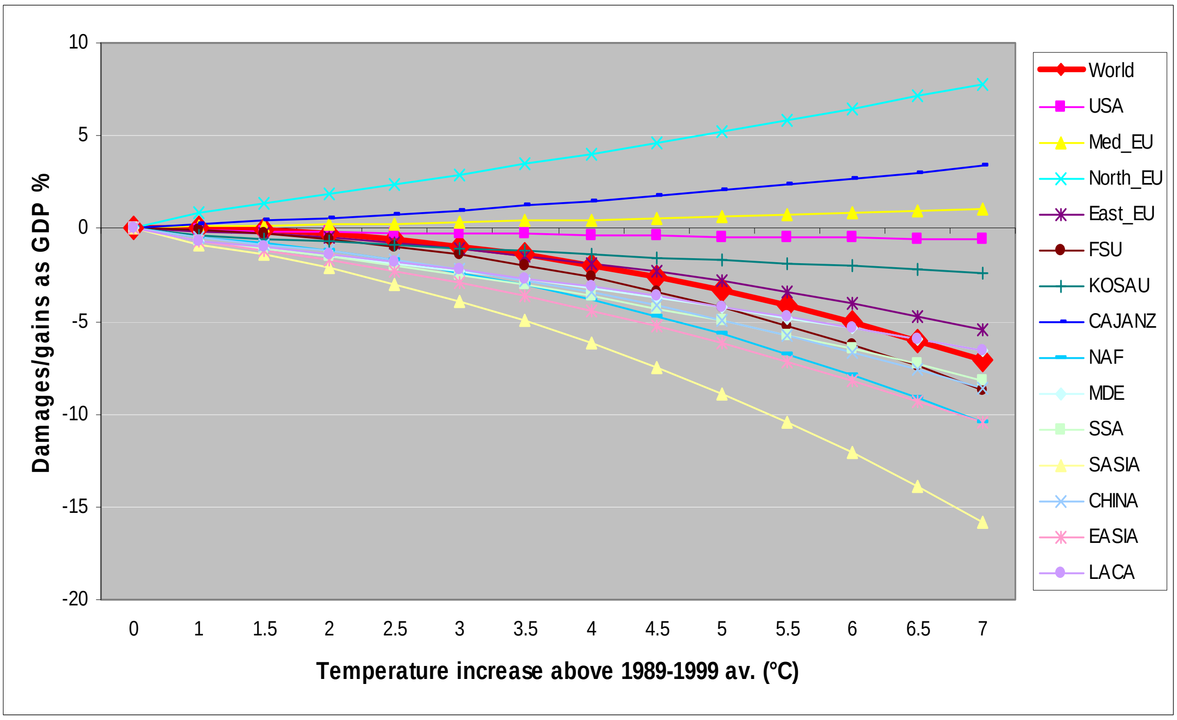
Figure 17 Here

Let us underline that the above results have been computed only for a subset of potential adverse effects of climate change (possible consequences of increased intensity and frequency of extreme weather events and of biodiversity losses for instance are not included). Irreversibilities or abrupt climate and catastrophic changes to which adaptation can be only limited are neglected. Then, the model assumes costless adjustments and no frictions. Finally, the world is currently on an emission path leading to higher temperature increases than the ones consistent with the A2 scenario. Hence, for these four reasons, our analysis is likely to yield a lower bound of climate change costs. It can be considered as optimistic and cautious at the same time. Nonetheless, the main conclusion can be phrased as follows.

Despite its impact smoothing potential, market-driven adaptation cannot be the solution to the climate change problem. The distributional and scale implications of climate related economic impacts need to be addressed by adequate policy-driven mitigation and adaptation strategies.

Our study of market-driven adaptation enabled us to re-compute the damage functions for the different regions modelled in WITCH. We have been able to compute the residual damage after market-driven adaptation has displayed its effects and a new equilibrium has been reached in the economic systems. Figure 18 reports our new estimates of world and regional climate damage functions. These new damage functions can be used to re-compute the benefit-cost ratios of different policy-driven adaptation and mitigation strategies.

Fig. 18. Economic cost of climate change including market-driven adaptation



Re-examining policy-driven adaptation: The effects of including market-adjustments

In this last section, previous results obtained with the AD-WITCH model are re-examined by accounting for the contribution of market-driven adaptation. To do so, firstly AD-WITCH climate damage function has been re-calibrated in order to replicate regionally damage patterns estimated by the ICES model. Then, optimal mitigation and adaptation strategies have been recomputed.

The first clear insight is that market driven adaptation has a strong damage smoothing potential at the global level (see Figure 19). This result hides some important distributional changes. Market-driven adaptation re-ranks winners and losers. In particular (see Figure 18 and 20), the main OECD countries are likely to gain from climate change, while all NON-OECD countries still loose (even though less than with previous estimates of climate damages). It also hides the fact that a positive effect can be the sum of positive and negative impacts. Accordingly the need to adapt can persist even in the presence of a net gain from climate change.

The policy implications are relevant. NON-OECD countries still face positive damages, but smaller than in the absence of market-driven adaptation, thus leading to lower adaptation spending also in these countries.

Accordingly, optimal mitigation and policy driven adaptation expenditures are smaller (see Figure 21). In particular, by the end of the century, adaptation expenditure is half of what it would have been in the absence of market-driven adaptation. Even though adaptation expenditure reaches anyway the remarkable amount of 1.5 US$ trillion. Almost all this expenditure is concentrated in developing countries.

Figure 19. Climate change damage with and without market driven adaptation

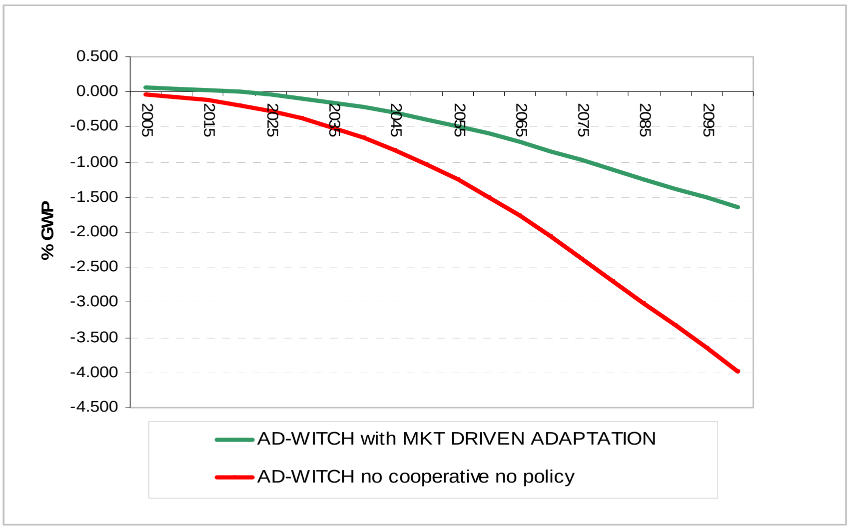


Figure 20. OECD and NON OECD climate change damage with and without market driven adaptation

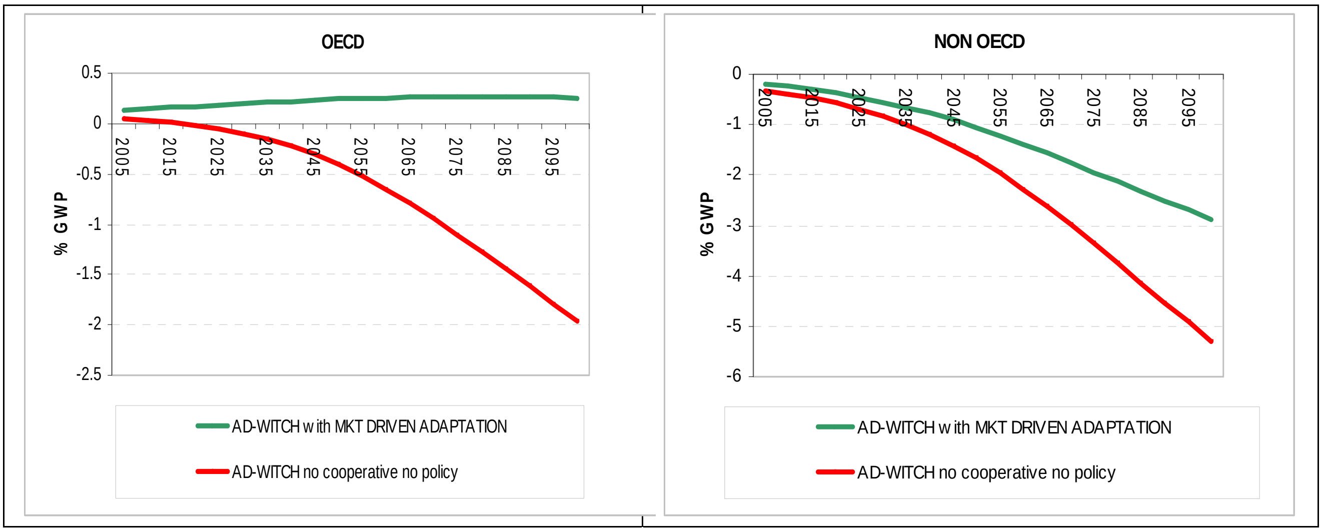
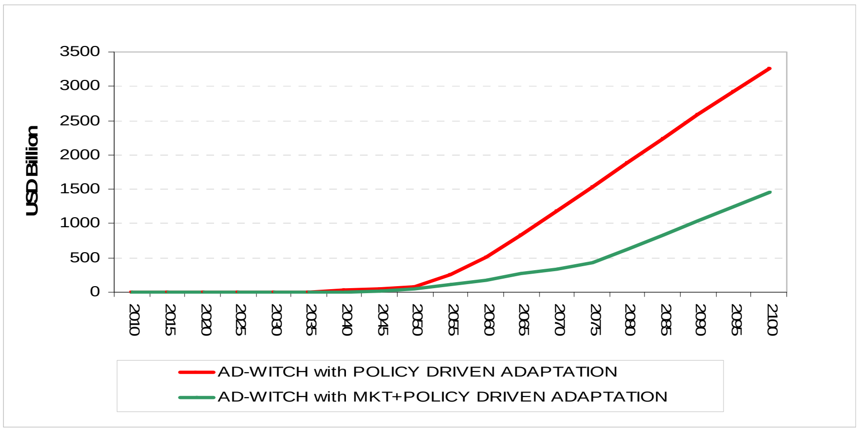


Figure 21: Total protection expenditure



As a consequence, benefit-cost ratios are slightly lower than in the absence of market-driven adaptation, both regionally and globally. The upper part of Table 18 shows global and regional benefit-cost ratios of adaptation, in comparison with those obtained without accounting for market-driven adaptation (lower part). The largest difference can be seen in OECD regions, where aggregate regional damages have turned positive (overall they have a benefit, see Figure 20). Only few OECD regions still face negative damages, and therefore find it optimal to spend resources on adaptation. Benefit-cost ratios are lower also in developing regions (NON-OECD), reflecting the fact that market-driven adaptation can reduce overall climate change impacts.

Table 18: Benefit-Cost Ratio (BCR) of policy driven adaptation in the presence of market driven adaptation

	with Market-driven adaptation		
Discounted values over the period 2010-2105	WORLD	OECD	NON OECD
Benefits	5282	202	5079
Costs	3123	164	2959
BCR	**1.69**	**1.24**	**1.72**
	w/o Market-driven adaptation		
Discounted values over the period 2010-2105	WORLD	OECD	NON OECD
Benefits	14	2250	11535
Costs	8	1550	6434
BCR	**1.73**	**1.45**	**1.79**

Specific adaptation strategies: insights from the existing literature

Two are the main policy implications that emerge from the analysis carried out in the previous sections of this report. First of all, the optimal response to climate change entails both mitigation and adaptation measures. Second, the adaptation mix consists of different strategies and such mix is region specific. In OECD countries most resources are devoted to anticipatory adaptation, whereas NON-OECD countries spend more in reactive adaptation.

