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Advancement report on adaptation and damage functions in the WITCH model and test runs

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SUMMARY This paper contributes to the normative literature on mitigation and adaptation by framing the question of the optimal policy balance in the context of climate catastrophic risk. The analysis uses the WITCH integrated assessment model presenting updates both in its climate change damage and adaptation components. Compared to previous model versions, the first includes a brand new damage specification accounting for the role of autonomous adaptation, ecosystems losses and, most importantly, models an endogenous link between the probability of experiencing a climate-change related catastrophic event and the temperature increase caused by GHG emissions. The second distinguishes between different adaptation types: anticipatory, reactive and investment in adaptive capacity building. Results indicate that the presence of catastrophic risk induces substantial mitigation effort even in a non-cooperative setting, that, according to the standard deterministic literature, usually presents very low mitigation efforts. Furthermore, 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 reduce 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.

Keywords: Climate change, mitigation, adaptation, climate risk, integrated assessment

JEL: C61, D58, Q5

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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. Moreover, the recent Durban talks confirmed the difficulty to negotiate emission reduction and achieve the 2°C temperature stabilization target. In this context, the role of adaptation as a strategy coping with climate change can become even more important.[1] Nonetheless, 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. Adapting to a catastrophe would be extremely costly, meaning that mitigation should keep a key role in climate change strategy (Wright and Erikson, 2003). Indeed research has identified a number of climate related 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).

The first contribution of this paper is to study with an applied model how climate catastrophic risk can shape the optimal mix between mitigation and adaptation. This research brings together different streams of applied and theoretical literature.

A first line of applied research is that investigating the role of uncertainty and irreversibility on mitigation choices. This presents mixed results. According to a group of studies, acquiring better information on future climate change damages warrants postponing costly abatement investments until uncertainty is resolved (Nordhaus and Popp, 1999, Ulph and Ulph 2007, Karp and Zhang, 2006). In contrast, a second group of works suggest that hedging might be a preferable response. Keller et al. (2004) show that climate threshold can render significant abatement a utility-maximizing choice. Other studies show that the risk of irreversible changes in the climate system induce anticipated precautionary abatement (Gjerde et al. 1998, Roughgarden and

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

Schneider 1999, Yohe et al. 2004). These analyses did not include adaptation as a possible climate change strategy though.

The second line of research refers to the effect of catastrophic risk on the mix between adaptation and mitigation, but mainly with a theoretical perspective. In this vein Kane and Shogren (2000) and Ingham et al. (2005, 2007). They developed an analytical model for the relation between mitigation and adaptation in the presence of uncertainty. Uncertainty 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. Their results are also mixed. Whether adaptation, mitigation, or both, grow in response to an increased climate change risk depends on a complex interaction between direct and indirect effects of risk on the marginal productivity of both strategies and their complementarity or substitutability. In general[2] the direct effect of a higher risk implies more mitigation or more adaptation. However, the final balance between the two strategies is determined by the indirect effect. This can both strengthen or counteract the direct effect. At the end Kane and Shogren (2000) conclude that what can be effectively observed is 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 find that an increase in risk always implies more adaptation and more mitigation. Still, the two strategies are economic substitutes: an increase in adaptation costs reduces adaptation and increases mitigation. Economic 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 and *vice versa*. This can arise for instance when the costs of adaptation depend on the stock of greenhouse gases because more mitigation slows the rate of change of climate or avoids a potential catastrophe and hence makes adaptation easier (Ingham et al., 2005).

The third stream of modelling literature is that investigating the relation between mitigation and adaptation, applying Integrated Assessment Models (IAMs). So far, it assumes neither uncertainty nor irreversibility. Those studies tend to emphasize how,

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

in a non-cooperative setting, mitigation remains negligible because of its public good nature. On the contrary, since adaptation entails almost fully appropriable benefits, it is basically the only climate change strategy pursued (Agrawala et al., 2010; de Bruin et al., 2009; Bahn et al., 2009; Bosello et al., 2011).

Substantive mitigation becomes optimal only when emission externalities are fully internalised. Alternatively, it had to be imposed exogenously to replicate given climate policy targets. When this is the 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 always consists of a mixture of the two. The inertia of the climatic system and the path-dependency of investments in the energy system play also a role: adaptation remains an important strategy even if policies aimed at stabilising CO_2 are successful, and mitigation expenditure needs to be anticipated even in the presence of early adaptation (Hof, 2009, 2010; Agrawala et al., 2011). Anyway, especially in cost-benefit analyses, the crowding out of mitigation on adaptation is considerably weaker than that of adaptation on mitigation.

