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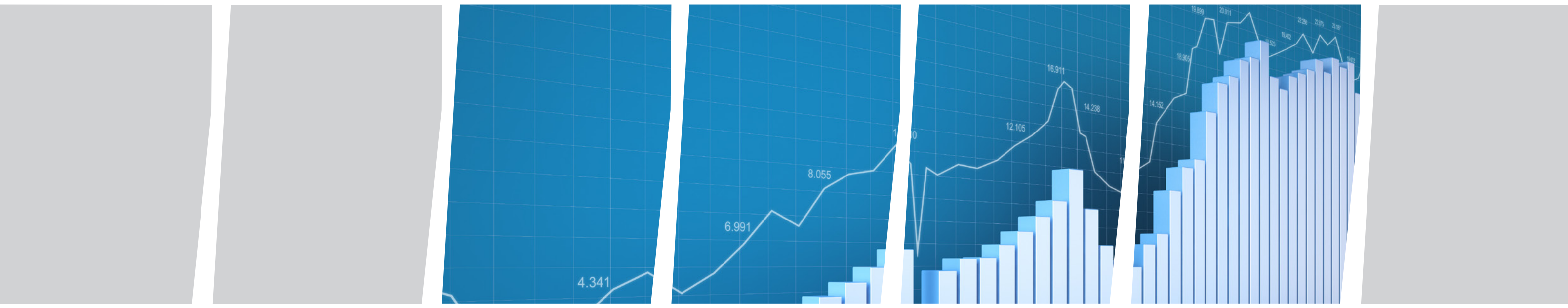

Choosing the optimal climate change policy in the presence of catastrophic risk

Francesco Bosello, Fondazione Eni Enrico Mattei.

Enrica De Cian, Fondazione Eni Enrico Mattei.

Licia Ferranna, Fondazione Eni Enrico Mattei.

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Abstract

This paper contributes to the normative literature on mitigation and adaptation by analyzing their optimal policy balance in the context of climate catastrophic risk. The investigation enriches an integrated assessment model introducing the endogenous link between the probability of experiencing a climate-change related catastrophic event, the temperature increase caused by GHG emissions, and ultimately abatement choices. Results indicate that the presence of catastrophic risk induces substantial mitigation effort even in a non-cooperative setting, where usually global cooperation on climate, and accordingly substantive emission reductions, do not succeed. The policy balance is realigned from adaptation toward more mitigation, and the responsiveness of mitigation to changes in adaptation decreases. Compared to a world without climate catastrophes, risk reduces the substitutability between adaptation and mitigation because only mitigation can influence the catastrophic probability. In this setting, our analysis also shows that adaptation funds and strategic unilateral commitments to adaptation are not the most efficient ways of buying emission reduction in less developed countries, though they could create some welfare gains and induce abatement in the recipient countries.

Key Word: Climate change, mitigation, adaptation, climate risk, integrated assessment.
JEL Classification: C61, D58, Q5

Francesco Bosello, Associate Researcher at FEEM[*]
Enrica De Cian, Senior Researcher[↑]
Licia Ferranna, Junior Researcher[↑]

[*] University of Milan, Fondazione Eni Enrico Mattei and Centro Euromediterraneo per I Cambiamenti climatici.
Corresponding author:
Fondazione Eni Enrico Mattei
Isola di S. Giorgio Maggiore 30124 Venice. Italy
francesco.bosello@feem.it
[↑] Fondazione Eni Enrico Mattei and Centro Euromediterraneo per i Cambiamenti Climatici

1. Introduction and background

As recently emphasised by strategic documents such as the 2009 EU White Paper on Adaptation and the 2010 Cancun Adaptation Framework, adaptation is recognised as an unavoidable complement to mitigation. The outcome of the recent Durban talks postponed the negotiation on emission reduction to 2015, making it more difficult to achieve the 2°C temperature target. In this context, adaptation is even more crucial.[1] On a different token, mitigation is the only instrument capable of tackling not only the smooth and continuous consequences of climate change, but also its potential catastrophic and irreversible outcomes. This idea supports the EU climate change strategy. The choice of limiting global warming below 2°C aims explicitly at limiting “the impacts of climate change and the likelihood of massive and irreversible disruptions of the global ecosystem” CEC (2007). Needless to say that stabilising climate change at less ambitious levels, such as +2.5 or 3°C, will still require significant mitigation.

Climate change could be much greater than expected and occur at a faster rate than what suggested by historical trends. Research has identified a number of discontinuous, irreversible, and low-probability occurrences that could bring a sudden and sharp decline in economic growth and social welfare, for instance, the collapse of North Atlantic thermohaline circulation, the runaway greenhouse effect, and the melting of West Antarctic or of Greenland ice sheets, (Pearce *et al.*, 1996; Posner, 2004; Guillerminet and Tol, 2008; Lenton *et al.* 2008).

Should the perception of these risky and uncertain consequences become a shared policy concern, it will very likely influence the entire climate policy design, including the combination of mitigation and adaptation. Adapting to a catastrophe would be extremely costly, meaning that mitigation should be the emphasis of the climate change strategy (Wright and Erikson, 2003).

While there is extensive economic literature related to uncertainty and mitigation policies building on the pioneering work of Arrow and Fisher (1974) ending with Weitzman (2009), the literature investigating the relation between mitigation and adaptation has only marginally tackled this issue.

The modelling approach to mitigation and adaptation, using Integrated Assessment Models, derives its conclusions in a context of full information and no irreversibility. Robust outcomes of these studies can be summarised as follows. In a non-cooperative setting mitigation is negligible due to its public good nature. Adaptation on the contrary, entailing almost fully appropriable benefits, is substantial and basically the only climate change strategy (Agrawala *et al.* 2010; de Bruin *et al.* 2009; Bahn *et al.* 2009; Bosello *et al.* 2011). Significant mitigation effort becomes optimal only in a cooperative setting, where emission externalities are fully internalised , or when countries decide to sign an agreement and work together toward the achievement of a given mitigation target (*i.e.* a cost effectiveness framework). In this case, the adaptation effort is crowded out. On the one hand, more mitigation reduces the climate change damage it is necessary to adapt to. On the other hand, scarce budgetary resources have to be allocated between two strategies instead of one. Nonetheless, the optimal climate policy, whether in a cost efficiency or cost effectiveness setting, always presents a mix of both. Climatic inertias also play a paramount role. The temperature increase and the related damages can be curbed by mitigation only with considerable delay, therefore adaptation effort remains far from negligible despite the presence of successful CO_2 stabilisation policies (Hof *et al.* 2009, 2010; Agrawala 2011). In

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

cost efficiency analyses, the crowding out of mitigation on adaptation is considerably weaker than that of adaptation on mitigation. Mitigation, especially in early periods, only slightly lowers environmental damages and thus, adaptation remains necessary. On the contrary, successful adaptation largely decreases the marginal benefit of mitigation. Climatic inertias also motivate an anticipated action on mitigation and a postponed one on adaptation. Cost efficiency studies finally stress that the bulk of the climate change policy budget should be devoted to adaptation, especially when the discount rate is high and when adaptation is modelled as a proactive strategy building a stock of “defensive” infrastructures.

Interesting questions will thus arise: in which direction can the presence of catastrophic risk and uncertainty change these findings? Is the trade-off between mitigation and adaptation weakened or strengthened? How can the timing and composition of the optimal policy portfolio be affected?

Some indications are offered by the theoretical work of Kane and Shogren (2000) and Ingham *et al.* (2007), which analytically treat the relation between mitigation and adaptation in the presence of uncertainty. This is not explicitly defined as an irreversible catastrophic event, but as a risk of a climatic damage that can be endogenously controlled by agents. In Kane and Shogren (2000) both adaptation and mitigation reduce the risk of adverse effects of climate change. Whether adaptation, mitigation, or both, increase in response to an increased climate change risk depends on two effects: a direct effect of risk on the marginal productivity of a strategy, and an indirect effect. The indirect effect is determined by two factors: the impact of risk on the other strategy and the relationship between the two strategies. In general[2], the direct effect of an increased risk implies more mitigation or more adaptation. However, the final balance between the two strategies is determined by the indirect effect. It amplifies the direct effect if the marginal productivity of the other strategy also increases and the two strategies are complements or if marginal productivity decreases and the strategies are substitutes. Kane and Shogren (2000) flag the ambiguity of the outcomes and stress that what can be effectively observed is at the end an empirical matter.

Ingham *et al.* (2007) assume that the climate risk can be reduced only by mitigation and the climate damage only by adaptation. In this set-up they found that an increase in risk always implies more adaptation and more mitigation. However, the two strategies remain economic substitutes: an increase in adaptation costs reduces adaptation and increases mitigation. Complementarity arises only when there is a strong cross effect of mitigation on adaptation costs. In this case, increasing mitigation costs will reduce both mitigation and adaptation. Interestingly, Ingham *et al.*, (2005) also note that complementarity can arise when the costs of adaptation depend on the stock of greenhouse gases because more mitigation slows the rate of climate change or avoids a potential catastrophe and hence makes adaptation easier.

Further investigating all these issues can be of practical relevance also for the analysis of international environmental negotiations. Recent literature shows that the joint presence of adaptation and mitigation, depending on their assumed degree of substitutability, can indeed influence the incentive to be part of the environmental agreement.

In this vein, Barrett (2010) 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 of the agreement closer to a non-cooperative effort. In conclusion, adaptation enhances participation by emptying the agreement of its mitigation content. In a non-cooperative setting, Buob and Stephan (2011) show that, in

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[2] The authors discuss examples where this is not the case.

principle, developed countries can use adaptation funding in developing countries to foster their abatement effort as well as global mitigation, if and only if mitigation and adaptation are complements. They also show however, that under strict complementarity for developed countries it would be economically rational to fund adaptation in developing regions only "exchanging it" with a lower abatement. But realistically, developing countries will not be willing to accept such an agreement. Auerswald *et al.* (2011) show that in a leader-follower game, early adaptation commitment from a group of countries can be used as a credible signal of low engagement in mitigation. 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.

Marrouch and Chaudhuri (2011) offer an interesting perspective which links Barrett (2010) and Auerswald *et al.* (2011). They show that, at given conditions, the presence of adaptation can enlarge participation to an abating coalition. Moreover, if the coalition acts as a Stackelberg leader, total emissions can decrease. The intuition is the following: if in addition to abatement a country can also adapt to climate damages, 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 consequently could enlarge participation. On the other hand, as now emissions reaction curves are no longer orthogonal, the abating coalition may increase its abatement effort to lower the emissions in non-participatory countries.

The present paper contributes to the on-going debate and existing literature in two respects. First the paper proposes an analysis of the role of climate catastrophic risk in shaping the optimal mix between mitigation and adaptation. Second, it investigates whether financial transfers directed at supporting adaptation needs in developing countries can be used as a leverage to increase their abatement effort, and under which conditions. The economic analysis of the paper is based on an updated version of the integrated assessment model, AD-WITCH. The model has been improved in the calibration of market and non-market climate change damage functions.

In what follows, section 2 introduces the improved AD-WITCH model and the design of climate change–related risk set–up. Section 3 presents the major model results and section 4 concludes.

2. Adaptation and catastrophic risk modelling

2.1 The AD-WITCH model

The modelling tool used to analyse mitigation, adaptation and uncertainty is an improved version of the AD-WITCH model (Bosello *et al.* 2011, Agrawala *et al.* 2010, Agrawala *et al.* 2011) whose main features are summarised below[3].

AD-WITCH builds on the WITCH model (Bosetti *et al.* 2006, Bosetti *et al.* 2009), of which it shares the main characteristics. It is an intertemporal, optimal growth model in which forward-looking agents choose the path of investments to maximise a social welfare function subject to a budget constraint. It can be solved in two alternative game theoretical settings. In the non-cooperative one, the twelve model regions behave strategically with respect to all major economic decision variables – including adaptation and emission abatement levels. This yields a Nash equilibrium, which does not internalise the environmental externality. The cooperative setting describes a first-best world, in which all

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[3] The interested reader is addressed directly to Bosello *et al.* (2011) for further detail.

externalities are internalised, because a benevolent social planner maximises a global welfare function[4].

In AD-WITCH, adaptation response is modelled as a set of control variables chosen optimally together with all the other controls, namely investments in physical capital, R&D, and energy technologies. The large number of adaptive responses that exist has been aggregated into four macro categories: generic and specific adaptive capacity-building, anticipatory and reactive adaptation. Generic adaptive capacity building captures the link between the status of the development of a region and the final impact of climate change on its economic system (Parry *et al.* 2007, Parry 2009). Specific adaptive capacity building accounts for all investments dedicated to facilitating adaptation activities (*e.g.* improvement of meteorological services, of early warning systems, the development of climate modelling and impact assessment etc.). Anticipatory adaptation gathers all the measures where a stock of defensive capital must already be operational when the damage materialises (*e.g.* dike building). By contrast, reactive adaptation gathers all actions that are put in place when the climatic impact effectively materialises (*e.g.* use of air conditioning) to accommodate the damages not avoided by anticipatory adaptation or mitigation.