As for specific adaptation measures, priority should be given to those measures offering no regret opportunities, i.e. benefits higher than the costs irrespectively of the adaptation (damage reducing) potential. Some of these measures are already well identified, e.g. better insulation of old buildings, improved insulation standards for new building, and more efficient air conditioning systems (McKinsey 2009).

These measures offer three advantages: they improve adaptation to warmer climates of urban areas, they create important energy savings opportunities which on their own can motivate their adoption, they finally entail carbon emission reductions. Indeed, they are primarily considered mitigation strategies. It would thus be wise to use scarce resources to foster the adoption of these measures first.

The composition of the optimal adaptation mix is related essentially to the regional and sectoral vulnerability, as different types of climate change impacts call for specific interventions. Moreover, whereas some adjustments can take place autonomously through markets, other responses require interventions by policy makers.

In developed countries, the higher share of climate change damages seems to be related to extreme and catastrophic events. Damages from sea level rise as well pose a risk on high income countries. Accordingly, resources can be conveniently used to improve the extreme-climate resilience of infrastructures - from settlements to transportation routes - but also to mainstream climate change adaptation into long-term spatial/landscape planning to reduce from scratch the probability of experiencing extreme losses from hydro geological risk respect to which, by definition, adaptation can only be partial. A net of accurate and efficient early warning systems seems to provide a particularly high benefit cost ratio. These forms of adaptation can be classified as anticipatory, as they are to be put in place before the occurrence of the damage.

The World Bank (2006) quantifies the costs of adapting vulnerable infrastructures to the impacts of climate change as a 5- 20 percent increase in investments in 2030, which is reported to amounting at 10 - 100 billions of 2000 US$. According to the Association of British Insurers, in the UK, accounting for climate change in flood management policies, and including developments in floodplains and increasing investments in flood defences, could limit the rising costs of flood damage to a possible four-fold increase (to 9.7 US$ billion) rather than 10 – 20 fold by the 2080s. If all properties in south Florida met the stronger building code requirements of some counties, property damages from another Hurricane Andrew (taking the same track in 2002 as it did in 1992) would drop by nearly 45 percent (ABI 2005).

These adaptation responses include better flood protection, stronger land-use planning, and catchment-wide flood storage schemes. A specific study on costs of flooding for the new developments in East London showed that pro-active steps to prepare for climate change could reduce annual flooding costs by 80 –90 percent, saving almost 1 US$ billion.

The major forms of adaptation to sea level rise are protect, accommodate, or retreat. Nicholls and Klein (2003) noted that the benefits of adaptation to sea level rise far outweigh the costs, though it is to not clear up to which sea level rise human being can adapt. Total costs including investment costs (beach nourishment and sea dykes) and losses (inundation and flooding) are estimated to be US$ 21 – 22 billion in 2030 (UNFCCC, 2007). Building sea dike coast is the most expensive option (8 US$ billion). However, costs in isolation are not very informative and what is to be considered is the benefit cost ratio.

According to Nicholls and Klein (2003), the costs of coastal protection are justified in most European countries. The avoided damage without protection, at least in the case of the Netherlands, Germany and Poland, would amount to the 69%, 30% and 24% of GDP respectively. These benefits largely offset the costs even in the case of highest protection costs. Although average estimates report costs below 1 percent of GDP (McCarty *et al.* 2001; Bosello *et al.* 2006), Nicholls and Klein (2003) found much higher costs, about 14% of GDP, which still remain low relative to the potential benefits. Smith and Lazo (2001) report benefit-cost ratios[20] for the protection of the entire coastlines of Poland and Uruguay, the Estonian cities of Tallin and Pärnu, and the Zhujian Delta in China. They are in the range of 2.6 to around 20 for a sea level rise of 0.3 – 1 m.

Developing countries are also highly vulnerable to sea level rise, especially densely populated deltas in the South, Southeast , and East Asia. Although absolute impacts are small at a global scale, in relative terms impacts are the highest (Nicholls 2004, Nicholls and Tol 2006)

In developing countries, in addition to catastrophic events, high losses and thus adaptation needs are associated to adverse impacts on agricultural activity and, particularly in Sub-Saharan Africa, on health. Assessing cost benefits of health care policies is always difficult, but these are associated to relatively low cost-benefit ratios as well.

---

[20] They represent the ratio between the monetized avoided damage and the cost of the intervention.

Many studies describe the possible adaptation strategies that can be implemented by health sectors in developed and developing countries (see e.g. Kirch *et al.* 2005; Bettina and Ebi 2006). Nevertheless, very few researches try a quantitative cost assessment of these measures. The problem here is twofold: firstly, there is a general lack of information concerning the potential costs of some interventions. Secondly, it is very difficult conceptually and practically to disentangle the costs of adaptation to changes in health status induced by climate change from those related to change in health status per se.

Agrawala and Fankhauser (2008) reports just one study (see Ebi 2008), providing direct adaptation costs for the treatment of additional number of cases of diarrhoeal diseases, malnutrition and malaria related to climate change. The additional cost for the world as a whole ranges between 4 and 12.6 US$ billion by 2030 while the World Bank (2010) estimated USD 2 billion per year between 2010 and 2050.. In the year 2000, the additional mortality attributable to climate change was estimated to be 154,000 deaths (0.3%), with a burden of 5.5 million (0.4%) DALYs.[21] According to the World Health Organization (WHO), in developing countries the most sensitive diseases to climate change are malnutrition, diarrhoeal disease and malaria. Assuming GHG stabilization at 750 ppm CO2 by 2200, Ebi (2008) estimates an increase in incidence of diarrhoeal disease, malnutrition and malaria due climate change in 2030, respectively of 3%, 10% and 5%. Almost all the malnutrition and malaria cases would be in developing countries, with 1-5% of the diarrhoeal disease affecting developed countries (UNFCC 2007).

According to the analysis brought about by Ebi (2008), the adaptation response corresponds to an increase of both preventive (anticipatory adaptation) and therapy costs (reactive adaptation). In the 750 ppm scenario, the projected climate change driven expenditure in 2030 would be 2-7 billion US$ for diarrhoeal disease, 81-108 million US$ for malnutrition and 2-5.5 billion US$ for malaria.

Tables 19-21 rank alternative adaptation strategies in the health sector according to the cost effectiveness criterion. It is worth noting that several strategies are considered even though are not strictly referred to the health sector. This is because, despite their lower cost-effectiveness, they may have advantages also in the health sector. For example, in the case of diarrhoeal disease, within the improvement of water and sanitation facilities there exist interventions like the installation of hand pumps, corresponding to US$ 94 per DALY averted, and the provision and promotion of basic

---

[21] The WHO define DALY (Disability-Adjusted Life Year) as: "a measure of overall disease burden. One DALY can be thought of as one lost year of "healthy" life. DALYs for a disease or health condition are calculated as the sum of the Years of Life Lost (YLL) due to premature mortality in the population and the Years Lost due to Disability (YLD) for incident cases of the health condition. The YLL basically correspond to the number of deaths multiplied by the standard life expectancy at the age at which death occurs. To estimate YLD for a particular cause in a particular time period, the number of incident cases in that period is multiplied by the average duration of the disease and a weight factor that reflects the severity of the disease on a scale from 0 (perfect health) to 1 (dead). (http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/index.html).

sanitation facilities, corresponding to US$ 270 per DALY averted, that are cost-effective (Jamison *et al.* 2006). Therefore, these may be considered no regret options, increasing development and health benefits at the society level also in the absence of climate change.

Table 19: Most cost/effective strategies against diarrhoeal disease

Strategies	Cost/effectiveness(US$ for DALY averted)
Breastfeeding promotion	527-2,001
Measles immunization	257-4,565
Oral Rehydratation Therapy	132- 2,570
Water and sanitation in rural areas	1,974

Source: Jamison *et al.* (2006)

Table 20: Most cost/effective strategies against malaria in Sub-Saharan Africa

Strategies	Cost/effectiveness($ for DALY averted)
Preventive treatment in pregnancy with newer drugs	2-11
Insecticide-treated bed nets	5-17
Residual household spraying	9-24
Preventive treatment in pregnancy with sulfa drugs	13-24

Source: Jamison *et al.* (2006)

Table 21: Most cost/effective strategies against malnutrition

Strategies	Cost/effectiveness($ for DALY averted)
Breastfeeding support programs	3-11
Growth monitoring and counseling	8-11
Capsule distribution	6-12
Sugar fortification	33-35

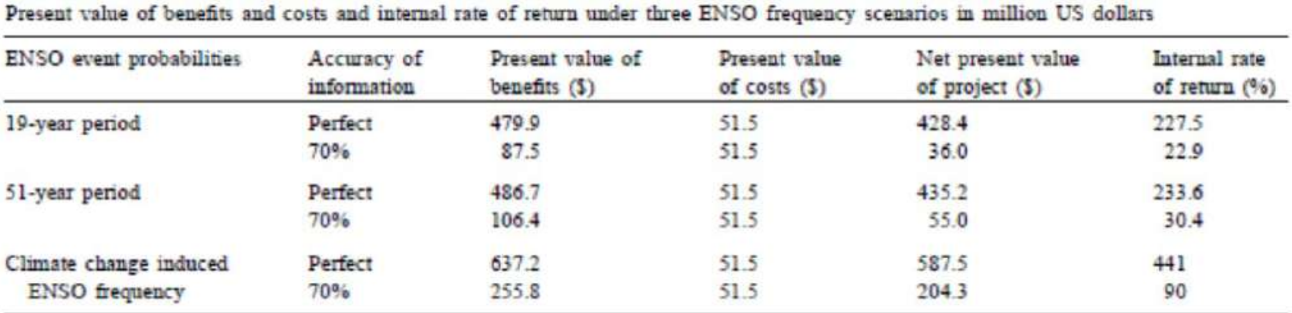
Source: Jamison *et al.* (2006)

Agriculture is another sector particularly vulnerable in developing countries. In the literature on adaptation, what is almost missing is the quantification of the costs of adaptation in agriculture (EEA 2007; Agrawala and Fankhauser 2008). This is mostly due to the fact that a large part of agricultural adaptation practices are implemented at the farm level and are decided autonomously by the farmers without the direct intervention of public agencies suggesting long term planning or investment activities. Moreover, it has to be considered that not only supply-side factors influence farmers' choices, but also demand-side considerations, on their turn dependent on the macroeconomic context, demand and prices, often set at the international level.

Typical examples of these practices are seasonal adjustments in the crop mix or timing, which in the literature are assumed to entail very low if not zero costs. Probably, the most significant cost component of climate change adaptation in agriculture is related to the improvement of irrigation, or water conservation systems. According to the OECD ENV-Linkage model, which simulates projections of the International Energy Agency World Energy Outlook (IEA WEO) scenario, the additional expenditure on adaptation to adverse impacts of climate change will be about 7 billions US$ in 2030; the highest share (about 5.8 billion US$) is estimated to be needed to purchase new capital, for example to improve irrigation system and adopt more efficient agricultural practices (UNFCCC 2007). As regarding the effectiveness of adaptation, Kirshen *et al.* (2006) reported broad ranges, depending on the type of measure adopted. Callaway *et al.* (2006), analyzing management adaptation costs for the Berg River in South Africa, has emphasized the role of water management system efficiency, which can increase the benefits of improved water storage capacity by 40 percent.

A case study on the Mexican agriculture suggests high benefit-cost ratios for proactive adaptation measures in the agricultural sector (Adams *et al.* 2000). This study assessed the effectiveness of establishing accurate early warning systems, capable of detecting enough in advance climate disturbances. Adams et al. (2000) found that the benefits of an ENSO early warning system for Mexico is approximately US$ 10 million annually, measured in terms of the saved cost for the agricultural sector that can plan in advance crop timing and mix. Figure 22 summarizes the present value of benefits and costs under different assumptions of information accuracy. Benefits, under different assumption of information accuracy far outweighs the costs, leading to an internal rate of return of at least 30 percent. Benefit-cost ratios are even higher for better level of accuracy.