A second research field this paper addresses empirically relates to the feedback that international adaptation support from a group of donor countries exerts on mitigation or adaptation efforts of the receivers. This is partly related to the recent theoretical literature analyzing the implications of the joint presence of adaptation and mitigation in international environmental agreements. It shows that the presence of adaptation can indeed influence the incentive to be part of the environmental agreement. 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, by reducing the need to mitigate, pushes the environmental effectiveness of the agreement closer to the non-cooperative effort. In conclusion, adaptation enhances participation by making the agreement empty of its mitigation content. In a non-cooperative setting, Buob and Stephan (2011) show that, in principle, developed countries could use adaptation funding to 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 it would be economically rational for developed countries to fund adaptation in developing regions only if this came in the exchange of lower abatement by developed regions. 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 willingness to mitigate. 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 Chauduri (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 a country can also adapt to climate damages, it may respond to higher emissions from another country with higher adaptation and lower abatement (thus higher emissions). 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 emission reaction curves are no more orthogonal, the abating coalition may increase its abatement effort to lower the emissions in non-participatory countries. In this paper we 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 remainder of the paper is organized as follows. Section 2 introduces the improved 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 WITCH MODEL AUGMENTED WITH ADAPTATION

This paper uses an improved version of the WITCH model as described in Bosello et al. (2011), Agrawala et al. (2010) and Agrawala et al. (2011) including adaptation. For brevity in the remainder of the paper we will call this model AD-WITCH. 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 one chosen in this study, 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 externalities are internalised, because a benevolent social planner maximises a global welfare function[3].

Adaptation consists of a set of control variables that are chosen optimally with all the other controls, namely investments in physical capital, R&D, and energy technologies. The large number of potential adaptive responses 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 facilitate adaptation activities (e.g. improvement of meteorological services, of early warning systems, the development of climate modelling and impact assessment). Anticipatory adaptation gathers all the measures where a stock of defensive capital must already be operational when the damage materialises (e.g. dike building). Reactive adaptation gathers all actions that are put in place when the climatic impact effectively materialises (e.g. use of air

[3] 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. The non-cooperative scenario does not internalise the technology externalities. For more insights on the treatment of technical change in the WITCH model see Bosetti et al. (2009).

conditioning) to accommodate the damages not avoided by anticipatory adaptation or mitigation.

The different adaptation strategies are linked into a CES (Constant elasticity of substitution) form. A first node distinguishes adaptive capacity building from adaptation activities *strictu sensu*. 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 takes one period - five years - to accrue to the defensive stock), and must be planned in advance. Once built, defensive capital 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)[4] as we consider basic socio-economic development (generic capacity), an essential perquisite for facilitating any form of adaptation. The analysis that follows assumes a cost-benefit, non-cooperative setting. Environmental externalities are not internalised globally, but only within the boundary of each given region.

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[4] 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.

2.2. MODELLING NON-CATASTROPHIC DAMAGES

For this study, the climate change damages of the AD-WITCH model, significantly based on Nordhaus (2001), have been recalibrated using new studies. Both market and non-market impacts are partly considered.