The adaptation tree in Figure 1 shows the relationship between the different adaptation strategies, which takes a CES (Constant elasticity of substitution) form. A first node distinguishes adaptive capacity building (left) from adaptation activities *strictu sensu* (right). In the first nest, generic adaptive capacity building is represented by an exogenous trend increasing at the rate of total factor productivity. Specific adaptive capacity building is modelled as a stock, which accumulates over time with adaptation-specific investments.

In the second nest, anticipatory adaptation is also modelled as a stock of defensive capital. It is subject to some economic inertia (investments in adaptation take one period - five years - to accrue to the defensive stock), and must be planned in advance. Once built, defensive capital does not disappear, but it remains effective over time subject to a depreciation rate. Reactive adaptation is modelled as a flow expenditure: it represents an instantaneous response to the damage faced in each period.

Adaptive capacity building and adaptation activities, and similarly reactive and anticipatory adaptation are modelled as mild substitutes (substitution elasticity is 1.2 in both cases) to reflect the current debate supporting both substitutability and complementarity. On the contrary, general and specific adaptive capacity are modelled as gross complements (elasticity of substitution equal to 0.2)[5] as we consider basic socio-economic development (generic capacity), an essential perquisite for facilitating any form of adaptation.

Investments in specific adaptive capacity building, in anticipatory adaptation measures, and reactive adaptation expenditure are three additional control variables. The cost of each item is also included within the national budget constraint.

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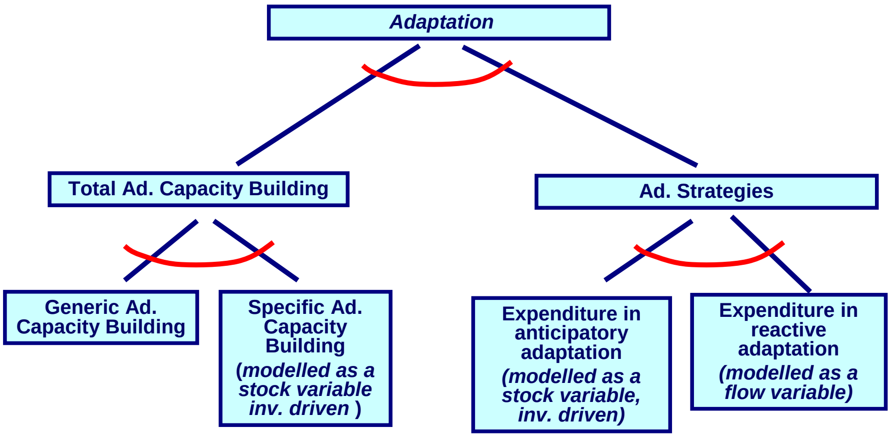
[4] AD-WITCH, as well as the WITCH model, features technology externalities due to the presence of Learning-By-Researching and Learning-By-Doing effects. The cooperative scenario internalises all externalities. For more insights on the treatment of technical change in the WITCH model see Bosetti *et al.* (2009).

[5] In a sequence of sensitivity tests we verify the robustness of our results to many different assumptions on the degree of substitutability among adaptive options. Results are robust to different parameterisation. They are available upon request.

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



The analysis that follows is performed in a cost-benefit, non-cooperative setting, where environmental externalities are not internalised.

2.2 Modelling non-catastrophic damages

Climate change damages, which in the AD-WITCH model are based on Nordhaus (2001), have been completely recalibrated. The market component of climate change damages has been revised using the recent estimates provided by an interdisciplinary work (the FP7 CLIMATECOST project, see Bosello *et al.* 2012). That project has quantified the physical and economic impacts of climate change on sea-level rise, energy demand, agricultural productivity, tourism flows, net primary productivity of forests, floods, and reduced work capacity because of thermal discomfort. Moreover, the economic impact partially assessed includes market driven adaptation as they have been estimated with a recursive-dynamic computable general equilibrium (CGE) model, ICES (Intertemporal Computable General Equilibrium System), therefore capturing those market adjustments triggered by price changes. The role of market-driven adaptation is not accounted for by the reduced-form damage functions used in integrated assessment models such as DICE/RICE99 and AD-WITCH as in Agrawala *et al.* (2010). Therefore, the market damage component included in the present study is net of the autonomous adaptation effects.

A non-market component has also been included. It primarily refers to potential ecosystem losses and non-market health impacts, assessed using a willingness-to-pay approach.

Figure 2 summarises the outcome of the calibration procedure (a dedicated appendix describes in detail the methodologies used). Global climate change damages are mildly convex in temperature, reaching a 4% loss of world GDP when there is a 3.6°C warming above pre-industrial levels. The largest discrepancy with the older data relates to South Asia and South East Asia, which are expected to lose 12% of their GDP while in the previous estimate the loss was 10%-5%. The EU loses roughly 0.5% of GDP in 2100. Eastern European countries are expected to gain until 2050. Economies in Transitions will have benefits until the end of the century, although at a decreasing rate due to positive non-market effects on health.

Figure 2. Regional climate change damages in the AD-WITCH model

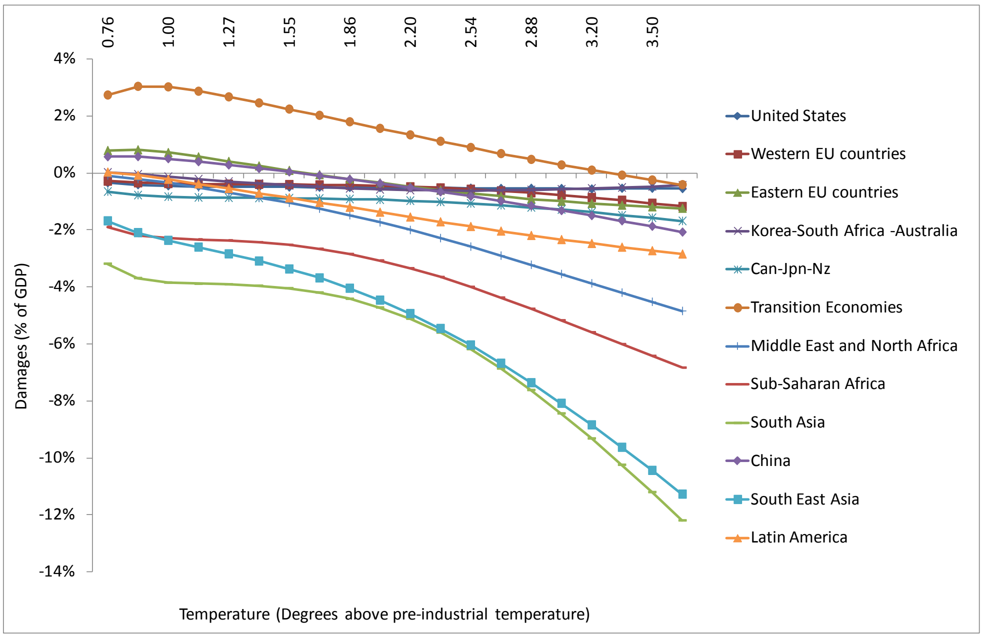
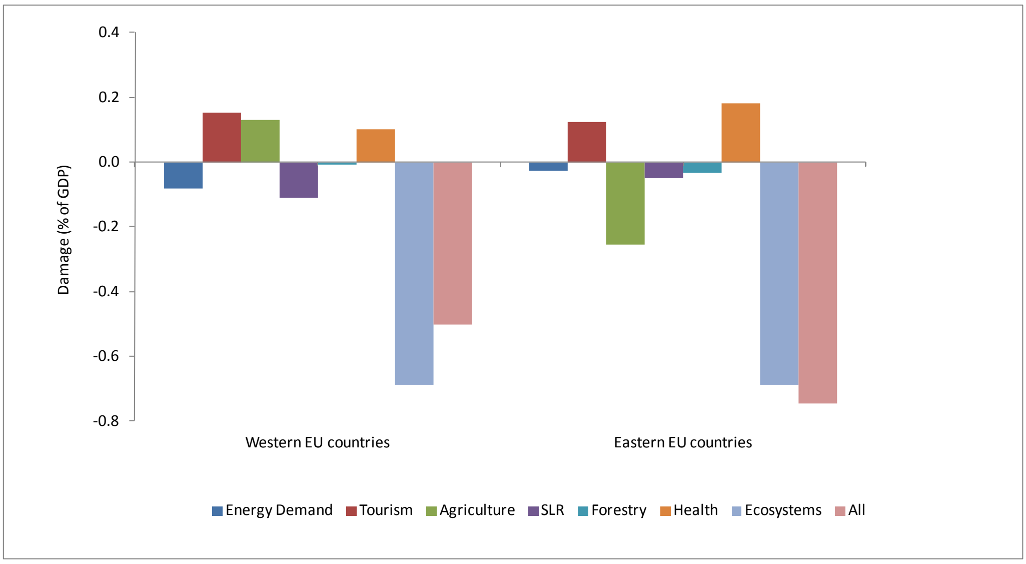


Figure 3 provides more details regarding Europe. Major drivers of impacts are the ecosystem loss component, followed by sea-level rise induced land losses and demand re-composition in the energy sector. Losses in the agricultural sector are particularly concerning in Eastern European countries, while Western EU reports gains in this sector. Impacts on tourism and health have positive effects on GDP.

Figure 3. Market and non-market impacts in Europe for a 2.5 Celsius degree temperature increase above pre-industrial levels (% of GDP)



2.3 *Modelling and Calibrating Climate Catastrophic Risk*

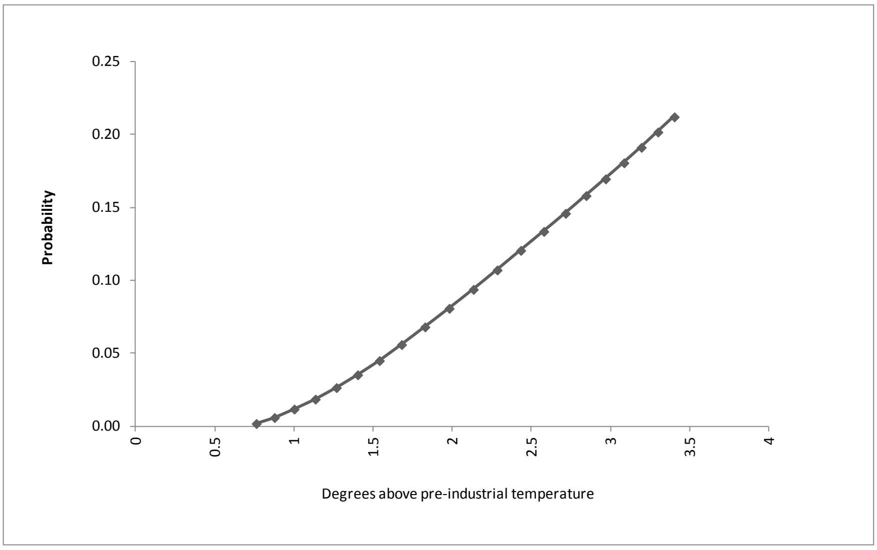
Following Gjerde *et al*. (1998), Bosello and Moretto (1999), catastrophic risk is implemented through a failure distribution function characterising the probability of a catastrophic event. It is denoted by a hazard rate, which assumes a Weibull form.

$$p(T_t) = \frac{1}{e^{\varphi \cdot \eta \cdot \left(T_t - T_0\right)^{1.5}}} \qquad (2)$$

$T_t - T_0$ is the temperature increase relative to the 2000 level, T_0. According to (2), maintaining the atmospheric temperature at the original level T_0 eliminates the possibility of catastrophic events, whereas it increases as temperature increases above T_0. Through mitigation, the planner can lower CO_2 emissions, CO_2 concentration, the temperature increase and ultimately the probability of the catastrophic event. However, the benefit of this endogenous control on temperature has to be compared with its costs (see below).

In (2) the causal relationship between temperature increase and catastrophic probability also depends on the two parameters φ and η. The parameter η is assigned the value of 2.5 to maintain the convexity of the hazard rate function. The parameter φ is calibrated to have a 16% probability of catastrophic occurrence, for a temperature increase of 3°C above the 2000 period ($\varphi=0.021$). In our model this happens at the end of the century. The 16% probability is an upward revision of the 4.8% value proposed by Nordhaus (1994), in view of more recent studies on the likelihood of catastrophic outcomes or trespassing of tipping points (Lenton *et al.*, 2008). For instance, Zickfeld *et al.* (2007) report probability estimates for the shutdown of Atlantic meridional overturning circulation in the range of 0–20% for low warming (2 °C) and between 0 and 60% for medium warming (2–4 °C). Tirpak *et al.* (2005) assign a 30% probability to the shutdown of Thermohaline Circulation. Arnell *et al.* (2005) report a probability between 4 and 75% for a collapse of the Greenland ice sheet. Gathering all the recent evidence, Kriegler *et al.* (2009) suggest a conservative lower bound for the probability of triggering at least 1 of those events of 16% for medium warming (2-4°C). Figure 7 shows the evolution of the catastrophic probability in the baseline.

Figure 4. Catastrophic probability and temperature Increase.



Catastrophic risk affects decision-making as the planner now faces an inter-temporal expected damage, which she can partially control[6] (eq. 3).