Figure 22. Benefit and costs of early warning systems



Present value of benefits and costs and internal rate of return under three ENSO frequency scenarios in million US dollars

ENSO event probabilities	Accuracy of information	Present value of benefits ($)	Present value of costs ($)	Net present value of project ($)	Internal rate of return (%)
19-year period	Perfect	479.9	51.5	428.4	227.5
	70%	87.5	51.5	36.0	22.9
51-year period	Perfect	486.7	51.5	435.2	233.6
	70%	106.4	51.5	55.0	30.4
Climate change induced ENSO frequency	Perfect	637.2	51.5	587.5	441
	70%	255.8	51.5	204.3	90

The values reported here are converted from pesos to dollars using the 2001 conversion rate of approximately 9 Pesos to the US dollar.

Source: Adams et al. (2000)

The NAPA (National Adaptation Programmes of Action) Project Database contains a list of ranked priority adaptation activities and projects in 39 Least Developed Countries (LDCs). Projects on agriculture and food security have the highest priority for one third of LDCs. The main adaptation activities in this sector are the introduction of drought-prone tolerant or rainfall resilient crops.

Another important area of intervention is Research and Development both in agriculture and health. Innovation is needed to develop climate-ready crops (heat-tolerant, drought-escaping, water proof crops) and to advance tropical medicine. This type of adaptation strategy requires some kind of North-South cooperation, because those who need these interventions lack the financial and technical resources to implement them. UNFCCC (2007) reported an additional expenditure on agriculture related R&D of about 3 US$ billion out of the 14 billion required to cope with climate change in agriculture in 2030. The case of innovation exemplifies how market-driven adaptation can accommodate damages only partly, and how policy-driven adaptation is needed to complement other forms of adjustments.

Conclusions and Policy Implications

Climate policy is a complex process. Many economic, environmental and social dimensions are strictly interrelated. The focus on mitigation efforts seems outdated. Recent international negotiations and the ongoing policy decisions give increasingly more emphasis to adaptation to climate change. It becomes then necessary to provide policy makers and governments with some indications on how to allocate climate related funding wisely and efficiently between the alternatives available to cope with present and expected climate change impacts.

In particular, it becomes relevant to understand to what extent market-driven adaptation can reduce climate change damages. Should short-run funds go to mitigation policies? Or should we postpone action by focussing more on policy-driven adaptation? Is there an optimal level of adaptation and mitigation? Let us summarise the main conclusions contained in this study.

First, markets cannot deal with all climate damages. Even under the optimist assumptions of this report, market driven adaptation can attenuate the total damage from climate change, but not fully eliminate it. The global, direct impacts of climate change would lead to a loss of about 1.55 percent of the Gross World Product in 2050. Market-driven adaptation reduces this loss to 1.1 percent of GWP. However, although market-driven adaptation has a strong damage smoothing potential, still global damage remain significant, especially in some less developed countries. The challenge for adaptation, therefore, lies in tackling climate change impacts in developing countries. Here, policy interventions are needed, beyond what market-driven adaptation can deliver.

Second, under a social optimum perspective (global cooperation to internalize the social cost of climate change), the optimal strategy to deal with climate change includes both adaptation and mitigation measures. Mitigation is always needed to avoid irreversible and potentially unmanageable consequences, whereas adaptation is necessary to address unavoidable climate change damages. The optimal mix of these two strategies has been shown to be welfare improving. At the global level, their joint implementation increases the benefit-cost ratio of each of them.

Third, there is a trade-off between mitigation and adaptation. The use of mitigation (adaptation) decreases the need to adapt (mitigate). In addition, resources are scarce. If some resources are used for mitigation (adaptation), fewer are available for adaptation (mitigation). Nonetheless, in the optimal policy mix, the possibility to abate never eliminates the need to adapt and vice versa.

Fourth, in terms of timing, mitigation, if needed, should be carried out earlier, because of its delayed effects driven by environmental inertia, while adaptation can be postponed until damages are effectively higher. Were damages considerable in earlier period, also adaptation would be carried out earlier.

Fifth, both higher damages and lower discount rates foster mitigation and adaptation efforts. However, in the first case, adaptation expenditures increase more than mitigation ones, while in the second case mitigation becomes relatively more important. The intuition goes as follows. If present and future damages increase uniformly, adaptation, which deals effectively with both, is to be preferred. If future damages increase relatively more (because of a lower discounting), mitigation, which is more effective on the distant future, is to be preferred.

Sixth, OECD countries should invest heavily in anticipatory adaptation measures. This depends on their damage structure. Planned anticipatory adaptation is particularly suited to cope with sea-level rise, but also with hydro geological risks induced by more frequent and intense extreme events, which are a major source of negative impacts in the developed economies. Thus, in OECD countries it would be more convenient to act ex ante rather than ex post.

In NON-OECD countries, climate change adaptation needs are estimated to be relatively low in the short run, 30 USD Billion at most in 2030[22]. However, they will rise dramatically as the economic impacts of climate change increase over time. In 2050, they will amount to 78 US$ Billion, in 2065 they will be above 500 US$ billion, to peak to more than 2 US$ trillion by the end of the century. NON-OECD countries are unlikely to have the resources to meet their adaptation needs, which call

---

[22] This are the estimated adaptation costs under the case of high damage and low discount rate.

for international aid and cooperation on adaptation and adaptation planning. In light of the current development deficit of developing countries, these resources are to be considered additional to development aids required to fill this gap. They can also offer an additional opportunity to foster development itself when they take the form of educational programmes, easier access to bank credit for dedicated project etc.

NON-OECD countries place little effort on adaptation R&D and rely primarily on reactive adaptation. This outcome however depends on the particular structure of NON-OECD economic systems. Being poor, other forms of adaptation expenditures, more rapidly effective, mainly of the reactive type, are to be preferred. This suggests that richer countries can help developing countries also by supporting their adaptation R&D (e.g. by technology transfers). The success of this policy is crucially dependent on the design of the technology transfer program that must take into account developing country absorptive capacity.

As shown by our sensitivity analysis, these results are robust to different model specifications and parameterizations.

There is a final important issue to be emphasised. We have shown that both mitigation and adaptation belong to the optimal policy mix to deal with climate change, even though with different timing (mitigation comes first) and different distribution across world regions (more mitigation in developed countries, more adaptation in developing countries). In this policy mix, the optimal balance between adaptation and mitigation depends on the discount rate and the level of damages. This is clearly shown by Table 22. With low discounting, a larger share of damage reduction is achieved with mitigation. With high damage, a larger share of damage reduction is achieved with adaptation.

Table 22. Share of damage reduction in the optimal policy mix

	TOTAL DAMAGE REDUCTION (Undiscounted cumulative sum 2010-2100)	ADAPTATION	MITIGATION
LDAM_HDR	44%	77%	23%
HDAM_LDR	73%	41%	59%
LDAM_LDR	60%	33%	67%
HDAM_HDR	62%	85%	15%

What are the environmental implications of the optimal policy mix? Figure 23 shows the global average temperature increase above pre-industrial level, ranging between 2.5 and 3 degrees Celsius.

Figure 23. Temperature change in the four scenarios

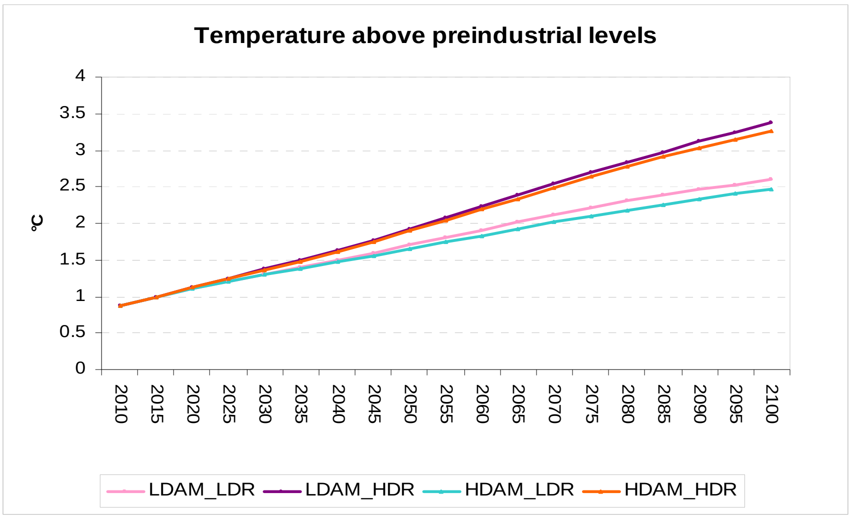
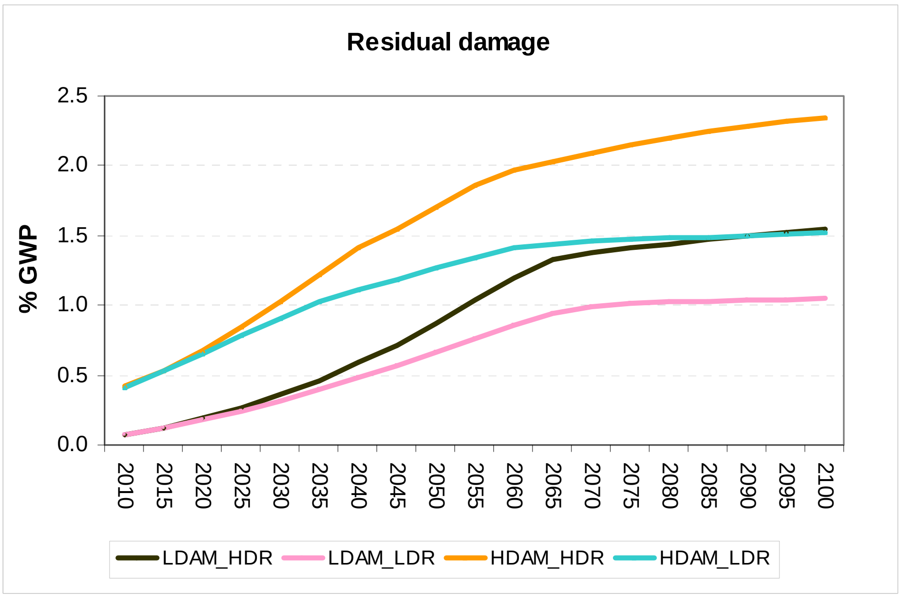


Figure 24 shows the significant effectiveness of adaptation at reducing residual damages, which are between 1 and 2 percent of Gross World Product ((Figure 24).

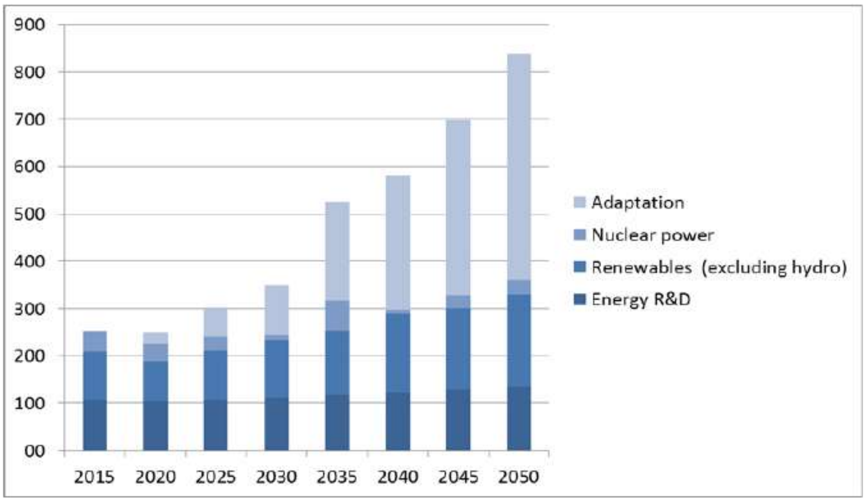
Figure 24. Residual damages from climate change in the four scenarios



What are then the implications for climate finance? Our analysis suggest that the optimal strategy is to undertake mitigation first to control future most dangerous damages from climate change, i.e. to stabilize them to the level that future damages can be dealt with through adaptation. Then, adaptation, if well-prepared in advance, will protect our socio-economic systems from climate change. In terms of climate funds allocation this implies that funding mitigation is more urgently needed than adaptation and fast-start investments should address mitigation, even though mitigation targets should not be too ambitious. It is important to stress that achieving less ambitious stabilisation targets will still require important financial resources. Bastianin, Favero and Massetti (2009) estimate that changing the energy infrastructure to manage a 550CO2-eq stabilisation target requires US$ 600 Billion of energy investments in 2030.