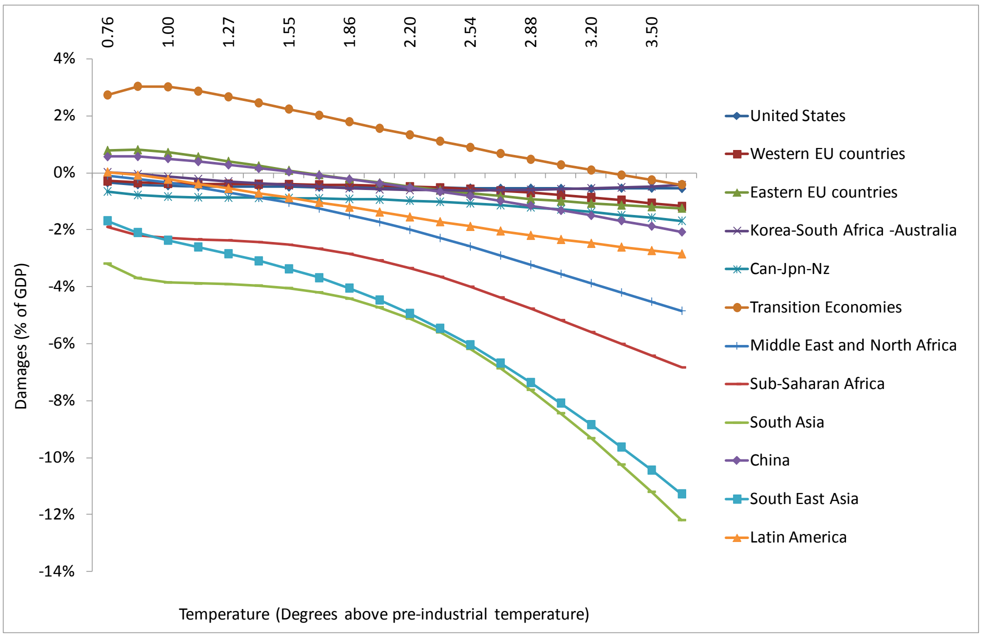
The market component of climate change damages has been revised using the recent estimates provided by the interdisciplinary work carried out within the ClimateCost project (Bosello et al. 2012). That project has quantified the physical and economic impacts of climate change on sea-level rise, energy demand, agricultural productivity, tourism flows, net primary productivity of forests, floods, and reduced work capacity because of thermal discomfort. The economic impacts have been estimated using a recursive-dynamic computable general equilibrium (CGE) model, ICES (Intertemporal General Equilibrium System). The estimated impacts incorporate the effect of market adjustments induced by price changes (e.g market driven adaptation). This is a first novelty compared to the DICE/RICE99 and AD-WITCH models described in Agrawala et al. (2010), as they do not account for the role of market-driven adaptation.

The non-market component, refers to potential ecosystem losses and non-market health impacts, assessed using a willingness to pay approach.

Figure 1 summarises the outcome of the calibration procedure[5]. 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 both expected to lose 12% of their GDP while in the previous estimate the loss was 10% and 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, though at a decreasing rate, due to positive non-market effects on health.

[5] Detailed results are available in Bosello, De Cian, Ferranna (2012)

Figure 1: Regional climate change damages in the AD-WITCH model without catastrophic risk



2.3. MODELLING AND CALIBRATING CLIMATE CATASTROPHIC RISK

Following Gjerde et al (1998), Bosello and Moretto (1999), Bosello and Chen (2010) 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:

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

$T_t - T_0$ is the temperature increase relative to the pre-industrial level, T_0. According to eq. (1), keeping the atmospheric temperature at the level T_0 would eliminate the possibility of catastrophic events. The probability of a catastrophe grows when temperature increases above T_0. The social planner of each given region can control the probability of the catastrophic event by choosing her investment in technology portfolio, which will ultimately affect temperature and hence the probability through GHG emissions and concentrations. However, the benefit of this endogenous control on temperature has to be compared with its costs (see below).

In (1) the relationship between temperature increase and catastrophic probability 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 such that the probability of a catastrophic occurrence for a temperature increase of 3°C above the pre-industrial period is 16%, ($\varphi=0.021$). In the model this happens at the end of the century. The 16% probability is relatively higher than the 4.8% value used by Nordhaus (1994). It accounts for the more recent studies on the likelihood of catastrophic outcomes or the trespassing of tipping points (Lenton et al., 2008, Kriegler et al., 2009). Catastrophic risk affects decision-making as the planner now faces an inter-temporal expected damage, which she can partially control[6] (eq. 2).

$$CCDA_{n,t} = p(T_t)\cdot\frac{1}{1+ADAPT_{n,t}}\cdot CCD_{n,t} + (1-p(T_t))\cdot CCR_{n,t} \qquad (2)$$

In (2) 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 (2) the component $CCR_{n,t}$ has been calibrated such that the catastrophic damage equals 25% of GDP in each given region at the calibration point. 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. The relationship between damage and economic activity is described in eq. (3):

$$YNET_{n,t} = \frac{1}{1+CCDA_{n,t}} YGROSS_{n,t} \qquad (3)$$

[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.