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[6] In fact, as noticed, the catastrophic probability could be eliminated if the temperature was blocked at its pre-industrial level, but in practice this would entail negative emissions.

$$CCDA_{n,t} = p(T_t)\cdot\frac{1}{1+ADAPT_{n,t}}\cdot CCD_{n,t} + (1-p(T_t))\cdot CCR_{n,t} \tag{3}$$

In (3) damage ($CCDA_{n,t}$) is a weighted sum of its non-catastrophic ($CCD_{n,t}$) and catastrophic ($CCR_{n,t}$) realisation. Weights are given by the probability of the catastrophic occurrence, $p(T_t)$, and its complement to one. In (3) the component $CCR_{n,t}$ has been calibrated such that the catastrophic damage equals 25% of GDP. According to equations (2) and (3), adaptation ($ADAPT_{n,t}$) does not play any direct role in decreasing the catastrophic probability. Nor does it play a role in decreasing the post-catastrophic penalty. This was motivated by the assumption that, by definition, a catastrophe is outside the system coping range.

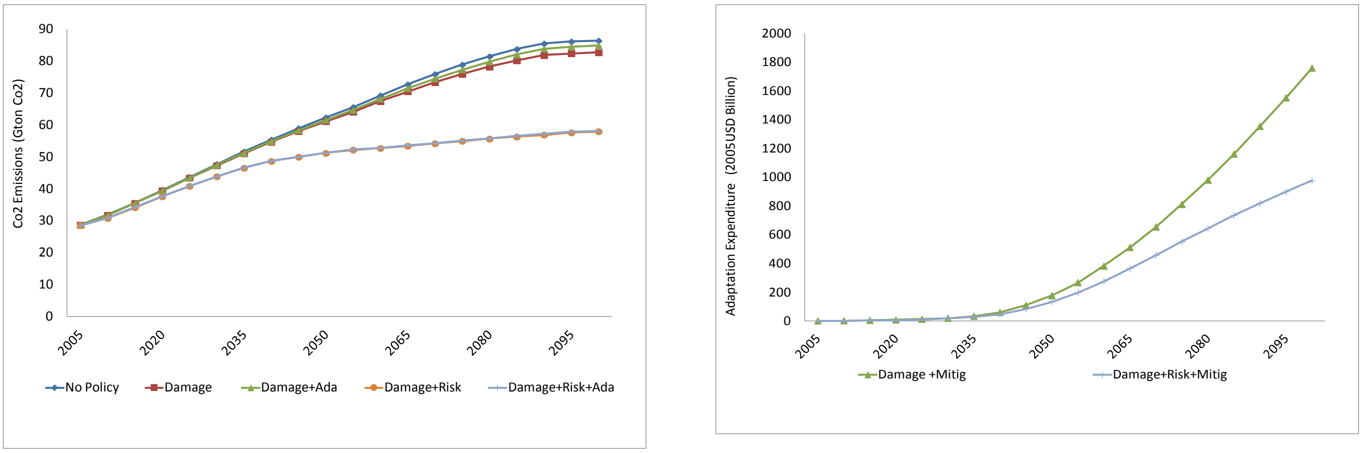
3. Results

3.1 Mitigation and adaptation under climate risk: global results

In a world without catastrophic risk, the standard results from the theoretical and empirical literature are confirmed. When available, both mitigation and adaptation policies would be used. Mitigation is close to zero due to free-riding incentives. In contrast, adaptation contributes almost entirely to damage reduction[7].

The introduction of catastrophic risk changes the picture. Despite the non-cooperative set-up, some degree of abatement becomes optimal, indicating that the risk of catastrophe mitigates the free-riding incentive. The optimal Nash abatement almost stabilises CO_2 emissions, which in 2100 are 58 instead of 84 $GtCO_2$ (Figure 5 left). Consequently, temperature increase is reduced from 3.8°C to 3.4°C in 2100, and the probability of the catastrophic outcome is reduced from 17% to 15%. More mitigation becomes optimal for each individual region because it helps to reduce not only the non-catastrophic damages, but also the probability of the adverse event occurrence. It is worth noticing that the emission path under risk is still much higher than that implied by a temperature stabilisation policy at 2°C that would require declining emissions after 2020.

Figure 5. CO_2 emissions (left, GtCO2) and adaptation expenditure (right, USD Billion) with and without catastrophic risk



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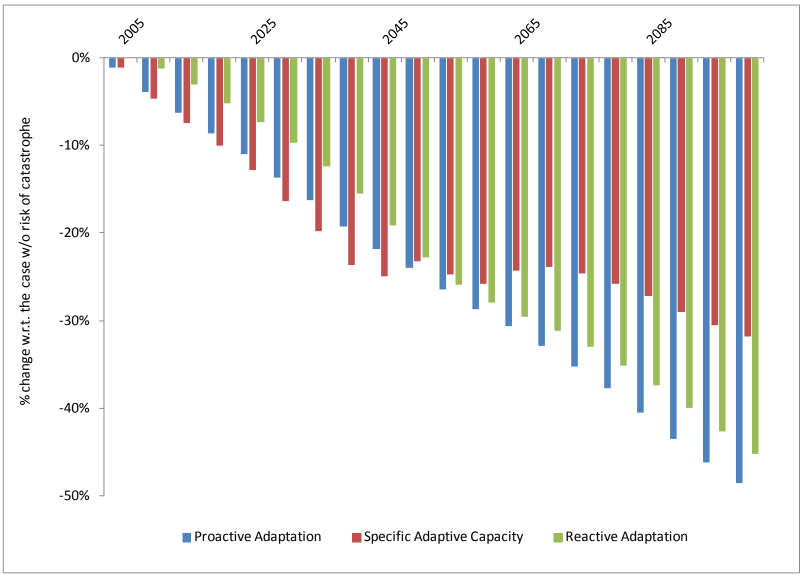
[7] In addition, the presence of adaptation reduces the mitigation effort compared to when only mitigation is viable, and vice versa. The crowding out of adaptation on mitigation is stronger than the opposite.

Catastrophic risk implies a lower crowding out effect of adaptation on mitigation and a higher crowding out effect of mitigation on adaptation. Throughout the century, adaptation reduces cumulative abatement by 48% without risk, but by less than 1% when risk is considered. Conversely, mitigation reduces cumulative adaptation expenditure by 1% without risk, and by 4.5% when risk is accounted for relative to the no mitigation case (Table 1).

Risk reduces the substitutability between adaptation and mitigation because only mitigation can manage the catastrophic probability. Nonetheless, some reciprocal degree of crowding out between the two strategies remains. Since part of the mitigation effort still responds by reducing the smooth climate-change damage component, it continues to be influenced by adaptation measures. Symmetrically, increased mitigation, which also acts on the non-catastrophic component of the damage, displaces adaptation.

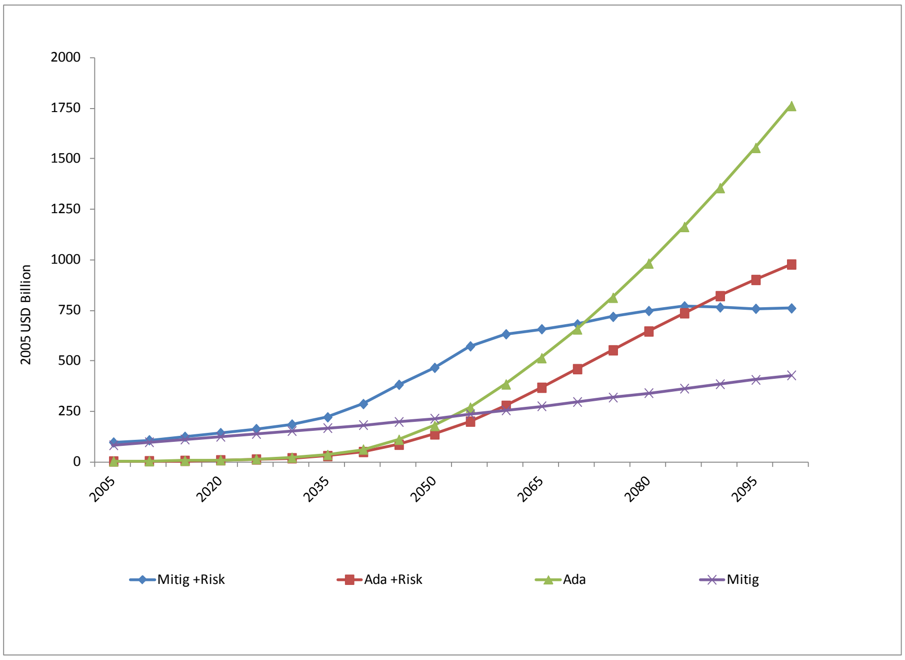
It is interesting to note that the crowding out effect of mitigation on adaptation is not uniform across different adaptation types (Figure 6). In particular, investment in adaptive capacity is most affected until 2040, and the least affected thereafter. This depends on the fact that until 2040, it is the prominent adaptation type, especially in developing countries, whereas other adaptation forms are negligible.

Figure 6. Effect of the risk of a catastrophe on different forms of adaptation



The presence of a climate catastrophic risk also implies that an increased amount of resources is devoted to mitigation (Figure 7). In sharp contrast with the no risk case, at the world level these are now primarily allocated to abatement (investment in energy saving R&D and renewable energy sources). Adaptation investment is therefore reduced not only because with increased mitigation there is a lower need to adapt, but also because, with a limited budget, resources are diverted from adaptation funding to foster mitigation.

Figure 7. Global mitigation (investments in clean power technologies*) and adaptation expenditure (USD billion) with and without catastrophic risk



**Mitigation expenditure includes investments in wind, solar, nuclear, and coal IGCC with CCS power, energy efficiency R&D, radical R&D (reducing the cost of advanced mitigation options),*

3.2 Mitigation and adaptation under climate risk: the Euro-Mediterranean picture

As one could expect, different regions react differently to the introduction of the same risk. In a non-cooperative setting, abatement is driven by the effective ability of a country to reduce overall temperature and thus catastrophic risk. Therefore, emissions are reduced especially by major emitters. At the same time, emissions reductions also tend to be higher in the regions where abatement costs are lower. Accordingly, strong reductions are observed in China, United States, Western Europe, Canada-Japan-New Zealand, South Asia, whereas moderate reductions occur in Middle East and North Africa and Latin America. Some regions (Non-EU Eastern Europe, Korea-South Africa-Australia, Sub-Saharan Africa, Eastern Europe) even increase emissions. Figure 8 shows the different reaction in terms of CO_2 emissions of Europe and MENA. When mitigation increases, adaptation decreases, but not proportionally. For instance, Europe, which doubles its mitigation effort, halves its adaptation expenditure from roughly 90 to 45 billion US Dollars by the end of the century (Figure 9). A comparable percent cut in adaptation expenditure also occurs in Middle East and North Africa, however, mitigation slightly increases (Figure 8). In these regions adaptation responds to local (non-catastrophic) damages, which are linked to the global average temperature increase. Therefore MENA, which benefits from emission cuts by other countries, can also spend less on adaptation. Finally, Figure 10 shows that risk does not substantively change the adaptation basket. Throughout the century, in the EU, the paramount adaptation type is proactive, followed by reactive expenditure and investment in adaptive capacity building. The situation is similar in MENA, with just a higher importance of investment in adaptive capacity building. The different mix reflects the priority of less developed areas to build a suitable environment for successful adaptation.