Figure 25 shows the differential in climate investments between the two extreme cases shown in Figure 23, HDAM_LDR and LDAM_HDR. It highlights that in order to reduce global average warming by 1 degree Celsius, investments in energy R&D, renewables, and nuclear power need to be scaled up by at least 200 USD billion between 2015 and 2030. In contrast, adaptation expenditure would be negligible until 2020, but become substantial after 2030.

Figure 25: Global investments in mitigation and adaptation (USD Billions). Additional spending in the HDAM_LDR case compared to the LDAM_HDR case



Short-term international cooperation on adaptation should mostly address soft adaptation measures including infrastructure development and some degree of cooperation on adaptation R&D. This is in line with what Fankhauser and Burton (2010) argue would be a good way to use money for adaptation. They advice financing soft, or less tangible, development activities that increase overall adaptive capacity.

To conclude, it is worth stressing again the important qualifications of our findings. First, the damage function used in AD-WITCH is highly stylized. The aggregation of different damage categories hides the existence of hot spots at the sectoral level, with the risk of underestimating adaptation needs. Second, this study only partially considers non-market impacts. Third, this study refers to a smooth world. It neither considers irreversibility and tipping points nor extreme temperature scenarios. Fourth, a perfect information world in which uncertainty does not play a role is assumed. These introduces another downward bias to mitigation needs and adaptation anticipatory strategies, which are mainly driven by precautionary motives.

References

Association of British Insurers 2005. *Financial Risk of Climate Change*. Summary Report

Adams, R. M., L.L. Houston and B. A. McCarl 2000. The benefits to Mexican agriculture of an El Niño-southern oscillation (ENSO) early warning system, *Agricultural and Forest Meteorology* 115: 183–194

Adger, N.W., Arnell, N.W. and E.L. Thompkins 2005. Successful adaptation to climate change across scales, *Global Environmental Change* 15: 77-86

Agrawala, S. and S. Fankhauser, (eds.) 2008. *Economics aspects of adaptation to climate change. Costs, benefits and policy instrument*. OECD

Agrawala, S., Bosello F., C. Carraro , E. De Cian, E. Lanzi, K. De Bruin and R. Dellink 2011. PLAN or REACT? Analisys of adaptation costs and benefits Using Integrated Assessment Models, *Climate Change Economics,* Vol.2 (3), 1-36.

Agrawala,S. F. Bosello, C. Carraro, E. De Cian and Elisa Lanzi 2011a. Adapting to Climate Change: Costs, Benefits, and Modelling Approaches", *International Review of Environmental and Resource Economics,* Vol.5: No.3, pp 245-284.

Antweiler, W. 2011., Mitigation+adaptation, What is the optimal climate change policy mix?, University of British Columbia, available at: http://ssrn.com/abstract=1802857

Bahn, O., M. Chesney, and J. Gheyssens. 2010. The Effect of Adaptation Measures on the Adoption of Clean Technologies." Paper presented at the WCERE Congress, Montr´eal, 2010. Viewed on December 22, 2010

Barrett, S. 2008. A Portfolio System of Climate Treaties, Discussion Paper 08-13. The Harvard Project on International Climate Change Agreements

Bastianin, A., A. Favero and E. Massetti 2009. Investments and Financial Flows Induced by Climate Mitigation Policies, FEEM Working Paper No. 0913.

Bettina, M. and Ebi, Kristie L. (eds.) 2006. *Climate change and adaptation strategies for human health*. Steinkopff Verlag.

Bosello, F., Roson, R. and R.S.J. Tol 2006. Economy Wide Estimates of the Implication of Climate Change: Human Health, *Ecological Economics* 58: 579-591.

Bosello, F., Roson, R. and R.S.J. Tol 2006. Economy Wide Estimates of the Implication of Climate Change: Human Health, *Ecological Economics* 58: 579-591.

Bosello, F., De Cian, E., Eboli, F. and R. Parrado (2009), Macro-economic assessment of climate change impacts: a regional and sectoral perspective, in: Impacts of Climate Change and Biodiversity Effects, final report of the CLIBIO project, European Investment Bank, University Research Sponsorship Programme.

Bosello, F. 2010. Adaptation, Mitigation and Green R&D to Combat Global Climate Change. Insights From an Empirical Integrated Assessment Exercise, FEEM Working Paper No. 22

Bosello, F., C. Carraro, and E. De Cian 2010. Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage, *Climate Change Economics,* 1: 71–92.

Bosello F., C. Carraro and E. De Cian 2011. Adaptation Can Help Mitigation: An Integrated Approach to Post-2012 Climate Policy, *FEEM Working Paper* No. 1169.

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni 2006. WITCH: A World Induced Technical Change Hybrid Model, *The Energy Journal. Special Issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down* 13-38

Bosetti, V. E. Massetti, M. Tavoni 2007. The WITCH Model. Structure, Baseline, Solutions, FEEM Working Paper 10-2007

Bosetti, V., C. Carraro, R. Duval, A. Sgobbi and M. Tavoni 2009. The Role of R&D and Technology Diffusion in Climate Change Mitigation: New Perspectives using the WITCH Model, *OECD Working Paper* No. 664

Bosetti, V., Carraro, C., De Cian, E., Duval, R. Massetti, E. and Tavoni, M. (2009). The incentives to participate in and the stability of international climate coalitions: a game-theoretic approach using the WITCH Model, *OECD Working Paper* No. 702

Boutkan, E. and A. Stikker 2004. Enhanced water resource base for sustainable integrated water resource management, *Natural Resources Forum,* 28: 150-15.

Bréchet, T., N. Hritonenko and Y. Yatsenko, 2010. Adaptation and Mitigation in Long-Term Climate Policies. Core Discussion Paper No. 2010.65, Oct 2010.

Buonanno, P., Carraro, C., Castelnuovo, E. and M. Galeotti 2000. Efficiency and Equity of Emission Trading with Endogenous Environmental Technical Change, in Carraro C. (ed.), *Efficiency and Equity of Climate Change Policy*, Dordrecht: Kluwer Academic Publishers.

Buob S. and G. Stephan 2008. Global climate change and the funding of adaptation, Bern University Discussion Papers, 08-04.

Buob S. and G. Stephan (2011). To mitigate or to adapt: How to confront global climate change. *European Journal of Political Economy*, 27: 1-16.

Burton, I. 1992. *Adapt and Thrive*. Unpublished manuscript, Downsview, Canadian Climate Centre

Butt T.A., McCarl B.A. 2004. Farm and forest carbon sequestration: Can producers employ it to make some money?, *Choices* 19: 3-11

Buchner, B., A. Falconer, M. Hervé-Mignucci, C. Trabacchi, M. Brinkman 2011. The Landscape of Climate Finance. *CPI Report*, Venice.

Fankhauser, S. and I. Burton 2010. Spending Adaptation Money Wisely Grantham Research Institute on Climate Change and the Environment Working Paper No. 37, Dec 2010.

Caparrós, A. y Jacquemont, F. 2003. Conflicts between biodiversity and carbon offset programs: economic and legal implications, *Ecological Economics* 46: 143-157

Carraro, C. and D. Siniscalco 1998. International Environmental Agreements: Incentives and Political Economy, *European Economic Review* 42: 561-572

Callaway, J.M., D.B. Louw, J.C. Nkomo, E. M. Hellmuth and D. A. Sparks 2006. The Berg River Dynamic Spatial Equilibrium Model: A New Tool for Assessing the Benefits and Costs of Alternatives for

Coping With Water Demand Growth, Climate Variability, and Climate Change in the Western Cape, AIACC Working Paper 31, The AIACC Project Office, International START Secretariat, Washington, DC, p. 41, available on line at www.aiaccproject.org

Dang, H.H., Michaelowa, A. and Tuan, D.D. 2003. Synergy of Adaptation and Mitigation Strategies in the Context of Sustainable Development: The case of Vietnam, *Climate Policy* 3: S81-S96.

Darwin, R. and R.S.J. Tol 2001. Estimates of The Economic Effects of Sea Level Rise, *Environmental and Resource Economics* 19: 113-129

de Bruin K.C., Dellink, R.B. and R.S.J. Tol 2009a. AD-DICE: An Implementation of Adaptation in the DICE Model, *Climatic Change*, Vol. 95: 63-81

de Bruin K.C., Dellink, R.B. and S. Agrawala 2009b. Economic aspects of adaptation to climate change: integrated assessment modelling of adaptation costs and benefits, *OECD Working Paper*, No. 6

Deke, O., Hooss, K. G., Kasten, C., Klepper, G., and Springer, K. 2001. Economic Impact of Climate Change: Simulations with a Regionalized Climate-Economy Model, Kiel Working Paper No. 1065

Ebi, K.L. 2008. Adaptation costs for climate change cases of diarrhoeal disease, malnutrition and malaria in 2030, *Globalization and health 2008* 4(9)

EIA 2008. *Annual Energy Outlook. Energy Information Administration*, Washington, DC.

European Environment Agency (EEA) 2005. Vulnerability and adaptation to climate change in Europe, EEA Technical Report No. 7/2005

European Environment Agency (EEA) 2007. Climate Change: The Cost of Inaction and the Cost of Adaptation, EEA Technical Report, No. 13/2007

European Commission 2005. *Winning the Battle Against Global Climate Change*, COM/2005/0035

European Commission 2007. *Limiting global climate change to 2 degrees Celsius - The way ahead for 2020 and beyond*, COM2007/0002

European Commission 2007a. *Green Paper from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions*, COM2007/0354

European Commission 2009. *White paper - Adapting to climate change : towards a* European framework for action, COM/2009/0147.

European Commission 2011. *Energy Roadmap*, COM(2011) 885/2

EEA (2010) "Adapting to Climate Change - SOER 2010 Thematic Assessment." European Environmental Agency, Nov 2010. [18.7 M]

Fankhauser, S. and I. Burton (2010). "Spending Adaptation Money Wisely." Grantham Research Institute on Climate Change and the Environment Working Paper No. 37, Dec 2010.