3. RESULTS

3.1. MITIGATION AND ADAPTATION UNDER CLIMATE RISK: GLOBAL RESULTS

In a world without catastrophic risk and with no global cooperation on climate, our numerical results confirm the findings from the existing theoretical and empirical literature. Mitigation is negligible due to free-riding incentives (Figure 2). In contrast, adaptation contributes almost entirely to damage reduction especially after 2050[7] (Figure 3). The introduction of catastrophic risk changes the picture. Despite the non-cooperative set-up, substantive abatement becomes optimal, indicating that the risk of a catastrophe mitigates the free-riding incentive. The optimal Nash abatement almost stabilises CO_2 emissions, which in 2100 are 58 instead of 84 $GtCO_2$. Accordingly, in contrast with the no risk case, an increased amount of resources is devoted to mitigation. At the world level these are now primarily allocated to abatement (investment in energy saving R&D and renewable energy sources) until 2085 while, without risk, adaptation expenditure would overtake mitigation already in 2050.

The effect on temperature and risk is small though. Temperature increases to 3.3°C rather than 3.6°C in 2100, and the probability of the catastrophic outcome declines from 24% to 21%. 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.

[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.

Figure 2. CO_2 emissions with and without catastrophic risk with and without adaptation

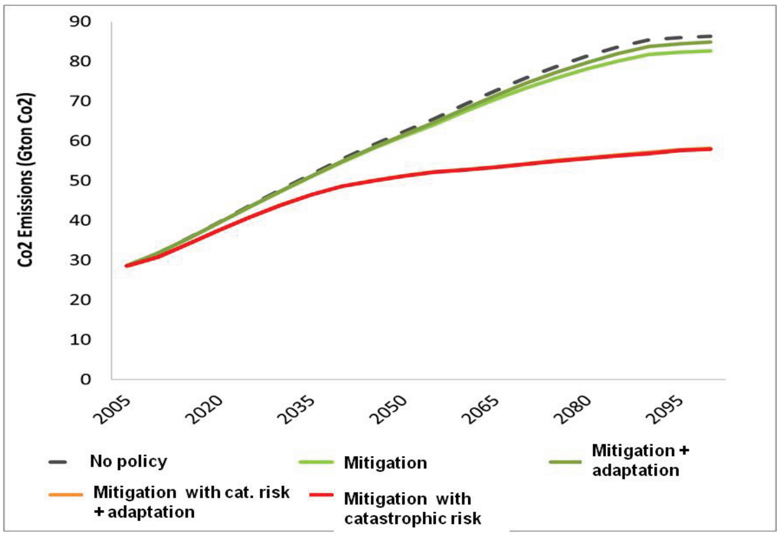
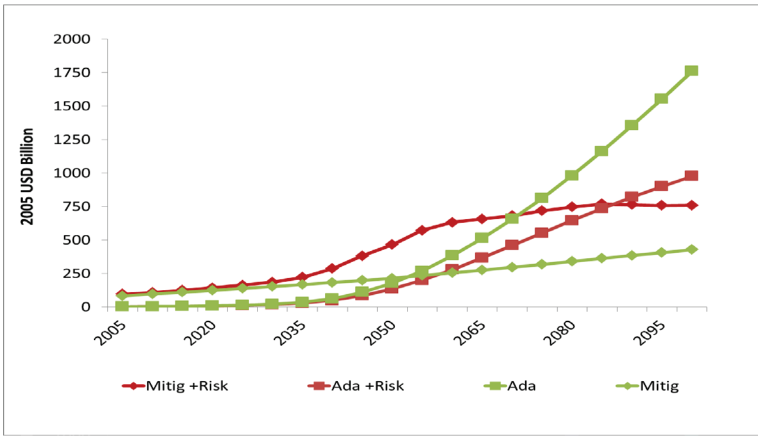


Figure 3: Global investments in clean energy technologies* (mitigation) and adaptation expenditure (US $ Billion) with and without catastrophic risk



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

The introduction of catastrophic risk also changes the size of the crowding out effect between mitigation and adaptation (Table 1). Thus, throughout the century, the possibility to adapt would reduce cumulative abatement by 48% without risk, but by less than 1% when risk is considered. On the contrary, mitigation reduces cumulative adaptation expenditure by 1% without risk, and by 4.5% when risk is accounted for.

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%

*Percentages are large numbers because the absolute values are small

Nonetheless, some reciprocal degree of crowding out between the two strategies remains since part of the mitigation effort still responds to the smooth climate-change damage component and continues to be influenced by adaptation measures and vice versa.