Figure 8. CO$_2$ emissions in Europe (left) and Middle East and North Africa (right)

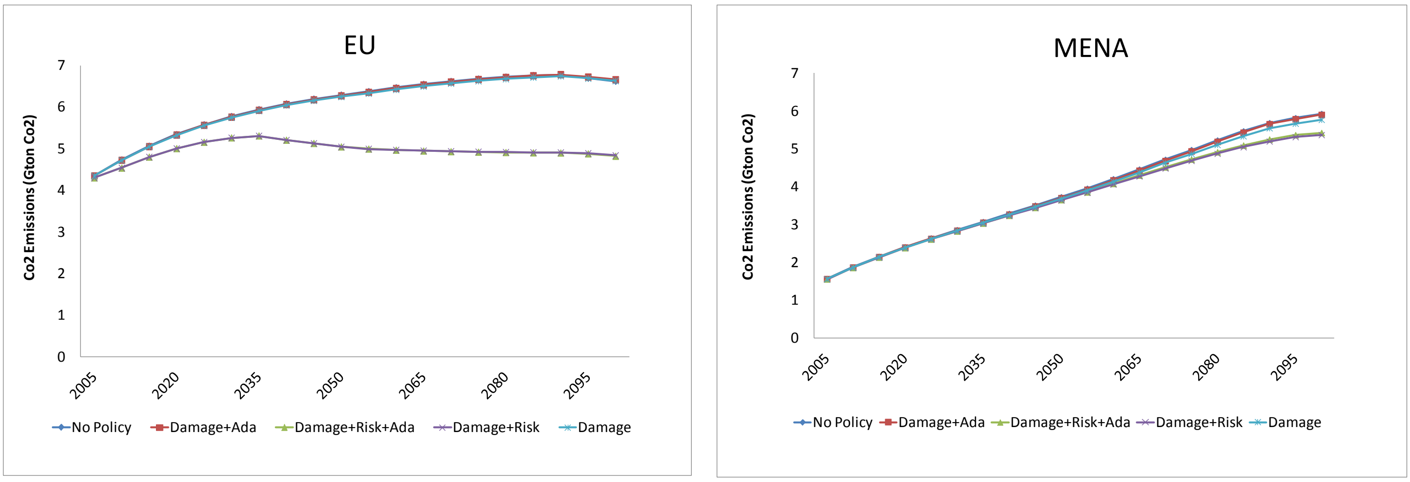


Figure 9. Mitigation (investments in clean power technologies) and adaptation expenditure (2005 USD billion) without (left) and with catastrophic risk (right). Results for Europe and Middle East and North Africa

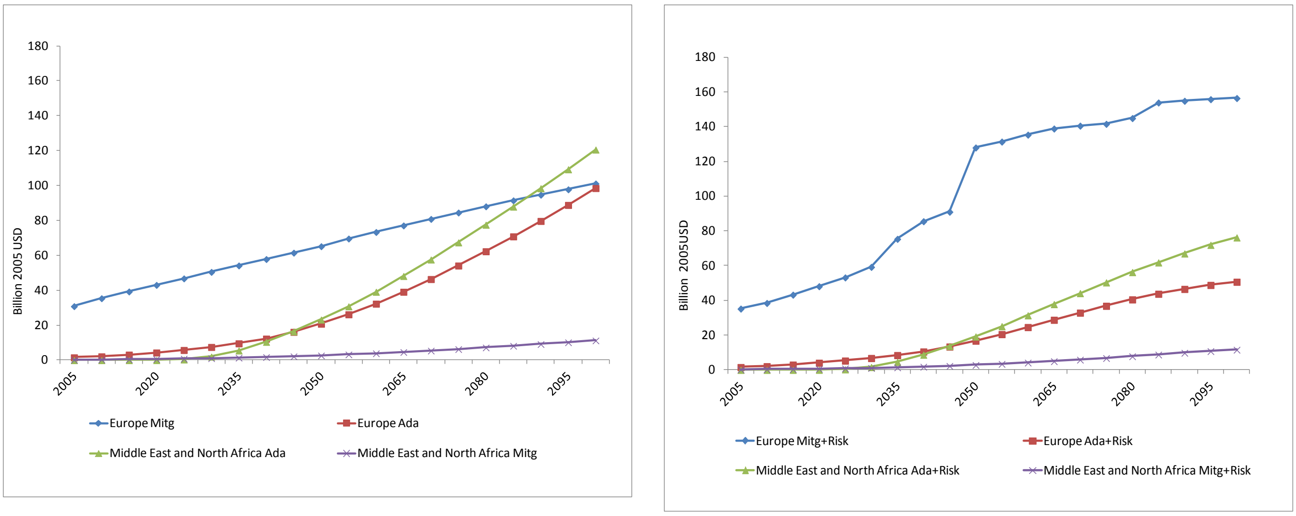


Figure 10. Cumulated expenditure in different adaptation forms, 2005-2100

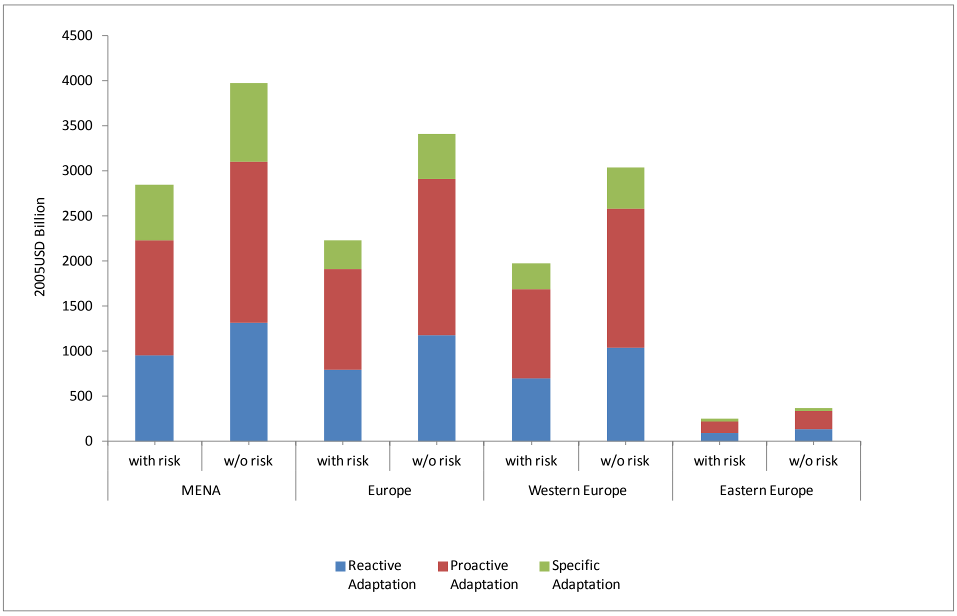


Table 1. Crowding out between adaptation and mitigation

	Impact of mitigation on cumulative adaptation investments		Impact of adaptation on cumulative emission reduction	
	With risk	W/o risk	With risk	W/o risk
World	-4.53%	-1.02%	-0.64%	-47.84%
Western Europe	-2.53%	-0.74%	-0.064%	-68.58%
Eastern Europe	-3.41%	-0.42%	-10.39%	-15.38%
Middle East and North Africa	-2.34%	-0.57%	-11.17%	-65.78%

The results discussed in this section have important policy implications. In a world characterised by smooth and reversible climate damages, mitigation is a marginal option. Although viable and welfare improving if coupled with adaptation, mitigation would be less effective than adaptation. However, in a world with catastrophic risk, mitigation is the only strategy capable of reducing the probability of the catastrophic outcome. Therefore, it becomes a key policy variable, irrespective of its ability to reduce the non-catastrophic damage. This clearly indicates that mitigation choices should be driven mainly by precautionary considerations and to some extent independently from adaptation, while adaptation should tackle the residual damage not accommodated by mitigation.

3.3 Sensitivity

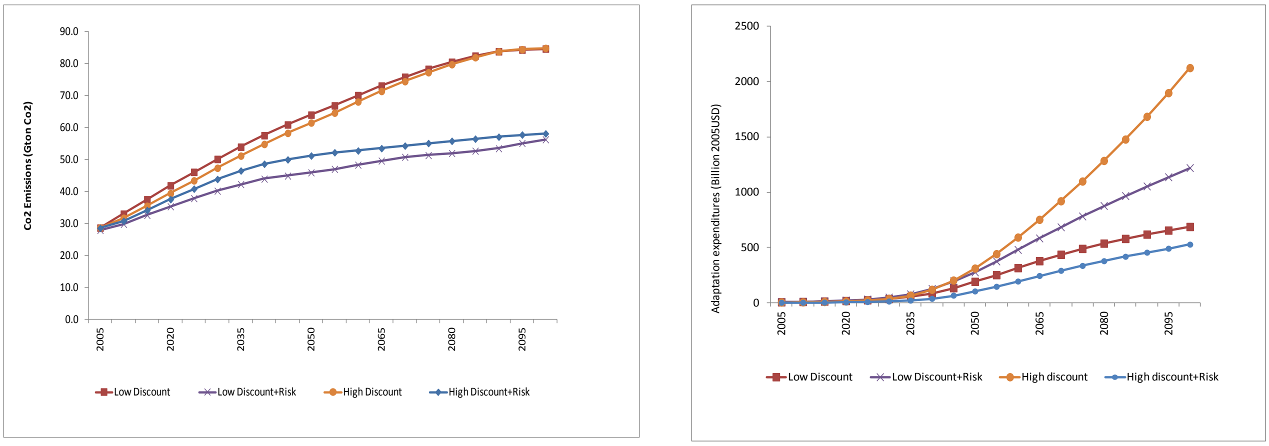
This section examines the sensitivity of our results, and in particular of the trade-off between adaptation and mitigation when the discount rate, the catastrophic risk, and the catastrophic penalty change.

Discounting

Both emissions and adaptation choices, as any intertemporal cost-benefit decision, are strongly influenced by the discount rate used to evaluate future damages. Within the environmental economics literature, different views on discounting originated a long, lively, and still unsettled debate (see for example recently Weitzman 2001, Stern 2006, and Nordhaus 2007). Both positive and normative arguments can be used to justify either low or high discount rates. However, recent studies show that in a non-cooperative framework, changing assumptions on discounting have a limited influence on the optimal level of mitigation action (Bosetti *et al.* 2011). This is a direct consequence of the inability of individual regions to internalise the environmental externality. Accordingly, if it is true that a lower discount rate should favour mitigation as future damages gain in importance, at the same time it favours future consumption levels and thus emissions. Without the internalisation of the emission negative externality, the two effects almost perfectly balance or the second even prevails.

This is no more the case once catastrophic risk is introduced, as lower discounting unambiguously implies more abatement (see Figure 11). Interestingly, adaptation, in turn, is not reduced. In fact, a lower discount rate also increases adaptation. Therefore, mitigation and adaptation move together. Higher weight on the future risk increases mitigation, whereas higher weight on the future non-catastrophic damage component increases adaptation. In other words, the introduction of risk narrows the difference between the non-cooperative and cooperative outcomes.

Figure 11. CO2 emissions (left) and adaptation expenditure (right). Sensitivity to discount rate



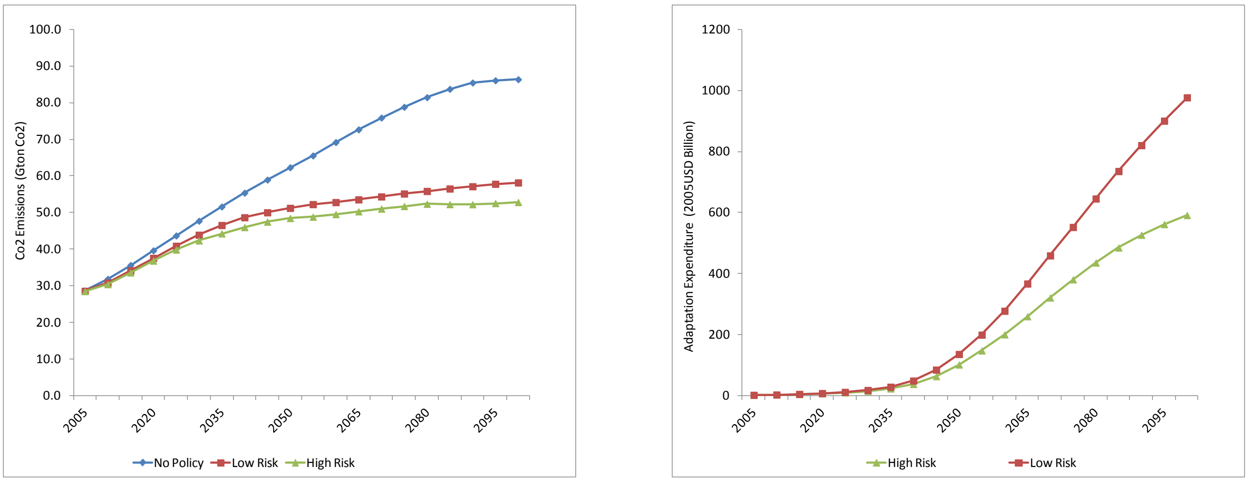
Risk

Results sensitivity to different catastrophic probabilities is tested contrasting the “default” risk case with a high-risk case.

The first, as previously mentioned, assumes a 25% loss of GDP in all regions with a probability of 16% for a +3°C; the second, a 25% loss of the GDP in all regions, but with a probability of 35%.

As expected, the higher probability associated with the catastrophic event has the effect of increasing abatement (see Figure 12, left). Differently from the previous case of reduced discount rate, adaptation is now crowded out (see Figure 12, right). Moreover, when the risk of a catastrophic event increases, the crowding out of abatement induced by adaptation is reduced basically to zero, from -0.65% to +0.07% (see Table 2).

Figure 12. CO_2 emissions (left) and adaptation expenditure (right). Sensitivity to risk



Catastrophic Damage

The sensitivity with respect to the size of catastrophic damages is tested comparing three different damage levels:

1) ***Lower catastrophic damage:*** 10% of regional GDP loss in each region with a 16% probability for a +3°C temperature increase;

2) ***Default catastrophic damage:*** 25% of regional GDP loss in each region with a 16% probability for a +3°C temperature increase;

3) ***Higher catastrophic damage:*** 99% of regional GDP loss in each region with a 16% probability for a +3°C temperature increase;

A higher catastrophic damage induces more mitigation and less adaptation (Figure 13). Moreover, the crowding out of adaptation on abatement is also reduced (Table 2). However, when the damage is large enough, adaptation and abatement can become complements, but only in the long run. Note that even with an enormous catastrophic loss, the trend in global emissions is never reverted from increasing to decreasing. At most, emissions are stabilised.