Fankhasuer, S. and R.S.J. Tol (1996). The Social Costs of Climate Change, the IPCC Assessment Report and Beyond, Mitigation and Adaptation Strategies for Global Change, Vol. 1, No. 4, pp 386-403

Fankhauser, S., Smith, J.B., and Tol, R.S.J. 1999. Weathering Climate Change: Some Simple Rules to Guide Adaptation Decisions, *Ecological Economics* 30: 67-78

Farrell A.E. and Brandt, A.R.(2005). Risks of the oil transition, Environmental Research Letters, Vol. 1, No. 1

Fisher-Vanden, K., I. Sue Wing, E. Lanzi and D.C. Popp (2011). Modeling Climate Change Adaptation: Challenges, Recent Developments and Future Directions. Available at http://people.bu.edu/isw/

Füssel H.M. and Klein R.J.T. 2006. Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking, *Climatic Change* 75: 301-329

Hanemann,W.M. 2008. What is the Cost of Climate Change?, CUDARE Working Paper No. 1027, University of California, Berkeley

Hof AF, de Bruin KC, Dellink RB, den Elzen MGJ, van Vuuren DP 2009. The effect of different mitigation strategies on international financing of adaptation, *Environmental Science and Policy* 12: 832–843

Hof AF, den Elzen MGJ, van Vuuren DP 2010. Including adaptation costs and climate change damages in evaluating post-2012 burden-sharing regimes, *Mitigation and Adaptation Strategies Global Change* 15:19–40

Hope, C. 2003. The marginal impacts of CO2, CH4 and SF6 emissions, Judge Institute of Management Research Paper No.2003/10, Cambridge, UK, University of Cambridge, Judge Institute of Management

Hope, C., Anderson, J. and P. Wenman 1993. Policy Analysis of the Greenhouse effect: an Application of the PAGE model, *Energy Policy* 21: 327-338

Hope, C. and Newbery, D. 2007. Calculating the social cost of carbon, Electricity Policy Research Group Working Papers, No. EPRG 07/20, Cambridge, UK, University of Cambridge

Huq, S., A. Rahman, M. Konate, Y. Sokona and H. Reid 2003. Mainstreaming Adaptation to Climate Change in Least Developed Countries (LDCs), IIED, London

IEA 2007. *World Energy Outlook 2007.* OECD/IEA

Ingham, A., Ma, J. and Ulph A.M. 2005. Can Adaptation and Mitigation be Complements?, Working Paper 79, Tyndall Centre for Climate Change Research, University of East Anglia

Ingham, A., Ma, J. and Ulph A.M. 2007. Climate Change, Mitigation and Adaptation with Uncertainty and Learning, *Energy Policy* 35 (11): 5354-5369

Jamison, D.T, J. G. Breman, A. R. Measham, G. Alleyne, M. Claeson, D. B. Evans, P. Jha, A.Mills and P.Musgrove (eds.) 2006. *Disease Control Priorities in Developing Countries.* World Bank, Washington, DC

Kane, S. and G. Yohe 2000. Societal adaptation to climate variability and change: an introduction, *Climatic Change* 45: 1-4

Kane, S. and J. Shogren 2000. Linking Adaptation and Mitigation in Climate Change Policy, *Climatic Change* 45: 75-102

Kirch, W., Menne, B. and Bertollini, R. (eds.) 2005. *Extreme Weather Events and Public Health Responses*. Springer Verlagh

Kirshen P, Ruth M and Anderson W. 2006. Climate's long-term impacts on urban infrastructures and services: the case of metro Boston, in Ruth, M. (ed.) *Regional Climate Change and Variability: Local Impacts and Responses*. Cheltenham, UK: Edward Elgar Publishers

Kirshen 2007. *Adaptation Options and Coast of Water Supply*. Tuft University, MA

Klein, R.J.T., S. Huq, F. Denton, T.E. Downing, R.G. Richels, J.B. Robinson, F.L. Toth, 2007. Inter-relationships between adaptation and mitigation. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 745-777

Klein, R.J.T., Schipper E.L. and Dessai, S. 2003. Integrating Mitigation and Adaptation into Climate and Development Policy: Three Research Questions, Working Paper 40, Tyndall Centre for Climate Change Research

Klein, R.J.T., Tol, R.S.J. 1997. Adaptation to Climate Change: Options and Technologies—An Overview Paper. Technical paper FCCC/TP/1997/3, United Nations Framework Convention on Climate Change Secretariat, Bonn, Germany

Kouvaritakis, N., A. Soria and S. Isoard (2000). Endogenous Learning in World Post-Kyoto Scenarios: Application of the POLES Model under Adaptive Expectations, International Journal of Global Energy Issues Vol. 14, No. 1-4, pp 228-248.

Kurukulasuriya P. and R. Mendelsohn 2008. How Will Climate Change Shift Agro-Ecological Zones and Impact African Agriculture? Policy Research Working Paper WPS4717, The World Bank

Kypreos, S. 2007. A MERGE model with endogenous technical change and the cost of carbon stabilization, *Energy Policy* 35: 5327-5336

Palutikof, P.J. van der Linden and C.E. Hanson (eds.) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp- 745-777

Leary, N.A. 1999. A Framework for Benefit-Cost Analysis of Adaptation to Climate Change and Climate Variability, *Mitigation and Adaptation Strategies for Global Change* 4: 307-318

Lecoq, F. and Z. Shalizi 2007. Balancing Expenditures on Mitigation and Adaptation to Climate Change: An Explorations of Issues Relevant for Developing Countries, World Bank Policy Research Working Paper 4299

Lim B. and E. Spanger-Siegfred (eds.) 2005. *Adaptation policy framework for climate change: Developing policies strategies and measures*. Cambridge University Press

McCarthy, J.J, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (eds.) 2001. *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press

McKibbin, W.J. and Wilcoxen P.J. 2004. Climate Policy and Uncertainty: The Roles of Adaptation Versus Mitigation, *Brookings Discussion papers in International Economics*, No 161

McKinsey&Company 2009. *Pathways to a Low-Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Curve*

Mendelsohn, R.O., W.N. Morrison, M.E. Schlesinger and N.G. Andronova (2000), Country-Specific Market Impacts of Climate Change, Climatic Change, Vol. 45, No. 3-4, pp 553-569

Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds.) 2007. *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press

Nemet, G. F. 2006. Beyond the learning curve: factors influencing cost reductions in photovoltaics, *Energy Policy* 34: 3218-3232

Nicholls, R. J. and R.J.T. Klein 2003. Climate change and coastal management on Europe's Coast, EVA Working Paper No.3

Nicholls, R.J. 2004. Coastal flooding and wetland loss in the 21st Century: changes under the SRES climate and socio-economic scenarios. *Global Environmental Change* 14(1), 69–86.

Nicholls, R.J., and Tol, R.S.J. 2006. Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century, *Philosophical Transactions of the Royal Society* A 364, 1073–95.

Nicholls, R.J., S. Brown, S. Hanson, J. Hinkel. 2010. Economics of Coastal Zone Adaptation to Climate Change. Discussion Paper No. 10. The World Bank, Washington, DC.

Nordhaus, W.D. 1994. *Managing the Global Commons: The economics of the greenhouse effect*. The MIT Press

Nordhaus, W.D. and J.G. Boyer 2000. *Warming the World: the Economics of the Greenhouse Effect*. The MIT Press

Parry, M., Arnell, N., McMichael, T., Nicholls, R., Martens, P., Kovats, S., Livermore, M., Rosenzweig, C., Iglesias, A. and G. Fischer 2001. Millions at risk: defining critical climate change threats and targets, *Global Environmental Change* 11: 181–183

Parry, M., O. Canziani, J. Palutikof, P. van der Linden, C. Hanson (eds.) 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report on Climate Change.* Cambridge University Press

Parry, M. 2009. Closing the loop between mitigation, impacts and adaptation, *Climatic Change,* 96: 23–27

Pearce, D.W., Cline, W.R., Achanta, A.N., Fankhauser, S., Pachauri, R.K., Tol, R.S.J. and Vellinga, P.: 1996: The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control, in Bruce, J.P., Lee, H. and Haites, E.F. (eds.), Climate Change 1995: Economic and Social Dimensions - Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge

Pielke, R.A. 1998. Rethinking the role of adaptation in climate policies, *Global Environmental Change* 8: 159-170

Smit, B. (ed.) 1993. *Adaptation to Climatic Variability and Change*, Environment Canada, Guelph

Smit, B., I.Burton, R.J.T. Klein and R.Street, 1999. The Science of Adaptation: A Framework for Assessment, *Mitigation and Adaptation Strategies for Global Change*, Vol. 4 , No. 3-4, pp 199-213

Smit, B., Burton, I., Klein, J.T. and J. Wandel 2000. An anatomy of adaptation to climate change and variability, *Climatic Change* 45: 223-251

Smit, B. and O. Pilifosova 2001. Adaptation to Climate Change in the Context of Sustainable Development and Equity, in *Climate Change 2001, Contribution of Working Group II to the Third Assessment Report of the IPCC*. Cambridge University Press, pp. 877-912

Smith, J. B. and Lazo, J. K. 2001. A summary of climate change impact assessments from the US Country Studies Programme, *Climatic Change* 50:1-29

Smith, J. B. and Tirpak, D. A. (eds) 1989. *The Potential Effects of Global Climate Change on the United States. Executive Summary*, US Environmental Protection Agency. Washington, DC

Smithers J., and Smit B. 1997. Human adaptation to climatic variability and change, *Global Environmental Change* 7: 129-146

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press

Stern, N. 2007. *The Economics of Climate Change. The Stern Review.*Cambridge University Press

Tol, R.S.J. 2005. Emission abatement versus development as strategies to reduce vulnerability to climate change: an application of FUND, *Environment and Development Economics* 10: 615-629

UNFCCC 2007. Investments and Financial Flows to Address Climate Change. Climate Change Secreteriat, Bonn

Watson, R.T. , M. C. Zinyowera, Richard H. Moss and D. J. Dokken (eds.) 1995. *Climate Change, 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific- Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press

Wheaton, E.E. and D.C. Maciver 1999. A Framework and Key Questions for Adapting to Climate Variability and Change, *Mitigation and Adaptation Strategies for Global Change* 4: 215-225

Wilbanks, T. J. 2005. Issues in developing a capacity for integrated analysis of mitigation and adaptation*, Environmental Science & Policy* 8: 541-547

World Bank 2006. *Clean energy and development: towards an investment framework.* World Bank, Washington, DC

World Bank. 2010. *Economics of Adaptation to Climate Change: Synthesis Report*. The International Bank for Reconstruction and Development/The World Bank.

Yohe, G. and Strzepek, K. 2007. Adaptation and mitigation as complementary tools for reducing the risk of climate impacts, Mitigation and Adaptation Strategies for Global Change, 12: 727-739

Zickfeld K, et al. (2007) Expert judgements on the response of the Atlantic meridional overturning circulation to climate change. *Climatic Change* 82:235–265

Appendix I : The AD-WITCH model

The WITCH model developed by the climate change group at FEEM (Bosetti et al., 2006; Bosetti et al., 2007) is an energy-economy-climate model designed to explicitly deal with the main features of climate change. It is a regional model in which the non-cooperative nature of international relationships is explicitly accounted for. It is a truly intertemporal optimization model, with a long term horizon covering all century until 2100. The regional and intertemporal dimensions of the model make it possible to differentiate climate policies across regions and over time. Finally, the model includes a wide range of energy technology options, with different assumptions on their future development, which is also related to the level of innovation effort undertaken by countries.

The core structure of the model is described at length in the technical report (Bosetti et al., 2007 and 2009). The focus of this Annex is on the new elements of the latest version used in this report, and in particular on the Adaptation module of WITCH.

Overall model structure

WITCH is a dynamic optimal growth general equilibrium model with a detailed (bottom-up) representation of the energy sector, thus belonging to a new class of hybrid (both top-down and bottom-up) models. It is a global model, divided into 12 macro-regions.

The world economy is indeed disaggregated into twelve macro regions: **USA** (United States), **WEURO** (Western Europe), **EEURO** (Eastern Europe), **KOSAU** (Korea, South Africa, Australia), **CAJANZ** (Canada, Japan, New Zealand), **TE** (Transition Economies), **MENA** (Middle East and North Africa), **SSA** (Sub-Saharan Africa), **SASIA** (South Asia), **CHINA** (China and Taiwan), **EASIA** (South East Asia), **LACA** (Latin America, Mexico and Caribbean). This grouping has been determined by economic, geographic, resource endowment and energy market similarities.

The model proposes a bottom-up characterisation of the energy sector. Seven different energy-generating technologies are modelled: coal, oil, gas, wind & solar, nuclear, electricity, and biofuels. Their penetration rate is driven also by endogenous country and sector specific innovation. The model distinguishes between dedicated R&D investments for enhancing energy efficiency from investment aimed at facilitating the competitiveness of innovative low carbon technologies in both the electric and non-electric sectors (backstops). R&D processes are subject to stand on shoulders as well on neighbours effects. Specifically, international spillovers of knowledge are accounted for to mimic the flow of ideas and knowledge across countries. Finally, experience processes via Learning by Doing are accounted for in the development of niche technologies such as renewable energy

(Wind&Solar) and the backstops. Through the optimisation process regions choose the optimal dynamic path of different investments, namely in physical capital, in R&D, energy technologies and consumption of fossil fuels.