Different regions react differently to the introduction of the same risk. 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. As said, the free riding incentive is weakened, but does not disappear completely. Some regions (Korea-South Africa-Australia, Sub-Saharan Africa, Eastern Europe) even increase their emissions compared to the no risk case. Figure 4 shows the different reaction in terms of CO2 emissions in the Mediterranean regions (Europe and MENA).

When the catastrophic risk increases mitigation, adaptation decreases responding to the reduced country specific damage. For instance (Figure 5), all over the century, Europe increases its cumulated mitigation expenditure by roughly the 57% and reduces its cumulated adaptation expenditure by the 34%, while Middle East and North Africa increase mitigation expenditure by the 5.8%, but still reduce adaptation expenditure the 28%. This also explains why Eastern EU decreases its adaptation effort even though its mitigation also declines. Figure 5 finally shows that risk does not significantly change the adaptation basket. Throughout the century, most adaptation in the EU is of proactive nature, 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 4. CO_2 abatement in Europe (left) and Middle East and North Africa (right)

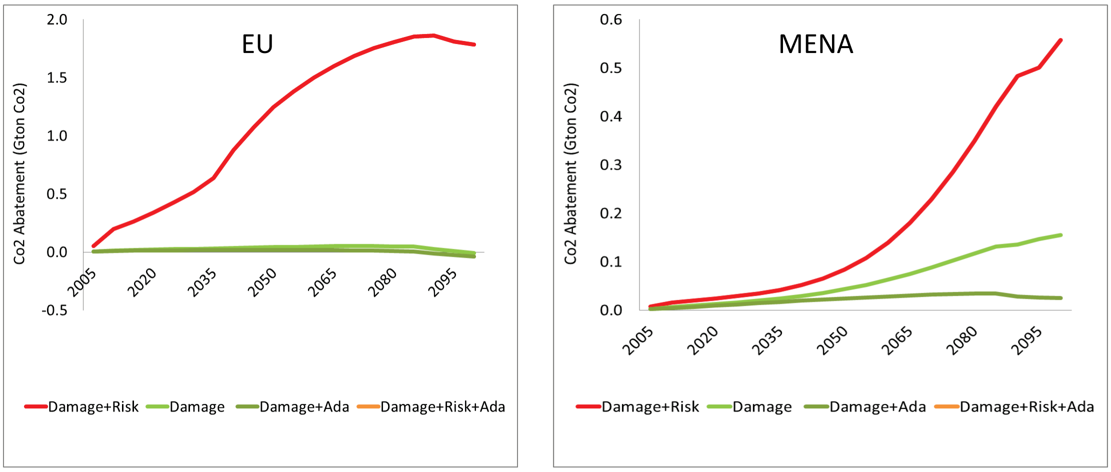
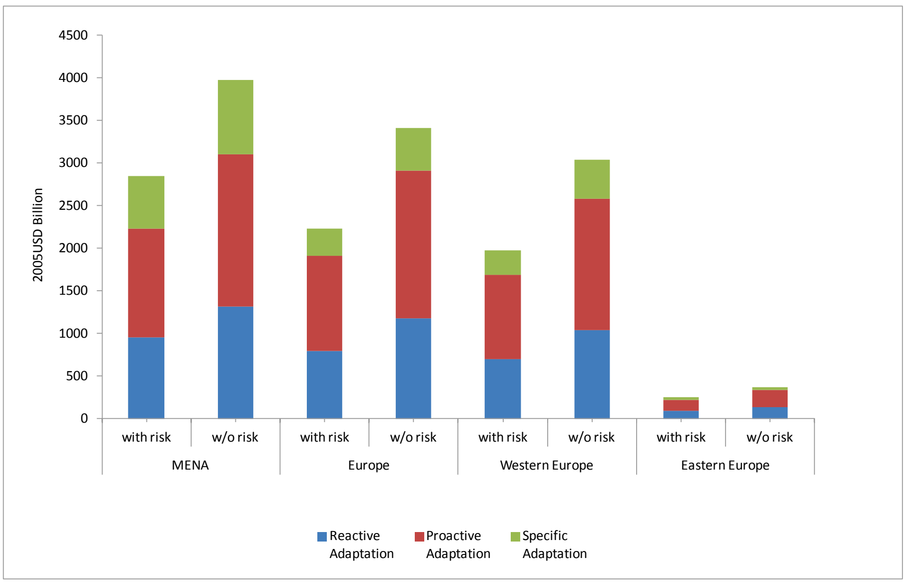


Figure 5. Cumulated expenditure in different adaptation forms, 2005-2100



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. On the contrary, 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, irrespectively 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. On the contrary, adaptation should tackle the residual damage not accommodated by mitigation.