Figure 13. **CO_2 emissions (left, GtCO2) and adaptation expenditure (right, USD Billion). Sensitivity to catastrophic penalty**

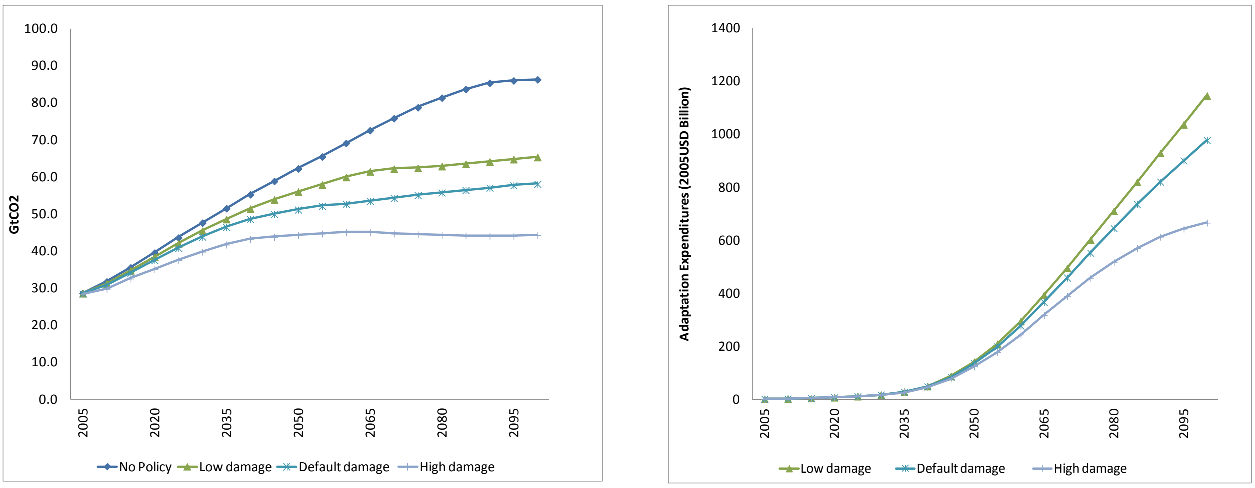


Table 2. **Crowding out of adaptation on mitigation. Sensitivity to damage**

	Crowding out of adaptation on abatement (Cumulative emission reduction 2005-2100)
Lower damage 10% GDP loss with P = 16% at +3°C	-3.40%
Default damage 25% GDP loss with P = 16% at +3°C	-0.64%
Higher damage 99% GDP loss with P = 16% at +3°C	1.02%
Higher risk 25% GDP loss with P = 35% at +3°C	0.07%

3.4 Mitigation and adaptation: a strategic analysis

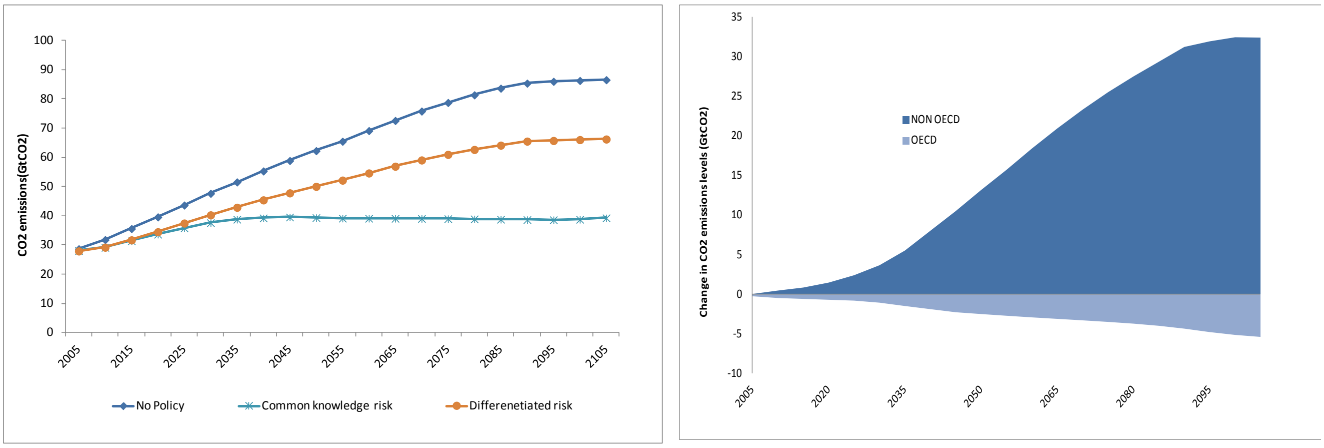
In this section we analyse the use of adaptation transfer and of adaptation expenditure by a group of countries as a strategic leverage to foster mitigation outside the group. More specifically, maintaining a non-cooperative and cost-benefit setting, we assume that the OECD countries perceive a high risk from climate change, whereas the non-OECD countries react only to the non-catastrophic damage component. The risk setting chosen is a combination of probability (50%) and penalty (99% of GDP) that would lead, if shared by all countries, to a stabilisation of CO_2 emissions by the mid-century.

We therefore assume that in this context, the OECD countries are not only inclined to stronger domestic abatement, but are also willing to foster abatement in non-OECD countries. Indeed, risk can be better curbed by an enlarged abatement effort since it depends on global temperature. Non-OECD countries, in turn, have to be convinced to abate more because they do not perceive the lower risk of a catastrophe associated with emission reduction. In a non-cooperative setting this is possible if they receive compensation at least equal to the additional abatement cost. The leverage used to get the desired result by the OECD is through financing adaptation needs in non-OECD. Specifically, OECD countries would finance all adaptation needs of non-OECD countries to a ceiling of USD 100 billion per year. This is just an indicative figure inspired by the annual transfers from developed to developing countries proposed during COP 15 at Copenhagen. Transfers are divided across donors proportionally to the respective GDP share of the group total. When the total adaptation expenditure of the recipients exceeds USD 100 billion, these are shared among receivers proportionally to the respective adaptation need share of the group total.

Our questions are then the following: is adaptation funding sufficient to foster mitigation in the group that is unwilling to abate? Under which conditions and to what extent? Are there more efficient solutions than adaptation funds to induce abatement?

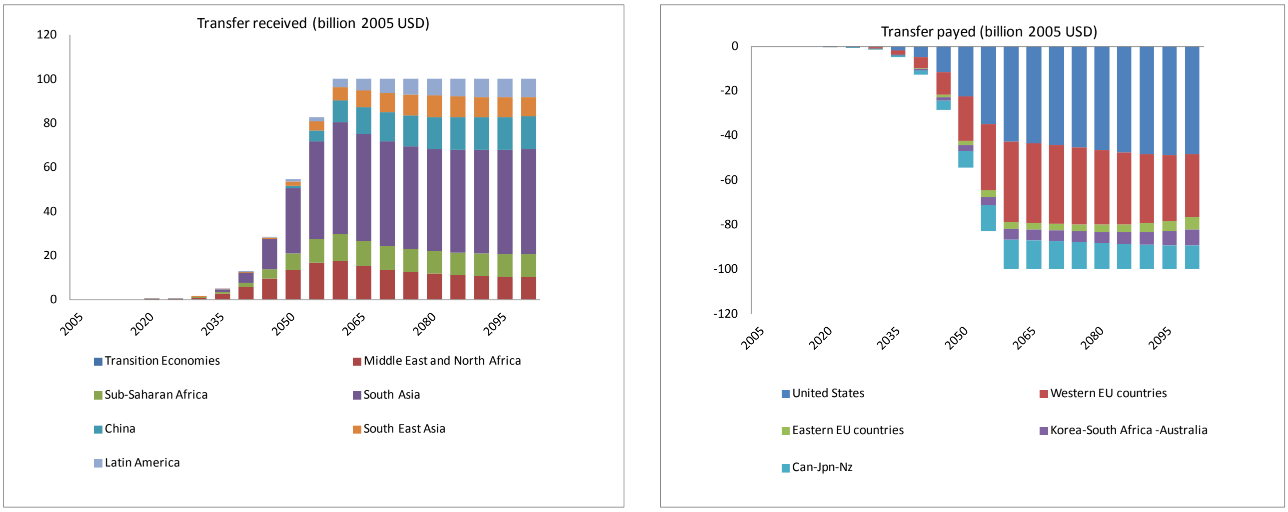
Figure 14 first compares the outcome of the non-cooperative game without any adaptation transfers from the OECD countries to the non-OECD countries when all the regions share the same risk perception (“Common risk perception” case) with the “differentiated risk perception” case - outcome of the non-cooperative game without transfers, but with a lower risk perception from the non-OECD countries. When only OECD countries perceive a high climate risk their abatement is higher than the case when the risk is a common global concern because they compensate the reduced abatement of the non-OECD countries. In fact, non-OECD countries abate even less than in the case with non-catastrophic risk.

Figure 14. Global CO_2 emissions ($GtCO_2$, left) and change in emission levels ($GtCO_2$, right) when differentiated risk perceptions are compared with common risk perceptions



In a second simulation (Transf A), adaptation transfers are activated. The major donors are the USA and Western Europe while the larger recipients are the Middle East and North Africa, South East Asia, Sub Saharan Africa (Figure 15). The ceiling of USD 100 billion is reached in 2060. As adaptation needs in developing countries rapidly increase after 2040, in 2100, USD 100 billion cover roughly 19% of the total adaptation needs.

Figure 15. Adaptation funding: recipients (non-OECD) and donors (OECD)



Adaptation funds almost completely replace domestic adaptation in receiving countries, which in fact only slightly increases. Investment in physical capital and in mitigation activities (energy saving R&D and renewable technologies) is basically unaffected. The additional available budget is almost totally used for consumption that (discounted) throughout the century increases by 0.046% (or by USD 265 billion) compared to the case with no transfers. In other words, mitigation behaves quasi-linearly in non-OECD preferences. After its optimal level is reached, consistent with the countries risk perception, this becomes insensitive to further shifts of the budget line. Therefore, our results partly confute theoretical findings from Buob and Stephan (2011). In our particular setting, when countries start from a non-cooperative optimum, the adaptation funds do not crowd out domestic mitigation. In contrast, the funds crowd out domestic adaptation, even when adaptation and mitigation are substitutes[8]. At the same time, even though mitigation is not displaced, it is confirmed that foreign adaptation funds do not create an incentive to further reduce emissions.

Accordingly, adaptation funds can only foster mitigation if a “conditionality clause” is included. Let us thus assume that adaptation funds will be delivered only in the presence of a binding-detectable mitigation commitment from the non-OECD countries.

To simulate this situation we start from the same adaptation transfer as in case Transf A, but imposing non-OECD countries to also invest in either energy-saving R&D or renewable energy. We design this deal to be welfare improving for the non-OECD countries by identifying the mitigation threshold that leaves non-OECD countries indifferent between accepting adaptation funds and engaging in additional mitigation or giving up the adaptation funds and avoiding further abatement effort. This is done by imposing different levels of additional mitigation investment in either energy- saving R&D (1/10 of the transferred resources for adaptation is depicted in Transf A+1/10R&D; 1/5 in Transf A+1/5R&D) or renewable energy (1/10 in Transf A+1/10 Ren respectively).

In terms of welfare, which in AD-WITCH is a function of consumption, non-OECD countries would benefit from this exchange, and therefore would be willing to accept, as

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[8] A potentially different situation would be one in which, because of an adaptive capacity deficit and a resource constraint, developing countries implement sub-optimal (lower than needed) adaptation levels. In this case, foreign and domestic adaptation can be expected to be additional. This issue, which will imply a change in the model setting, will be explored in further research.

long as the required investments in energy-saving R&D or renewable energy is not much larger than 1/5 of the adaptation funds received[9] (see Table 4). One dollar received in adaptation funds "weighs" 1/5th of one dollar spent in mitigation. This happens because every additional abatement effort in non-OECD countries is strategically balanced by an increase in emissions in the OECD countries (Figure 15), which therefore erodes part of the benefit of the non-OECD mitigation.

Does this conditional transfer succeed in cutting emissions? The overall impact of the transfer on non-OECD emissions is almost negligible, though it moves in the expected direction (Figure 16). Despite the small magnitude of the effect, it can be noticed that allocating the same resources to renewable energy entails higher emission reductions than when allocated to energy-saving R&D. AD-WITCH nicely captures the well-known rebound effect: more efficient energy input implies also as a secondary effect a higher energy use. If the funds allocated to energy-saving R&D are low enough (1/10 of the adaptation fund received), emissions in non-OECD countries can in fact increase. At the world level, emissions decrease only when adaptation funds are coupled with investment in renewable energy. In AD-WITCH the cost of renewables declines endogenously with installed capacity (Learning-By-Doing). Therefore, the additional capacity installed in the non-OECD countries reduces the technology cost in the OECD countries as well.

As a final experiment we examine the effect of adaptation implemented in OECD countries on mitigation and adaptation in the non-OECD ones. The aim, following the ideas put forward by Auerswald *et al.* (2011) and Marrouch and Chaudhuri (2011) is to test whether adaptation can be used as strategic signal or leverage by a group of countries to induce more abatement in other countries. Specifically, we assume that OECD countries unilaterally decide a 10% increase of adaptation expenditure. As adaptation and mitigation are substitutes, abatement in OECD regions decreases (cumulated OECD emissions increase by 18.38%). As a reaction, abatement in non-OECD regions slightly increases (cumulated emissions decline by 0.55%) while adaptation remains basically unchanged (-0.009%). More precisely, the mild increase in reactive adaptation, +0.074%, is compensated by a reduction in proactive and capacity building, -0.059% and -0.072%). This seems to confirm Auerswald *et al.* (2011) intuition and to confute Marrouch and Chaudhuri (2011) point. The reaction to decreased mitigation in one country or group is always contrasted with an increase in mitigation outside the group, notwithstanding the possibility to adapt. However, the effect on overall abatement is negative, as world cumulated emissions increase by 3%. This increase is much higher than that in the case of adaptation transfers. This raises some caution on the practical possibility of using adaptation as a credible signal of low mitigation commitment in one country in order to induce mitigation in other countries.