We updated the model base year to 2005, and use the most recent estimates of population growth. The annual estimates and projections produced by the UN Population Division are used for the first 50 years.[23] For the period 2050 to 2100, the updated data is not available, and less recent long term projections, also produced by the UN Population Division[24] are adopted instead. The differences in the two datasets are smoothed by extrapolating population levels at 5 year periods for 2050-2100, using average 2050-2100 growth rates. Similar techniques are used to project population trends beyond 2100.

The GDP data for the new base year are from the World Bank Development Indicators 2007, and are reported in 2005 US$. We maintain the use of market exchange rates (MER). World GDP in 2005 equals to 44.2 Trillions US$. Although GDP dynamics is partly endogenously determined in the WITCH model, it is possible to calibrate growth of different countries by adjusting the growth rate of total factor productivity, the main engine of macroeconomic growth.

The prices of fossil fuels and exhaustible resources have been revised, following the dynamics of market prices between 2002 and 2005. Base year prices have been calibrated following Enerdata, IEA WEO2007 and EIA AEO2008.

Climate Module and GHG Emissions

We continue to use the MAGICC 3-box layer climate model[25] as described in Nordhaus and Boyer (2000). CO_2 concentrations in the atmosphere have been updated to 2005 at roughly 385ppm and temperature increase above pre-industrial at 0.76 degrees Celsius, in accordance with IPCC Fourth Assessment Report (Parry *et al.*, 2007). Other parameters governing the climate equations have been adjusted following Nordhaus (2007).[26] We have replaced the exogenous non-CO_2 radiative forcing in equation with specific representation of other GHGs and sulphates. The damage function of climate change on the economic activity is left unchanged.

---

[23] Data are available from http://unstats.un.org/unsd/cdb/cdb_simple_data_extract.asp?strSearch=&srID=13660&from=simple.

[24] UN (2004), *World Population to 2300*, Report No. ST/ESA/SER.A/236, Department of Economic and Social Affairs, Population Division, New York.

[25] Wigley, T.M.L. 1994. MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change): User's Guide and Scientific Reference Manual. National Center for Atmospheric Research, Boulder, Colorado.

[26] http://nordhaus.econ.yale.edu/DICE2007.htm

In this version of WITCH we maintain the same initial stoichiometric coefficients as in previous versions. However, in order to differentiate the higher emission content of non-conventional oil as opposed to conventional ones, we link the carbon emission coefficient for oil to its availability. Specifically, the stoichiometric coefficient for oil increases with the cumulative oil consumed so that it increases by 25% when 2000 Billions Barrels are reached. An upper bound of 50% is assumed. The 2000 figure is calibrated on IEA 2005[27] estimates on conventional oil resource availability. The 25% increase is chosen given that estimates[28] range between 14% and 39%.

Non-CO_2 GHGs are important contributors to global warming, and might offer economically attractive ways of mitigating it.[29] Previous versions of WITCH only considers explicitly industrial CO_2 emissions, while other GHGs, together with aerosols, enter the model in an exogenous and aggregated manner, as a single radiative forcing component.

In this version of WITCH, we take a step forward and specify non-CO_2 gases, modelling explicitly emissions of CH_4, N_2O, SLF (short lived fluorinated gases, i.e. HFCs with lifetimes under 100 years) and LLF (long lived fluorinated, i.e. HFC with long lifetime, PFCs, and SF6). We also distinguish SO_2 aerosols, which have a cooling effect on temperature.

Since most of these gases are determined by agricultural practices, we rely on estimates for reference emissions and a top-down approach for mitigation supply curves. For the baseline projections of non-CO_2 GHGs, we use EPA regional estimates.[30] The regional estimates and projections are available until 2020 only: beyond that date, we use growth rates for each gas as specified in the IIASA-MESSAGE-B2 scenario,[31] that has underlying assumptions similar to the WITCH ones. SO_2 emissions are taken from MERGE v.5[32] and MESSAGE B2: given the very large uncertainty associated with aerosols, they are translated directly into the temperature effect (cooling), so that we only report the radiative forcing deriving from GHGs. In any case, sulphates are expected to be gradually phased out over the next decades, so that eventually the two radiative forcing measure will converge to similar values.

The equations translating non-CO_2 emissions into radiative forcing are taken from MERGE v.5. The global warming potential (GWP) methodology is employed, and figures for GWP as well as

---

[27] IEA 2005, Resources to Reserves – Oil & Gas Technologies for the Energy Markets of the Future

[28] Farrell and Brandt, 2005

[29] See the Energy Journal Special Issue (2006) (EMF-21), and the IPCC Fourth Assessment Report - Working Group III (Metz *et al.*, 2007)

[30] EPA Report 430-R-06-003, June 2006. the report is available from: http://www.epa.gov/climatechange/economics/mitigation.html.

[31] Available at http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=htmlpage&page=regions

[32] http://www.stanford.edu/group/MERGE/m5ccsp.html

base year stock of the various GHGs are taken from IPCC Fourth Assessment Report, Working Group I (Solomon *et al.*, 2007). The simplified equation translating CO_2 concentrations into radiative forcing has been modified from WITCH06 and is now in line with IPCC (Solomon *et al.*, 2007).

We introduce end-of-pipe type of abatement possibilities via marginal abatement curves (MACs) for non-CO_2 GHG mitigation. We use MAC provided by EPA for the EMF 21 project,[33] aggregated for the WITCH regions. MAC are available for 11 cost categories ranging from 10 to 200 US$/tC. We have ruled out zero or negative cost abatement options. MAC are static projections for 2010 and 2020, and for many regions they show very low upper values, such that even at maximum abatement, emissions would keep growing over time. We thus introduce exogenous technological improvements: for the highest cost category only (the 200 US$/tC) we assume a technical progress factor that reaches 2 in 2050 and the upper bound of 3 in 2075.

We however set an upper bound to the amount of emissions which can be abated, assuming that no more than 90% of each gas emissions can be mitigated. Such a framework enables us to keep non-CO_2 GHG emissions somewhat stable in a stringent mitigation scenario (530-CO2-eq) in the first half of the century, and subsequently decline gradually. This path is similar to what is found in the CCSP report,[34] as well as in MESSAGE stabilisation scenarios. Nonetheless, the very little evidence on technology improvements potential in non-CO_2 GHG sectors indicates that sensitivity analysis should be performed to verify the impact on policy costs.

Technological Innovation

WITCH is enhanced by the inclusion of two backstop technologies that necessitate dedicated innovation investments to become economically competitive, even in a scenario with a climate policy. We follow the most recent characterization in the technology and climate change literature, modeling the costs of the backstop technologies with a two-factor learning curve in which their price declines both with investments in dedicated R&D and with technology diffusion. This improved formulation is meant to overcome the main criticism of the single factor experience curves[35] by providing a more structural -R&D investment led- approach to the penetration of new technologies, and thus to ultimately better inform policy makers on the innovation needs in the energy sector.

---

[33] http://www.stanford.edu/group/EMF/projects/projectemf21.htm

[34] http://www.climatescience.gov/Library/sap/sap2-1/finalreport/default.htm

[35] Nemet, 2006

More specifically, we model the investment cost in a backstop technology as being influenced by a Learning by Researching process (main driving force before adoption) and by Learning by Doing (main driving force after adoption), the so called 2 factor learning curve formulation.[36]

We set the initial prices of the backstop technologies at roughly 10 times the 2005 price of commercial equivalents (16,000 US$/kW for electric, and 550 US$/bbl for non-electric). The cumulative deployment of the technology is initiated at 1000twh and 1000EJ respectively for the electric and non-electric, an arbitrarily low value.[37] The backstop technologies are assumed to be renewable in the sense that the fuel cost component is negligible; for power generation, it is assumed to operate at load factors comparable with those of baseload power generation.

Backstops substitute linearly nuclear power in the electric sector, and oil in the non-electric one. We assume that once the backstop technologies become competitive thanks to dedicated R&D investment and pilot deployments, their uptake will not be immediate and complete, but rather there will be a transition/adjustment period. The upper limit on penetration is set equivalent to 5% of the total consumption in the previous period by technologies other than the backstop, plus the plus the electricity produced by the backstop itself.

Adaptation

Our goal with the AD-WITCH model is firstly to disentangle the different components of climate change costs separating adaptation costs from residual damage; secondly, to attribute adaptation costs and benefits to different adaptation strategies. In the AD-WITCH model these have been clustered in three large categories.

Proactive or anticipatory adaptation, represented by all those actions taken in anticipation to the materialization of the expected damage, aiming at reducing its severity once manifested. Typical examples of these activities are coastal protection, or infrastructure and settlements climate-proving measures. They need some anticipatory planning and (if well designed) are effective along the medium, long-term.

Reactive adaptation, represented by all those actions that need to be undertaken every period in response to those climate change damages that cannot be or were not accommodated by anticipatory adaptation. They usually need to be constantly adjusted to changes in climatic conditions. Examples

---

[36] Kouvaritakis et al., 2000

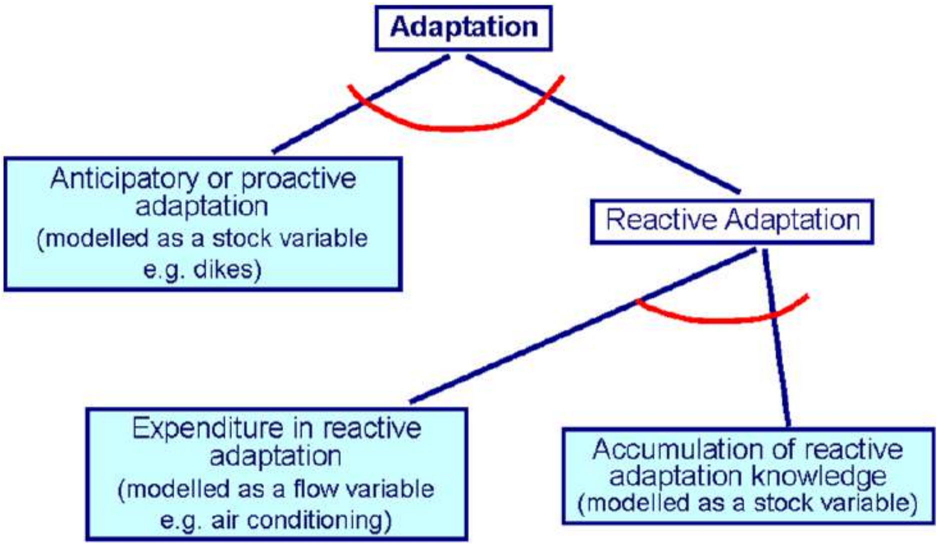
[37] Kypreos, 2007.

of these actions are energy expenditures for air conditioning or farmers' yearly changes in seasonal crops' mix.

Innovation activity in adaptation or simply knowledge adaptation, is represented by all those R&D activities making adaptation responses more effective. These are especially important in some sectors such as agriculture and health where the discovery of new crops and vaccines are keys to reduce vulnerability to climate change.

The adaptation basket, which exhibits decreasing marginal productivity, reduces the negative impact from climate change on gross output reducing the climate change damage coefficient in the WITCH damage function. It is composed by the different adaptation activities which are modeled as a sequence of Constant Elasticity of Substitution (CES) nested functions (see Figure AI.1).

Figure AI.1: The adaptation tree in the AD-WITCH model



In the first CES nest, total adaptation is a combination of proactive and reactive adaptation. Proactive adaptation is modelled as a stock variable: some defensive capital, accumulates over time because of an adaptation-specific investments activity. As defensive capital does not disappear, investment is needed to cope with incremental climate change damage. Proactive adaptation is also subjected to an economic inertia: an initial investment in adaptation takes 5 years to accrue to the defensive stock and thus to become effectively damage reducing.