Summarising, the results presented so far seem to suggest that using adaptation, through international financing or as a strategic device, does not seem the most efficient and effective way of buying emission reduction in non-OECD countries. A legitimate question then is whether OECD countries could achieve better results by directly financing abatement in the non-OECD ones. Let us assume this would be possible, neglecting for experimental sake all the transaction costs potentially involved. In a last simulation (Trans M) we assume that what is available to adaptation is directly invested by OECD countries to support investment in renewable energy in the non-OECD countries. The region thus experiences an increase in its investments in renewables from USD 12 to USD 55 billion in 2050, from USD 47 to USD 100billion in 2100. Emission reduction in non-OECD countries is effectively higher (-0.4%) and, because of the technical change effect, OECD´s emission

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[9] Indeed when the investment in mitigation is 1/3rd of the adaptation transfers, non-OECD countries would be worse off than in the case of no transfers.

reduction is also higher (-1%) as the global cost of renewable energy is 10% lower compared to the case with no transfer.

In terms of discounted consumption, developing countries, albeit still better off with a mitigation transfer than without, would slightly prefer a support on adaptation (Table 4 third vs. fourth column). Indeed, the benefit from additional abatement is a public good, whereas the benefit from adaptation is fully appropriable. Moreover, adaptation funding is replacing what developing countries would have done anyway, while mitigation funding is financing something additional with respect to what is optimal for them. Contrary to OECD countries, which perceive the risk of a catastrophe, non-OECD countries lack this perception and therefore under evaluate the benefit of mitigation.

This suggests two partly countervailing messages. On the one hand, albeit in principle, adaptation funding can be used by developed countries as a leverage to induce more mitigation in developing countries, but the effectiveness of this strategy is very limited. The resources needed by developing countries to de-carbonise their production and energy system are much higher than USD 100 billion yearly. When also non-OECD countries perceive the risk of a catastrophe and global emissions are stabilised, their additional investments in clean energy will reach USD 100 billion in 2035 and climb to USD 300 billion in 2080 just to stabilise emission levels.

On the other hand, although the transfer would reduce consumption possibilities in the OECD countries, in terms of GDP they could experience small gains, especially when the transfer goes to financing renewables (see Tables 5, case Trans M and Trans A+1/10 Ren). The mechanism behind this is the technological change effect that is induced by the transfer. This is quite a powerful insight. Even though a financial support to adaptation from developed countries would be insufficient to spur significant mitigation in developing countries, it could be beneficial for the donor countries. This happens if the transfer is specifically designed to foster investments in those technologies that, because of other market failures, are sub-optimal in the receiving countries.

Figure 16. CO2 cumulated emissions 2005-2100, percentage change compared to the case without transfer

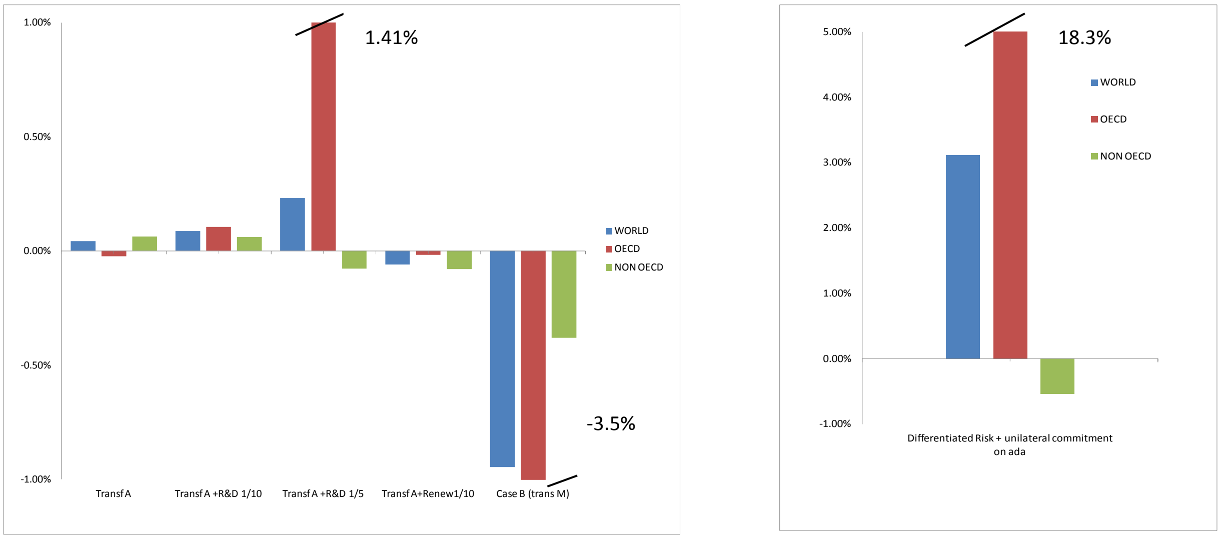

Table 4. Consumption: % change compared with the case with no transfer (discounted over the century).

% change (USD Billion)	Transf A	Transf A+Renew1/10	Transf M	Transf A +R&D 1/10	Transf A +R&D 1/5	+10% adaptation in OECD
WORLD	0.001% (7.78)	0.002% (29.22)	-0.001% (-21.12)	-0.001% (-22.55)	-0.003% (-48.93)	-0.020% (-303.80)
OECD	-0.026% (-257.42)	-0.024% (-232.28)	-0.028% (-278.29)	-0.027% (-263.38)	-0.016% (-155.80)	0.030% (293.09)
NON-OECD	0.046% (265.20)	0.045% (261.50)	0.045% (257.17)	0.042% (240.83)	0.018% (106.87)	-0.103% (-596.89)
Europe	-0.025% (-97.76)	-0.022% (-88.11)	-0.056% (-220.46)	-0.017% (-68.31)	-0.057% (-223.66)	-0.012% (-48.24)
MENA	0.086% (52.42)	0.086% (51.93)	0.078% (47.34)	0.081% (49.34)	0.048% (29.27)	-0.141% (-85.32)

Note: World and non-OECD figures do not include Transition Economies as in the simulation they neither receive nor give adaptation funds, being positively affected by climate change.

Table 5. GDP difference compared to the case with no transfer. Percentage point difference

% change (USD Billion)	Transf A	Transf A+Renew1/10	Transf M	Transf A +R&D 1/10	Transf A +R&D 1/5	+10% adaptation in OECD
WORLD	0.001% (18.99)	0.004% (73.53)	0.026% (501.88)	-0.001% (-21.74)	-0.007% (-142.42)	-0.087% (-1698.61)
OECD	0.003% (35.69)	0.005% (63.62)	0.022% (277.23)	-0.002% (-30.95)	-0.004% (-49.40)	-0.077% (-952.10)
NON-OECD	-0.002% (-16.70)	0.001% (9.91)	0.032% (224.65)	0.001% (9.21)	-0.013% (-93.02)	-0.105% (-746.51)
Europe	0.004% (17.78)	0.006% (28.17)	-0.013% (-63.97)	-0.005% (-22.70)	-0.033% (-163.43)	-0.090% (-449.29)
MENA	-0.004% (-3.17)	0.004% (2.77)	0.066% (50.36)	0.008% (5.76)	-0.008% (-6.38)	-0.135% (-102.77)

Note: World and non-OECD figures do not include Transition Economies as in the simulation they neither receive nor give adaptation funds, being positively affected by climate change.

4. Conclusions

As stressed by important strategic documents like the 2009 EU White Paper on Adaptation or the 2010 "Cancún Adaptation Framework", mitigation and adaptation are amply recognised as necessary strategies to combat climate change. Against this background a rapidly expanding scientific literature is trying to devise normative indications on the optimal combination of the two. This paper contributes to the literature by framing the policy balance problem in a context of climate catastrophic risk. In the proposed setting, the probability of experiencing a climate-change related catastrophic event is linked to temperature increase and thus to emissions levels. Therefore, through mitigation, regional representative policy makers can partly control the probability of the adverse occurrence. At the same time mitigation and adaptation concur to reduce the smooth or continuous climate change damages. The analysis is performed applying AD-WITCH, a climate-economics integrated assessment model, whose damage function has been completely revised to incorporate the latest available information. The exercise is developed in a non-cooperative environment where regions act without internalising the effect of other regions' actions.

The presence of catastrophic risk induces substantive mitigation effort even in the non-cooperative setting as the incentive to free ride on others' abatement is greatly weakened. The policy balance shifts in favour of mitigation and away from adaptation and the responsiveness of mitigation to changes in adaptation decreases. Compared to a world without climate catastrophes, mitigation action is much stronger and only marginally influenced by the presence of adaptation efforts. Symmetrically, adaptation action is weaker and more easily affected by mitigation.

Nonetheless, the strategic complementarity between mitigation and adaptation does not vanish. Even though, as we do assume, adaptation cannot influence the catastrophic probability, it still complements mitigation to address the residual damage that cannot be accommodated by mitigation alone. By the same token, a trade-off between mitigation and adaptation persists: when adaptation increases, the need to mitigate the "smooth part" of climate change damages decreases. Therefore, even though greatly reduced, a minimal crowding out of adaptation on mitigation remains. As usual, higher mitigation crowds out adaptation.

These findings suggest a first important policy implication: in a world characterised by catastrophic risk, mitigation becomes the key policy variable as it is the only strategy able to curb the catastrophic probability. Therefore, mitigation should be decided mainly on the basis of precautionary considerations and only marginally considering its capacity to reduce the smooth climate change damage; adaptation has to be subsequently deployed to tackle that part of environmental damage that mitigation cannot accommodate.

The second part of the paper investigates whether remaining in a strictly non-cooperative environment, adaptation in a country or group can be used as a leverage to increase abatement effort outside the group. Two experiments are designed.

In the first experiment it is assumed that OECD countries would finance all adaptation needs of non-OECD ones to a ceiling of USD 100 billion.

The first unpleasant result is that adaptation funding *per se* doesn't induce developing countries to either abate or adapt more. Domestic adaptation expenditure is displaced almost perfectly by international adaptation aid and mitigation remains unchanged. Therefore adaptation funds should be conditional on additional mitigation. In this case, two major messages emerge. It is effectively possible that adaptation funding fosters some additional mitigation in developing countries, but the practical effectiveness of this strategy is very limited. On the one hand the resources needed by developing countries to substantively de-carbonise their production and energy system are much higher than USD 100 billion yearly. On the other hand, in the chosen non-cooperative setting any additional abatement effort in non-OECD countries is strategically balanced by an increase in emissions in the OECD ones, which therefore erodes part of the benefit of the non-OECD mitigation. Consequently, investing in mitigation is more costly than investing in adaptation. Notwithstanding the negligible effect on mitigation, when adaptation funding is conditional on an increased investment in renewable energy sources in developing countries, the GDP in developed countries slightly increases. The final result is also the highest world abatement across all the cases examined. This is quite a powerful insight. Even though a financial support to adaptation from developed countries would be insufficient to spur significant mitigation in developing countries, it could be beneficial for the donor countries. This happens if the transfer is specifically designed to foster investments in those technologies that, because of other market failures, are sub-optimal in the receiving countries.

In a second simulation it is assumed that OECD regions unilaterally decide an increase of their adaptation expenditure as strategic signal to induce more abatement in other countries. As a reaction, abatement in non-OECD regions effectively increases, confirming that the presence of adaptation does not change the response to decreased mitigation in one country or group, which is always contrasted with an increase in mitigation outside the group. However, the effect on overall abatement is negative, as world cumulated emissions increase.

Summarising, the results presented so far seem to suggest that using adaptation, through international financing or as a strategic device, does not seem the most efficient and effective way of buying emission reduction in non-OECD countries. This of course does not mean that adaptation funding should not be pursued. It can effectively address adverse distributional implications of climate change impacts and, with appropriate conditionality, may contribute to correct some inefficiencies with mutual benefit for the receivers and the donors.

To conclude two important qualifications of these results are necessary. First, the outcomes are based on a situation in which both adaptation and mitigation are at their (non-cooperative) optimum. Welfare implication of a reaction to adaptation transfers can be different in a second-best condition assuming for instance that resource or capacity constraints would impose sub optimal adaptation levels in the non-OECD countries.

Second, the overall setting is non-cooperation. Although we strongly believe that this framework is the most realistic, (and therefore also the most interesting to study), a cooperative optimum can offer partly different insights.