Services from reactive adaptation are described by a second CES nest compounding reactive adaptation expenditures *strictu-sensu*, and improvements in adaptation knowledge. Expenditure on reactive adaptation is modelled as a flow variable: each simulation period, some expenditure is needed to cope with climate change damages irrespectively on the expenditure in the previous period. Accumulation of adaptation knowledge is modelled as a stock accrued by a periodical adaptation-specific investment in R&D representing an endogenous progress in reactive adaptation technologies.[38]

Then the cost of each of the adaptation activities considered (i.e.: investment in proactive adaptation, investment in adaptation knowledge and expenditure in reactive adaptation) are included into the national accounting identity. Investment in proactive adaptation, in adaptation knowledge and reactive adaptation expenditure are three additional control variables the AD-WITCH regional decision makers are endowed with, which compete with alternative uses of regional income in the maximization of welfare. These alternative uses are: consumption, investments in physical capital, investments in different energy technologies, investments in energy efficiency R&D.

Calibration of AD-WITCH

As in DICE/RICE the WITCH climate change damage function includes both the cost of adaptation and residual damages from climate change. As a consequence, calibrating adaptation in the AD-WITCH model requires the separation of those two components, which requires implementing an adaptation function explicating costs and benefits of the different forms of adaptation. The adaptation function is then to be parameterised so as to replicate the damage of the original WITCH model. Detailed description of the calibration process is reported in an appendix available upon request. Here it is worth mentioning three major points.

Firstly, we gathered new information on climate-change damages consistent with the existence of adaptation costs and tried to calibrate AD-WITCH on these new values and not on the original values of the WITCH model.

Secondly, due to the optimising behaviour of the AD-WITCH model, when a region gains from climate change, it is impossible to replicate in that region any adaptive behaviour and positive adaptation costs. Accordingly, when our data estimate gains from climate change we rather referred to Nordhaus and Boyer (2000) results if they reported costs. If both sources reported gains (as in the

---

[38] In fact adaptation R&D could improve also the effectiveness of proactive adaptation. However, we consider mostly R&D activities in the health care sector, which in the model is related to the treatment of climate-related diseases and in agriculture, which are both reactive.

case of TE and KOSAU) we calibrated a damage with the AD-WITCH model originating adaptation costs consistent with the observations.

Thirdly, the calibrated total climate change costs are reasonably similar with the reference values, however correspondence is far from perfect. The main explanation is that consistency need to be guaranteed between three interconnected items: adaptation costs total damage and protection levels. Adaptation costs and damages move together, thus for instance it is not possible to lower WEURO adaptation costs to bring them closer to their reference value (see Table AI.2) without decreasing total damage which is already lower than the reference.

Table AI.1: Different adaptation strategies

Proactive Adaptation Activities → Modeled as “stock” variable
Coastal Protection Activities Settlements, Other Infrastructures (Excluding Water) and Ecosystem Protection Activities Water Supply (Agriculture and Other) Protection Activities Setting-up of Early Warning Systems
Reactive adaptation activities → Modeled as “flow” variable
Agricultural Adaptation Practices Treatment of Climate-Related Diseases Space Heating and Cooling Expenditure
Innovation in adaptation constituting → Modelled as “stock” variable
Research Activities for the Development of Climate-Resilient Crops Research Activities in the Health Sector

Table AI.1 summarizes the different adaptation activities for which data were available; Table AI.2 reports the costs of each of these strategies as they emerged from the available literature and the values calibrated for the AD-WITCH model; Table AI.3 summarizes estimated and calibrated protection levels; Table AI.4 introduces total damages proposed by Nordhaus and Boyer (2000), by the original WITCH model, those newly estimated by this study and the calibration results by the AD-WITCH model.

Table AI.2: Adaptation costs in response to a doubling of CO2 concentration in absolute values and as percentage of GDP. Extrapolation from the literature and calibrated values with the AD-WITCH model

	Water in Agriculture (irrigation) (Billion $)	Water in Other Vulnerable Markets (Billion $)	Early Warning Systems (Million $)	Coastal Protection (Billion $)	Settl.mnts (Billion $)	Cooling Expenditure (Billion $)	Disease Treatment Costs (Billion $)	Adapt. R&D (Billion $)	TOTAL (Billion $)	TOTAL (% of GDP)	AD-WITCH (% of GDP)
USA	5.0	2.1	5.0	3.6	31.3	1.1	2.9	2.92	49.0	0.12	0.15
WEURO	7.8	3.3	5.0	5.0	63.3	-0.7	2.4	2.44	83.6	0.21	0.38
EEURO	12.3	5.3	5.0	0.3	2.4	-0.1	0.0	0.03	20.3	0.54	0.17
KOSAU	0.1	0.1	5.0	1.8	3.7	1.9	0.3	0.29	8.1	0.29	0.27
CAJANZ	2.7	1.1	5.0	2.9	23.1	3.0	1.7	1.66	36.1	0.21	0.22
TE	16.9	7.2	5.0	1.7	2.0	0.1	0.1	0.06	28.1	0.40	0.26
MENA	79.1	33.9	5.0	1.2	3.2	2.1	0.1	0.14	119.8	1.48	1.01
SSA	16.1	6.9	5.0	2.7	4.0	0.5	0.0	0.01	30.2	0.78	0.96
SASIA	28.4	12.2	5.0	1.3	12.8	1.1	0.0	0.04	55.9	0.54	0.66
CHINA	12.5	5.4	5.0	1.3	9.7	0.3	0.2	0.16	29.4	0.22	0.08
EASIA	31.2	13.4	5.0	4.3	6.0	4.7	0.0	0.04	59.6	0.84	0.65
LACA	7.2	3.1	5.0	7.7	15.0	5.7	0.1	0.07	38.9	0.19	0.52

Table AI.3: Effectiveness of adaptation (1=100% damage reduction) against doubling of CO2 concentration Extrapolation from the literature and calibrated values with the AD-WITCH model

	Agriculture	Other vulnerable markets	Cat. Events	Coastal systems	Settlements	Non market time use	Health	Weighted total (*)	AD-WITCH
USA	0.48	0.80	0.100	0.75	0.40	0.90	0.90	0.25	0.23
WEURO	0.43	0.80	0.100	0.54	0.40	0.80	0.90	0.20	0.26
EEURO	0.43	0.80	0.100	0.63	0.40	0.80	0.60	0.34	0.35
KOSAU	0.27	0.80	0.100	0.62	0.40	0.80	0.81	0.24	0.25
CAJANZ	0.38	0.80	0.100	0.37	0.40	0.90	0.69	0.25	0.25
TE	0.38	0.80	0.100	0.37	0.40	0.80	0.70	0.20	0.16
MENA	0.33	0.40	0.100	0.55	0.40	0.63	0.60	0.38	0.52
SSA	0.23	0.40	0.001	0.30	0.40	0.30	0.20	0.21	0.14
SASIA	0.33	0.40	0.001	0.47	0.40	0.50	0.35	0.19	0.08
CHINA	0.33	0.40	0.100	0.76	0.40	0.70	0.40	0.22	0.14
EASIA	0.33	0.40	0.010	0.25	0.40	0.43	0.40	0.19	0.11
LACA	0.38	0.40	0.001	0.46	0.40	0.70	0.90	0.38	0.31

(*) Reduction in each category of damage is weighted by the % contribution of that damage type to total damage. Then weighted damages are summed.

Table AI.4: Total climate change costs (residual damages and adaptation cost) for a doubling of CO2 concentration

	Nordhaus and Boyer (2000)	WITCH model	This study	AD-WITCH model
USA	0.45	0.41	0.37	0.44
WEURO	2.84	2.79	2.25	1.58
EEURO	0.70	-0.34	0.82	0.55
KOSAU	-0.39	0.12	-0.05	0.82
CAJANZ	0.51	0.12	0.01	0.52
TE	-0.66	-0.34	-0.01	0.80
MENA	1.95	1.78	2.41	2.93
SSA	3.90	4.17	4.19	5.09
SASIA	4.93	4.17	4.76	5.51
CHINA	0.23	0.22	0.22	0.50
EASIA	1.81	2.16	1.93	4.17
LACA	2.43	2.16	2.13	2.31

Appendix II: Estimating market-driven adaptation with the ICES model

Through a meta analysis and extrapolations from the exiting impact literature, the set of direct impacts reported in Table AII.1 has been computed for the regions of the ICES model.

Table AII.1: climate change impacts (% change 2000 – 2050)

	HEALTH						LAND PRODUCTIVITY					
	Labour Product.		Public Exp.		Private Exp.		Wheat		Rice		Cereal Crops	
	1.2°C	*3.2°C*	*1.2°C*	*3.2°C*	*1.2°C*	*3.2°C*	*1.2°C*	*3.2°C*	*1.2°C*	*3.2°C*	*1.2°C*	*3.2°C*
USA	-0.06	-0.18	-0.15	-0.28	-0.02	-0.03	-5.66	-18.89	-6.19	-20.37	-8.18	-25.15
Med_Europe	0.01	0.01	-0.10	-0.18	0.00	-0.01	-1.14	-8.33	-4.62	-18.94	-2.00	-11.84
North_Europe	0.06	0.16	-0.35	-0.88	-0.01	-0.03	1.50	-7.74	-5.90	-26.01	50.00	107.82
East_Europe	0.09	0.23	-0.47	-1.17	-0.01	-0.02	-1.13	-10.50	-2.64	-13.57	-4.60	-18.35
FSU	0.11	0.28	-0.41	-1.03	-0.01	-0.03	-6.12	-21.92	-7.47	-24.64	-9.73	-30.10
KOSAU	-0.43	-1.14	0.57	1.62	0.04	0.11	-7.78	-17.00	-2.90	-7.41	-3.11	-7.38
CAJANZ	0.09	0.22	0.03	0.24	0.00	0.00	-0.74	-12.33	-1.87	-14.31	-2.24	-15.17
NAF	-0.28	-0.69	2.02	4.41	0.10	0.23	-12.81	-42.14	-10.78	-41.00	-12.62	-45.97
MDE	-0.22	-0.34	1.34	1.81	0.10	0.14	-8.40	-32.40	-11.73	-38.52	-13.60	-43.12
SSA	-0.31	-0.84	0.47	1.34	0.07	0.19	-9.89	-15.02	-7.17	-7.42	-8.81	-10.59
SASIA	-0.11	-0.30	0.28	0.76	0.06	0.17	-2.96	-13.37	-4.89	-17.39	-6.61	-21.43
CHINA	0.14	0.37	0.65	1.80	0.06	0.17	0.93	2.69	0.50	1.79	-1.42	-2.37
EASIA	-0.11	-0.32	1.05	2.96	0.06	0.17	2.45	9.82	0.34	5.04	-1.15	1.93
LACA	-0.14	-0.39	0.68	1.98	0.07	0.19	-6.69	-68.10	-6.61	-55.65	-8.25	-76.37

	SEA LEV. RISE		TOURISM				HOUSEHOLDS' ENERGY DEMAND					
	Land Losses		Market Serv. Demand		Income Flows		Natural Gas		Oil Products		Electricity	
	1.2°C	*3.2°C*	*1.2°C*	*3.2°C*	*1.2°C*	*3.2°C*	*1.2°C*	*3.2°C*	*1.2°C*	*3.2°C*	*1.2°C*	*3.2°C*
USA	-0.026	-0.055	-0.68	-1.76	-0.17	-0.43	-13.67	-35.31	-18.52	-47.84	0.76	1.96
Med_Europe	-0.007	-0.015	-1.86	-4.81	-0.40	-1.02	-12.68	-32.76	-15.84	-40.91	0.76	1.96
North_Europe	-0.020	-0.041	7.54	19.47	1.78	4.61	-13.75	-35.51	-15.52	-40.09	-2.20	-5.68
East_Europe	-0.022	-0.046	-2.46	-6.36	-0.33	-0.86	-12.93	-33.41	-17.39	-44.92	0.76	1.97
FSU	-0.007	-0.015	0.00	-0.01	0.00	0.00	-13.02	-33.65	-17.39	-44.92	0.75	1.94
KOSAU	-0.005	-0.011	-1.31	-3.39	-0.32	-0.82	nss	nss	-13.03	-33.66	12.31	31.81
CAJANZ	-0.004	-0.009	5.54	14.30	1.40	3.61	-5.05	-13.04	-12.63	-32.63	-4.80	-12.40
NAF	-0.017	-0.036	-2.52	-6.52	-0.24	-0.63	-8.60	-22.22	-13.25	-34.22	5.95	15.37
MDE	-0.004	-0.007	-4.67	-12.06	-0.91	-2.34	-13.12	-33.89	-17.39	-44.92	0.74	1.92
SSA	-0.066	-0.139	-4.43	-11.45	-0.37	-0.96	nss	nss	-6.51	-16.83	16.35	42.23
SASIA	-0.204	-0.427	-1.21	-3.12	-0.10	-0.25	nss	nss	nss	nss	20.38	52.65
CHINA	-0.045	-0.094	-4.99	-12.89	-0.33	-0.85	nss	nss	nss	nss	20.38	52.65
EASIA	-0.316	-0.662	-4.69	-12.10	-0.53	-1.38	nss	nss	nss	nss	20.38	52.66
LACA	-0.025	-0.052	-2.68	-6.91	-0.56	-1.45	nss	nss	nss	nss	21.37	55.20

Notes:
- Nss: non statistically significant.
- In red those impacts potentially negative

It is firstly evident that, except for the case of land losses to sea-level rise, they are not all necessarily negative. For instance, labor productivity decreases in some regions (at the lower latitude) where the decrease in cold-related mortality/morbidity cannot compensate the increase in heat related mortality/morbidity, but increases in others (typically at the medium to high latitudes) where the opposite happens. The same applies to crops productivity: in hotter regions it decreases (note that the loss of the aggregate KOSAU is mainly due to agricultural losses in Australia) whereas in the cooler regions it tends to increase as for cereal crops in the Northern Europe. Climatic stimuli are indeed regionally differentiated and affect populations or crops with different sensitivity.