Disclaimer

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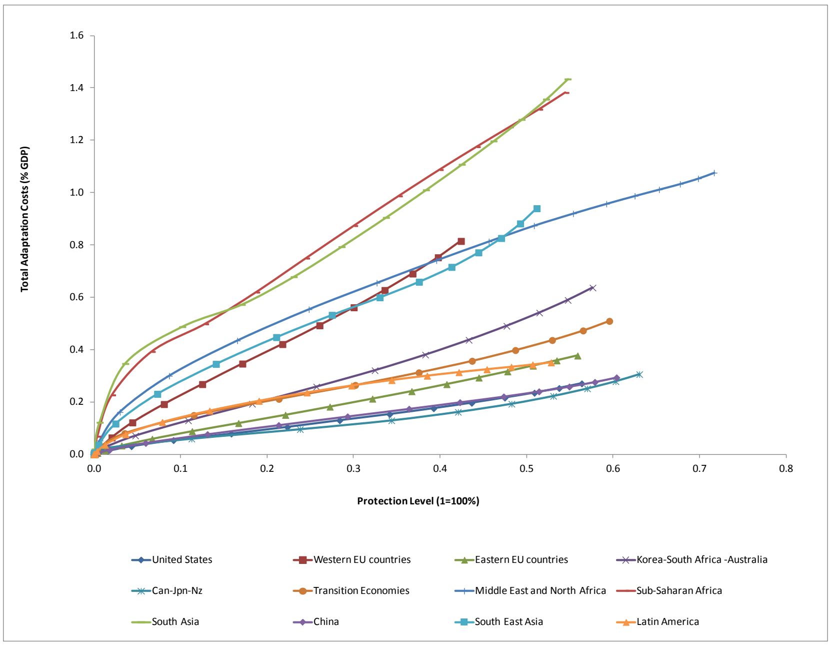
Appendix: Model calibration

Adaptation cost curves

The calibration of macro-regional adaptation costs and effectiveness is based on the estimates reviewed in Agrawala and Fankhauser (2008), which provides one of the most recent and complete assessment on costs and benefits of adaptation strategies, integrated with a number of other bottom-up, sectoral specific studies, reviewed and described in Agrawala *et al.* (2010). Figure AI depicts the adaptation cost curves illustrating the relationship between adaptation expenditure and the protection level achieved in the different model regions. Further details on the calibration data and procedure are described in Agrawala *et al.* (2010).

Figure AI: Calibrated adaptation cost curves in the AD-WITCH model



What differs from the model calibration proposed in Agrawala *et al.* (2010) is the damage component.

Damage calibration

The market component of climate change damages has been revised using the estimates provided by the interdisciplinary work of the FP7 CLIMATECOST[10] project (see Bosello *et al.* 2012). That project quantified the physical and economic impacts of climate change on sea-level rise, energy demand, agricultural productivity, tourism flows, net primary productivity of forests, floods, reduced work capacity because of thermal discomfort. All impacts, except those on floods and health, which focus on the EU, have been assessed for a number of macro regions covering the world as a whole. The joint macro-economic effect of all climate change impacts has then been assessed using the top-down, recursive-dynamic computable general equilibrium (CGE) model, ICES(Intertemporal Computable Equilibrium System). This procedure made it possible to capture the role of market-driven adaptation (also named autonomous adaptation) triggered by price changes, which is not accounted for by the reduced-form damage functions used in integrated

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[10] CLIMATECOST; research program: FP7 Environment; project reference number: 212774. http://cordis.europa.eu/search/index.cfm?fuseaction=result.document&RS_LANG=EN&RS_RCN=11479505&q=; www.climatecost.cc

assessment models such as DICE/RICE99 and AD-WITCH as in Agrawala *et al.* (2010). Therefore, the market damage component included in the present study is net of the autonomous adaptation effects. The non-market damage component, referring primarily to potential ecosystem losses and non-market health impacts, has been assessed using a willingness to pay approach. The next two sections describe more in detail the methodologies used to evaluate market and non-market impacts.

The market damage component

The above-mentioned bottom-up impact studies and the resulting CGE impact assessment are summarised below. For further details, the interested reader should directly address the specific research.

Estimates of coastal land loss due to *sea-level rise*, are based upon the DIVA model outputs (Vafeidis *et al.* 2008). DIVA (Dynamic Integrated Vulnerability Assessment) is an engineering model designed to address the vulnerability of coastal areas to sea-level rise. The model is based on a world database of natural system and socio-economic factors for world coastal areas reported with a spatial resolution of 5°. The temporal resolution is 5-year time steps until 2100 and 100-year time steps from 2100 to 2500. Changes in natural as well as socio-economic conditions of possible future scenarios are implemented through a set of impact-adaptation algorithms. Impacts are then assessed both in physical (*i.e.* sq. km of land lost) and economic (*i.e.* value of land lost and adaptation costs) terms.

Changes in *tourism flows* induced by climate change are derived from simulations based on the Hamburg Tourism Model (HTM) (Bigano *et al.* 2007). HTM is an econometric simulation model, estimating the number of domestic and international tourists by country, the share of international tourists in total tourists and tourism flows between countries. The model runs in time steps of 5 years. First, it estimates the total tourists in each country, depending on the size of the population and of average income per capita; then it divides tourists between those that travel abroad and those that stay within their country of origin. In this way, the model provides the total number of holidays as well as the trade-off between holidays at home and abroad. The share of domestic tourists in total tourism depends on the climate in the home country and on per capita income. International tourists are finally allocated to all other countries based on a general attractiveness index, climate, per capita income in the destination countries, and the distance between origin and destination.

Changes in average crops' productivity per world region derive from the ClimateCrop model (Iglesias *et al.* 2009; Iglesias *et al.* 2010). Crop response depends on temperature, CO_2 fertilisation and extremes. Water management practices are also taken into account. Spatially integrating all these elements, the model estimates climate change impacts and the effect of the implementation of different adaptation strategies.

Responses of residential energy demand to increasing temperatures derive from the POLES model (Criqui 2001, Criqui *et al.* 2009). It is a bottom-up partial-equilibrium model of the world energy system extended to include information on water resource availability and adaptation measures. It determines future energy demand and supply according to energy prices trend, technological innovation, climate impacts and alternative mitigation policy schemes. The present version of the model considers both heating and cooling degree-days in order to determine the evolution of demand for different energy sources (coal, oil, natural gas, electricity) over the time-horizon considered.

Data on changes in forest net primary productivity *(NPP)* are provided by the LPJmL Dynamic Global Vegetation Model developed at the PIK – (Boundeau *et al.* 2007, Tietjen *et al.* 2009). The LPJ model, endogenously determines spatially explicit transient vegetation composition and the associated carbon and water budgets for different land-uses including forestry. It estimates the effects of climate change on forest (NPP) for all countries in the world, with or without carbon fertilisation effect on vegetation and the role of forest fires.

Data on climate change impacts on river floods are based on results from the LISFLOOD model (Van der Knijff *et al.* 2009, Feyen 2009). This is a spatially distributed hydrological model embedded within a GIS environment. It simulates river discharges in drainage basins as a function of spatial information on topography, soils, land cover and precipitation. This model has been developed for operational flood forecasting at European scale and it is a combination of a grid-based water balance model and a 1-dimensional hydrodynamic channel flow routing model. The LISFLOOD model can assess the economic loss in the EU27 countries per different macro-sectors: residential, agriculture, industry, transport and commerce together with the number of people affected. The role of climate change, and of economic growth in determining the final losses can be disentangled. Differently from other impact studies, LISFLOOD is an EU model, thus the Non-EU regions remain outside the scope of its investigation.

Finally, climate change impacts on the job performance in Europe are derived from Kovats and Lloyd (2011). They assess the change in working conditions due to heat stress produced by the increase in temperature and their effects on labour productivity. By linking climate data, a combined measure of heat and humidity (the “Wet Bulbe Globe Temperature”) and effects on the human body (Kjellstrom *et al.* 2009), they are able to estimate the expected decrease in labour productivity for four European macro-regions (Western, Eastern, Northern and Southern). Authors also consider sectoral impacts taking into account future changes in distribution of labour force across sectors.

The outputs of these studies have been translated into appropriate changes in key variables of the ICES CGE model. This has been run to determine the economic implication of those changes. Table AI compares these new damage estimates, jointly and individually, with those of Nordhaus (2007).

Table AI. **Market impacts of 1.92°C global average temperature increase (reference year 2050) on real GDP by region and impact: % change compared to the case with no temperature increase**

	All impacts		Energy		Tourism		SLR		River Floods		Agriculture		Forestry		Health	
	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)	Used this study	Nordhaus (2007)
USA	0.17	0.12	-0.01	0	0.18	0.22	-0.05	-0.08			0.05	-0.02	0.00			
MEUR	-0.15	-0.25	-0.05	0	0.07	0.33	-0.03	-0.35	-0.01	-0.19	0.07	-0.02	-0.01		-0.19	-0.02
NEUR	0.18	-0.25	-0.07	0	0.15	0.33	-0.11	-0.35	-0.01	-0.19	0.23	-0.02	0.00		0.00	-0.02
EEUR	-0.21	0.15	-0.02	0	0.10	0.28	-0.04	-0.01	-0.05	-0.08	-0.15	-0.02	-0.03		-0.03	-0.02
FSU	0.81	1.78	0.01	0.61	0.32	0.58	-0.03	-0.04			0.49	0.63	0.00			
KOSAU	0.09	0.48	-0.04	0.25	0.15	0.27	-0.04	-0.07			0.01	0.04	0.00			
CAJANZ	-0.09	0.02	-0.02	0	-0.10	0.24	-0.16	-0.21			0.19	-0.02	0.00			
NAF	-2.67	-0.97	-0.03	-0.25	-0.54	-0.19	-0.02	-0.02			-2.10	-0.51	0.01			
MDE	-0.83	-0.64	-0.19	-0.15	-0.42	-0.18	-0.10	-0.03			-0.10	-0.27	-0.03			
SSA	-1.50	-0.97	0.00	-0.25	-0.31	-0.19	-0.02	-0.02			-1.09	-0.51	-0.10			
SASIA	-3.10	-0.77	0.22	-0.22	0.04	-0.23	-0.32	-0.07			-3.02	-0.25	-0.02			
CHINA	0.20	-0.12	0.04	-0.25	-0.24	0.20	-0.03	-0.06			0.43	-0.02	0.00			
EASIA	-2.82	-0.60	0.01	-0.16	-0.36	0.03	-0.10	-0.07			-2.36	-0.40	-0.02			
LACA	-0.71	-0.58	-0.04	-0.22	-0.49	0.03	-0.05	-0.08			-0.11	-0.32	-0.01			

The extended names of the regions are: USA – United States, MEURO – Mediterranean Europe, NEURO – Northern Europe , EEURO - Eastern Europe, CAJANZ - Canada, Japan, New Zealand, CHINA - China and Taiwan, SASIA - South Asia, SSA - Sub-Saharan Africa, LACA - Latin America, Mexico, and the Caribbean, KOSAU - Korea, South Africa, Australia, FSU – Former Soviet Union, EASIA - South East Asia, MED-Middle-East, NAF - North Africa. The results presented in the table have been obtained using a model with a slightly finer regional disaggregation (14 instead of 12 regions) than that of the WITCH model. This is also why the regional matching is not perfect.

The non-market damage component

The non-market component that is captured in this study refers to two specific types of climate change damages. The first type refers to ecosystems and biodiversity losses that induce welfare losses not directly priced by market transactions, such as the loss of recreational and amenity value of natural environments when they are enjoyed under free access, losses of option and existence values. The second type of impact refers to the changes in welfare related to modifications in the health status[11].

To calibrate the ecosystem losses component, we follow the Willingness To Pay (WTP) approach used in the MERGE model (Manne *et al.* 2005). In principle, an elicited WTP to avoid a given loss in ecosystems should encoDigitare l'equazione qui.mpass all their non-market values and therefore reasonably approximate the lost value in case they are not protected[12]. In MERGE, the WTP to avoid the non-market damages of a of 2.5°C temperature increase above pre-industrial levels is 2% of GDP when per capita income is above USD 40,000 1990. The 2% figure was the US EPA expenditure on environmental protection in 1995. An S-shaped relationship between per capita income and WTP is then used to infer the WTP for other regions. We follow a similar approach, but using an updated proxy for the WTP, for which we consider the EU expenditure on environmental protection. The most recent Eurostat data referring to the public sector expenditure reports a total value in 2001 of EUR 54 billion, 0.6% of EU25 GDP, or of EUR 120 per capita[13]. This value encompasses activities such as protection of soil and groundwater, biodiversity and landscape, noise protection, radiation, along with more general research and development, administration and multifunctional activities. We then use the expression reported in Warren *et al.* (2006) that links average per capita environmental expenditure and per capita income to extrapolate

$$WTP_{n,t|t=2.5°C} = \gamma \Delta T^{\varepsilon}_{n,t|t=2.5°C} \frac{1}{1+100e^{(-0.23 * GDPn,t|t=2.5°C\,/\,POPn,t|t=2.5°C)}} \qquad \text{(AI)}$$

In (AI) the parameters γ and ε have been calibrated to give exactly 0.6% of GDP when per capita income is USD 28,780 and ΔT=2.5°C. Figure AII shows the s-shaped relationship between per-capita income and WTP that has been used to compute the WTP in the different model regions, which is reported in Table AII.

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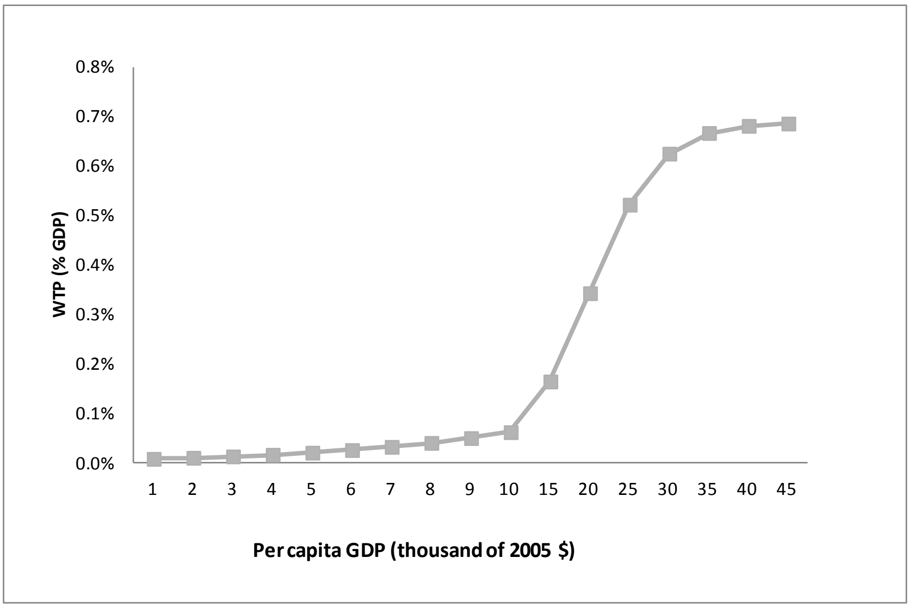
[11] Climate related health impacts are also associated with obvious market effects, directly measurable by changes in labour productivity, or in public and private health care expenditure. The focus here is instead placed on welfare losses associated with the disability or discomfort of living as an ill person, which is a typical non-market aspect.

[12] In practice the limitations of this approach are well known and many criticisms are raised against WTP and other stated preference approaches. However, the usual response is that in the end, they represent the only viable way to capture existence values.

[13] "Environmental Protection Expenditure in Europe by public sector and specialized producers 1995-2002" http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-NQ-05-010/EN/KS-NQ-05-010-EN.PDF viewed on November 24th 2011.

Figure AII. Willingness to pay as a function of per capita GDP



Note: The black marker refers to the calibration point, a WTP equal to 0.6% for the EU income per-capita in 2001, USD 28,780.

Table AII also compares the resulting values with Hanemann (2008), who applies the same procedure but starting from a WTP estimates for the US equal to 0.1% of GDP; Nordhaus and Boyer (2000) as embedded in the RICE99 model, and by the MERGE model as described in Warren *et al.* (2006).

Table AII. WTP for ecosystems protection related to a temperature increase of 2.5°C (% of regional GDP)

	AD-WITCH	Hanemann (2008)	Nordhaus and Boyer (2000)	(Merge as in Warren, 2006)
USA	0.69	0.10	0.10	2.00
Western EU	0.69	0.10	0.25	2.00
Eastern EU	0.69	0.10	0.10	2.00
KOSAU	0.69	0.10	0.10	1.99
CAJAZ	0.69	0.10	0.25	2.00
TE	0.50	0.08	0.05	1.47
MENA	0.31	0.05	0.05	0.89
SSA	0.01	0.002	0.10	0.04
SASIA	0.06	0.009	0.10	0.18
CHINA	0.61	0.09	0.05	1.76
EASIA	0.10	0.02	0.10	0.30
LACA	0.66	0.099	0.10	1.92
WORLD	0.49	0.07	0.10	2.00
USD billion (2005)	1120	169		4569

As shown in table AII, the reference WTP value used for rich countries crucially determines the final results[14]. Using the EU values as the benchmark for calculations gives lower damages than in the MERGE model, but anyway higher than in Hanemann (2008) and Nordhaus and Boyer (2000). This also emphasises the large uncertainty when assigning an economic value to non-market impacts.

Table AII also clearly shows that a WTP approach tends to produce higher evaluations for non-market ecosystem losses in high-income countries, although ecosystem/biodiversity richness is highly concentrated in developing countries.

The non-market costs related to changes in health status have been estimated using a value of statistical life approach (VSL). We derived the number of climate-change related additional deaths from two sources. The first is the PESETA project (Ciscar *et al.* 2009). The PESETA research dedicated to the health impacts of climate change computed heat-and cold-related (cardiovascular and respiratory) deaths or avoided deaths for different degree of warming (1°C, 2.5°C, and 3.9°C above pre industrial levels) in Europe. The number of heat-related deaths is convex in temperature, while the number of avoided cold-related deaths is decreasing and concave. Hence, the relationship between net additional deaths and warming is n-shaped with a turning point at 2.5°C. We assumed this same relationship for all world regions.

Heat- and cold-related diseases are particularly concerning in developed regions, while in developing regions large impacts will occur through vector-borne diseases, primarily malaria, dengue, schistosomiasis. For this aspect we extrapolated upon Tol (2002) estimating the number of deaths associated with 1°C of warming in different world regions. The study assumes that as per-capita income grows, mortality decreases until disappearing at a per-capita income level of USD 4,000 in 2005. This implies that vector-born disease impacts will stay positive until 2070 only in Sub-Saharan Africa, until 2035 in South Asia, until 2015 in China, until 2020 in East Asia.

Abstracting from the moral implications, the money evaluation associated to loss of lives will crucially determine the final economic assessment of climate–change related health impact and will introduce a degree of uncertainty-subjectivity very similar to that related to the assessment of ecosystem losses. Aldy and Viscusi (2003) surveying the literature on VSL point to a quite wide range of available estimates (see Box 1). Our choice was to assign each life the value of USD 1 million which is in the upper range of estimates obtained with stated preference methodologies.

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[14] Nordhaus and Boyer (2000) estimate an annual willingness to pay to avoid the disruption of settlements and ecosystem associated with a 2.5°C increase in global average temperature to about USD 67 per household (2006 values). Both relate to irreversible effects on immobile ecosystems or infrastructures. Hanemann (2008) revised Nordhaus and Boyer' estimates for the United States almost doubling them to USD 120 (in 2006 values).

BOX1. The Value of Statistical Life

According to Aldy and Viscusi (2003) the compensating wage method usually produces higher VSL in a range of USD 4-9 million. It consists of a revealed preferences approach (hedonic wage) where the average risk of mortality is evaluated by a wage premium. This last reflects the “wage-risk trade-offs” of workers with similar jobs in different environmental conditions. Estimates below the USD 5 million value usually come from studies using the Society of Actuaries data. These report wages from workers who have self-selected themselves into jobs that are an order of magnitude riskier than the average. There are also some studies yielding estimates beyond USD 12 million, but these did not estimate the wage-risk trade-off directly or their authors reported unstable estimates. Estimates with this methodology are available only for small segment of the population and usually refer only to current risk of accidental deaths (*e.g.* no deaths caused by air pollutants after a latency period are considered).

Estimates of roughly USD 1 million are produced by averting behaviour approaches. These Stated Preference Methods directly ask individuals how much they would be willing to pay to compensate for a small reduction in risk. The lower estimates compared with compensating wage methods may reflect several characteristics of these studies that distinguish them from the labour market studies. First, some product decisions do not provide a continuum of price-risk opportunities (unlike the labour market that does offer a fairly continuous array of wage-risk employment options) but rather a discrete safety decision. Second, the types of products considered in some studies may induce selection based on risk preferences. Third, several studies are based on inferred, instead of observed, price-risk trade-offs.

This methodology has been also applied in the PESETA study. A contingent valuation survey in which people of various ages – including elderly persons – have been asked to report their willingness to pay (WTP) for a reduction in their risk of dying has been conducted in UK, France and Italy. The results yielded exactly EUR 1.1 million.

Table AIII reports the value obtained for the AD-WITCH world regions

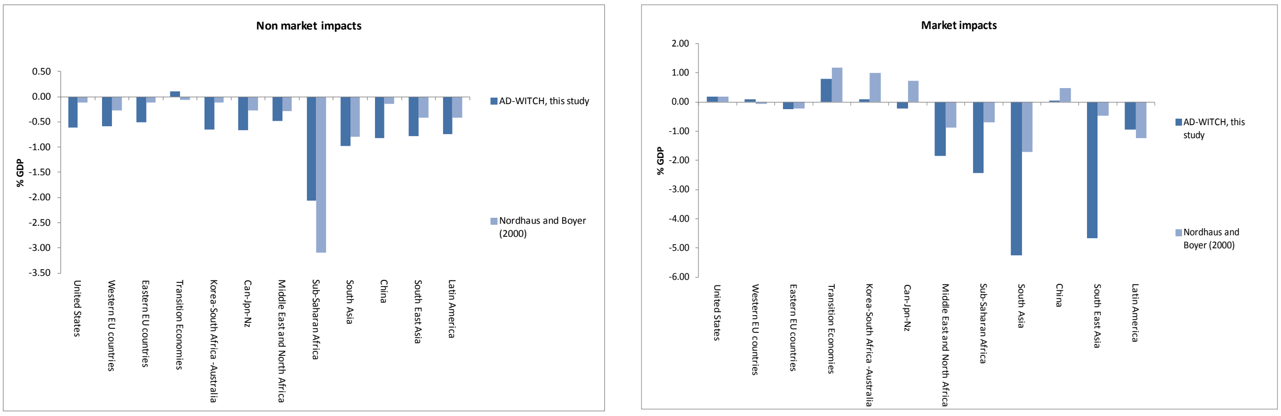
Table AIII. Climate change impacts on health. Economic estimates for a temperature increase of 1, 2.5, and 3.5°C (% of regional GDP)

°C	USA	Western EU	Eastern EU	FSU	KOSAU	CAJANZ	MENA	SSA	SASIA	CHINA	EASIA	LACA
1.0	0.294	0.332	1.206	2.652	0.156	0.042	-0.173	-3.423	-3.272	0.333	-1.521	0.019
2.5	0.076	0.098	0.171	0.591	0.028	0.016	-0.171	-1.592	-0.864	-0.225	-0.685	-0.090
3.5	0.085	0.112	0.202	0.647	0.030	0.018	-0.155	-0.519	-0.717	-0.233	-0.832	-0.087

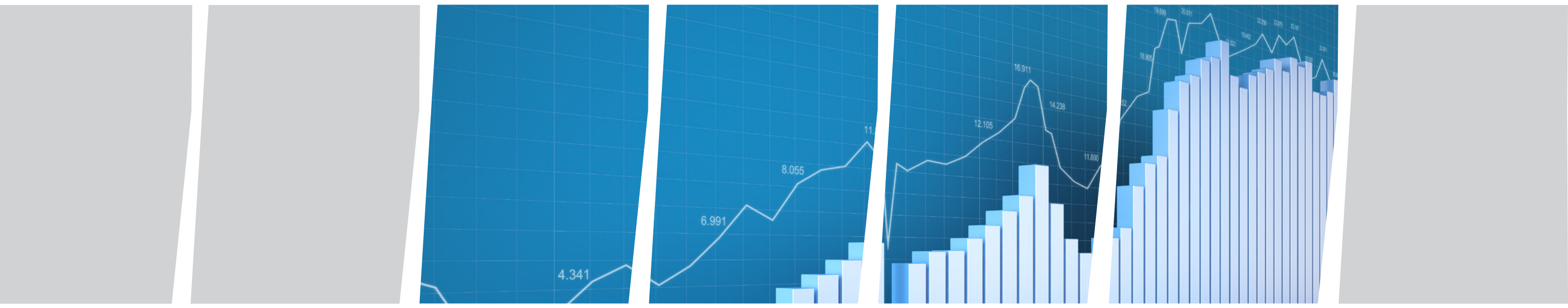
Benefits are expected in cooler, richer regions, particularly Transition Economies and Eastern Europe, where decrease in cold-related mortality compensates increases in the heat-related one and where vector borne diseases are absent. Such a result is in contrast with Nordhaus (2007) and Nordhaus and Boyer (2000), since they assumed that any increased mortality in the summer is completely offset by the respective decrease in mortality from winter warming. Regions that suffer from vector-borne diseases face large economic impacts associated with health, but decreasing throughout time, as they get richer.

Figure AIV compares the newly estimated impacts embedded in the AD-WITCH model with Nordhaus and Boyer (2000), showing the market and non-market components at the temperature calibration point (+2.5°C). Note that for the sake of comparison, Nordhaus and Boyer (2000) figures for non-market impacts are net of the catastrophic damages and only refer to health, ecosystems and settlements.

Figure AIII: Estimated regional non-market (left) and market (right) damages for a +2.5°C temperature increase above pre-industrial levels.



European Investment Bank The EU bank



Contacts

For general information:

Information Desk
Corporate Responsibility and
Communication Department
☎ (+352) 43 79 - 22000
📠 (+352) 43 79 - 62000
✉ info@eib.org

European Investment Bank
98-100, boulevard Konrad Adenauer
L-2950 Luxembourg
☎ (+352) 43 79 - 1
📠 (+352) 43 77 04
www.eib.org/economics