Secondly, impacts concern both the supply and the demand side of the economic system. In the first case they can be unambiguously defined as positive or negative: a decrease in labor productivity due to adverse health impact is a sure initial loss for the economic system. In the second case, when agents' preferences change, assigning a positive or negative label to an impact is more difficult. For instance, when, due to warmer climates, oil and gas demand for heating purposes decreases, this cannot be considered straightforwardly a cost or a gain before redistributional effects are analyzed.

This said, the larger supply-side impacts in per cent terms concern agricultural markets, whereas labor productivity and land losses to sea-level rise are much smaller. Among demand shifts, the larger relate to household energy consumption: electricity demand for space cooling could increase up to 50% in hot regions depending on the climate scenario; it decreases in the cooler regions like Northern Europe and in CAJANZ this last dominated by the Canada effect. Natural gas and oil demand for heating purposes declines everywhere. Highly relevant are also demand changes for market services, driven by redistribution of tourism flows, accompanied by income inflows (outflows) in those regions where climatic attractiveness increases (decreases). The larger beneficiaries are cooler regions, Northern Europe and CAJANZ (this last again dominated by Canada effect) whereas China, East Asia and Middle East experience a loss.

When all these impacts are used as an input to the CGE model, Figure 17 is obtained.

Final effects are dominated by impacts on crops' productivity and on the tourism industry. It can be surprising that sea-level rise and health impacts appear so negligible.

This depends on two facts:

(a) The initially low estimates of the impacts themselves. In the case of sea-level rise, only land losses are part of the assessment and whereas capital losses or people displacement are not considered. In the case of health, both heath and cold related diseases are considered thus the increase in the first is partly counterbalanced by the decrease in the second.

(b) The nature of the analysis. Here what is shown is the reduced (or increased) ability of economic systems to produce goods and services because of climate change. This is what GDP, typically a flow variable, measures. Thus, say a land loss, is not evaluated in terms of

> loss of property value which can be very high, but in terms of the lower capacity of the economic system hit by that land loss to produce (agricultural) goods. Given the possibility to substitute at least partially a scarcer input with one more abundant, usually effects on GDP are smaller.[39]

Final effects also present Northern Europe, CAJANZ and Mediterranean Europe as winners from climate change. In Northern Europe all impacts except sea-level rise bring gains. In CAJANZ huge positive impacts on tourism demand can explain its gain. More interesting is to comment the case of Mediterranean Europe which benefits from climate change even though, except for a slight gain in labor productivity, all impacts are negative. Indeed if measured in terms of direct costs, climate change entails a net loss higher than the 3% of GDP (see fig. 15) for the region. However two mechanisms turn this into a small gain. Firstly, an improvement in terms of trade. This is driven by the decrease in energy prices due to the global contraction of GDP and thus of world energy demand, and to the increased agricultural goods prices induced by their reduced supply. This benefits particularly a net energy importer and food exporter like Mediterranean Europe. Secondly, foreign capital inflows. In the model these are driven by expected rate of return to capital. Mediterranean Europe is one region attracting capital as, its rental prices are decreasing, but less than in other regions. These resources spur investment and growth. These two second order effects are stronger than the direct effect.

It is worth stressing that this kind of analysis cannot be performed with models like RICE (or WITCH) which lacks some economic details (the most important is sectoral and international trade) and where damages are summarised by reduced-form equations. While a these *assume* a given relation between damage and temperature, and the damage usually includes property losses, our exercise *estimates* that relation quantifying the change in the capacity of an economic system hit by a joint set of impacts to produce goods and services.

As a final remark: the analysis performed does not include the effect of catastrophic losses, we decided to omit them due to the uncertainty of those estimates. They are extremely relevant in other studies though, e.g. in Nordhaus and Boyer (2000) they constitute from the 10% to the 90% of total regional damages (see Table 2). This means that slightly different assumptions on catastrophic outcomes may change considerably results.

---

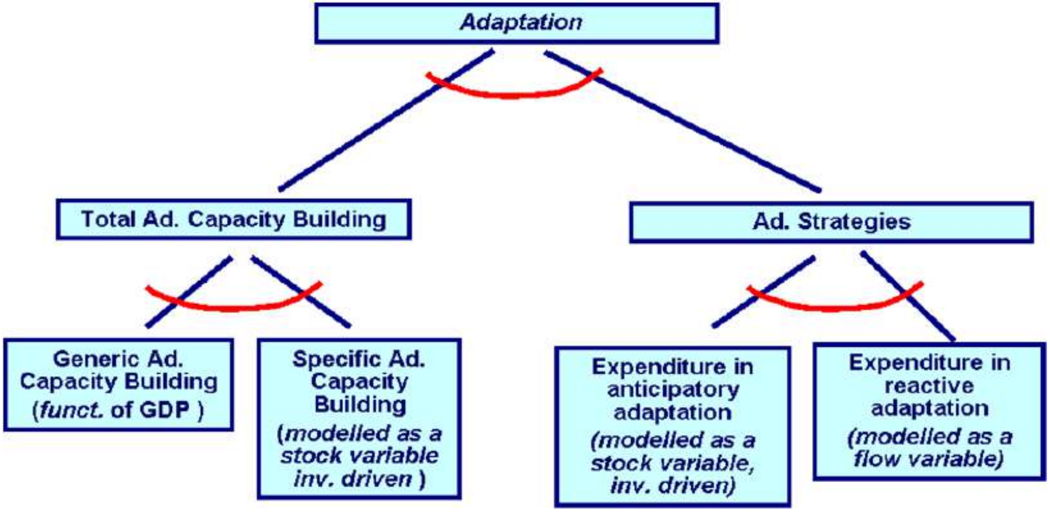
[39] This is for instance why today catastrophic events, entailing huge property losses, translate in no or just very little effects on GDP.

Appendix III: An alternative formulation of adaptation

Two critical aspects of our exercise relate to the choice to model (tiny) adaptation knowledge as efficiency improver of reactive adaptation only, and on the assumption of very low damage until 2040. The first assumption is driven by data evidence as investment in adaptation knowledge basically takes place in agriculture and health sector where reactive adaptation is preponderant, the second is an assumption embedded in Nordhaus' damage function. The main consequences are that investment in adaptation knowledge remains very small, that they are performed mainly by developed countries and that adaptation (either proactive or reactive) starts only after 2040.

To test the robustness of our result we propose here a different specification and calibrate the damage in order to have some climate change impacts already at the beginning of the century. Adaptation strategies are now clustered in four large categories as depicted in Figure AIII.1. A first decision is whether spend resources on activities (adaptation strategies) or capacity building. Both groups contain some further distinction into other sub-investments or activities. Total capacity consists of two components: generic capacity which is not necessarily related to adaptation and specific capacity, which instead includes capacity specific for adaptation. Adaptation activities include reactive and proactive adaptation measures, as in the main specification considered in the text.

Figure AIII.1: The adaptation tree in the AD-WITCH model: an alternative specification

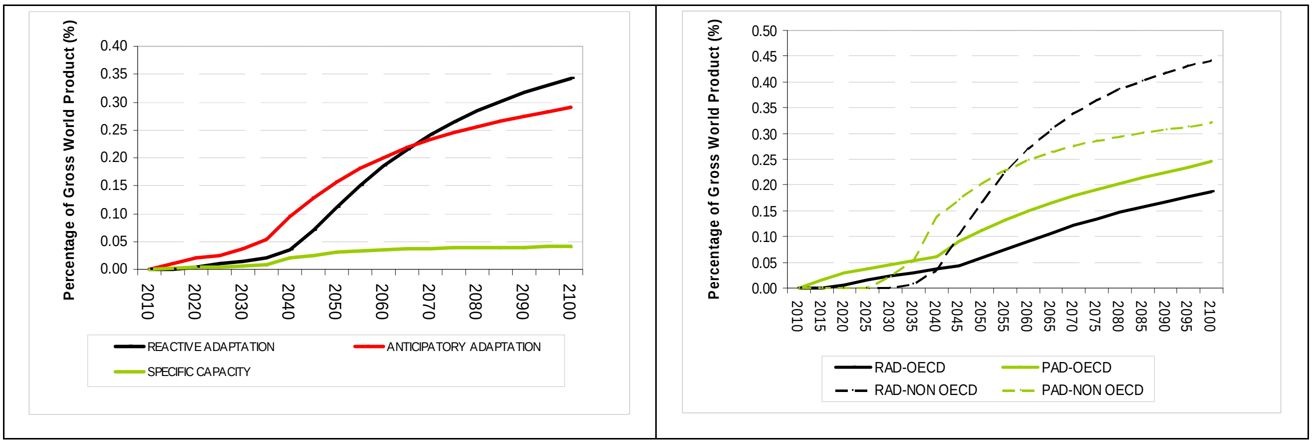


Using this new specification, we have re-computed the optimal adaptation-mitigation mix in the non cooperative scenario. All the qualitative results found with the old specification hold: mitigation is close to zero; the optimal adaptation mix is composed by reactive, proactive and specific capacity

(Figure AIII-1). Anticipatory adaptation is undertaken in advance, because of its stock nature, whereas reactive adaptation becomes more important when the damage is sufficiently large. In the long-run anticipatory adaptation stabilizes whereas reactive adaptation keeps increasing.

The regional differentiation of the adaptation basket is also robust to the new specification. NON OECD spend more on adaptation than OECD regions. In the second half of the century, reactive adaptation becomes the main adaptation form in NON OECD, whereas in OECD countries anticipatory measures are always the dominant strategy. Once more, the explanation lies in the different climate vulnerability.

Figure AIII.2: Adaptation expenditure



What changes is the path of adaptation. It starts immediately and is smoother. To conclude Table AIII-1 reports benefit-cost ratio of all adaptation strategies jointly in the non cooperative scenario. They show the same ranking of the previous analysis.

Table AIII.1: Benefits and costs of adaptation without mitigation (Non cooperative)

US$ 2005 Billion ***3% Discounting 2010-2105***	WORLD	OECD	NON OECD
Benefits	29444	8641	20802
Costs	11237	3548	7690
BCR	**2.62**	**2.44**	**2.71**

Therefore, even under a different structural specification the model, i.e. even when testing the sensitivity to a different model functional form, our results are largely confirmed and seem to be robust to changes in the specification of the adaptation module.