We examine the sensitivity of our results[8], and in particular of the trade-off between adaptation and mitigation when the discount rate, the catastrophic risk, and the catastrophic penalty change. We find that, once catastrophic risk is introduced, lower discounting unambiguously implies more abatement and also an increase in adaptation. The higher probability associated with the catastrophic event has the effect of increasing abatement while adaptation is crowded out. When the risk of a catastrophic event increases, the crowding out of abatement induced by adaptation is reduced basically to zero.

[8] Available upon request.

3.3 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, perceive and react to catastrophic risk, whereas the non-OECD, react only to the non-catastrophic damage component[9].

We therefore assume that, the OECD are not only inclined to strong domestic abatement, but are also willing to foster abatement in non-OECD. Indeed risk can be better curbed by an enlarged abatement effort since it depends on global temperature. Non-OECD, on their turn, need to find their additional abatement profitable. That is they need to receive a 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.

In a first experiment we assume that the OECD would finance all adaptation needs of non-OECD to a ceiling of $ 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 $ 100 billion, these are shared among receivers proportionally to the respective adaptation need share of the group total. In this simulation, (Transf A in Figure 7), 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. The ceiling of $ 100 billion is reached in 2060. As adaptation needs in developing countries rapidly increase after 2040, the $ 100 billion amount covers roughly 19% of the total adaptation needs in 2100.

Adaptation funds almost completely replace domestic adaptation in receiving countries, which in fact only slightly increases. Investment in physical capital and in

[9] To highlight clearer results, the risk setting chosen is different from that used in section 2. Namely both the probability and the catastrophic penalties have been increased respectively to the 50% and 99% of GDP for a temperature increase of 3.6°C.

mitigation activities (energy saving R&D and renewable technologies) is basically unaffected. The additional available budget is almost totally used for consumption. Discounted consumption throughout the century increases by 0.046% (or by US $ 265 Billions) compared with the case with no transfers. In other words, mitigation behaves quasi-linearly in non-OECD preferences. After optimal adaptation is reached, consistent with the countries damage/risk perception, adaptation becomes insensitive to further shifts of the budget line. In our particular setting, when countries start from a non-cooperative optimum, the adaptation fund does not crowd out domestic mitigation, but domestic adaptation, even when adaptation and mitigation are substitutes [10]. At the same time, even though mitigation investment in the non-OECD does not shrink, higher consumption and production implies slightly higher emissions.

Accordingly, adaptation funds can only foster mitigation if a conditionality clause is included, stating that the adaptation fund will be delivered only in the presence of a binding-detectable mitigation commitment from the non-OECD. We consider the same adaptation transfer as in the case Transf A, but now non-OECD are required to invest in either energy saving R&D or renewable energy. We design this deal to be welfare improving for the non-OECD by identifying the mitigation threshold that leaves non-OECD indifferent between accepting adaptation funds and engage in additional mitigation or giving up the adaptation funds and avoid further abatement effort. This is done by imposing different levels of additional mitigation investment in either energy saving R&D (1/10 or 1/5 of the transferred resources for adaptation, Transf A+1/10R&D, Transf A+1/5R&D in Figure 7 left panel respectively) or renewable energy (1/10 of the transferred resources for adaptation in Transf A+1/10 Ren in Figure 7 left panel).

In terms of welfare, which in AD-WITCH is a function of consumption, non-OECD would benefit from this exchange, and therefore would be willing to accept, as long as the required investments in energy saving R&D or renewable energy is not greater

[10] 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 future research.

than 1/5 of the adaptation funds received[11] (see Table 2). One dollar received in adaptation funds weights 1/5th of one dollar spent in mitigation. This happens because every additional abatement effort in non-OECD is strategically balanced by an increase in emissions in the OECD (Figure 7), 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 7). 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, can in fact increase. At the world level, emissions decrease only when adaptation funds are coupled with investment in renewable energy. In AD-WICTH the cost of renewables declines endogenously with installed capacity (Learning-By-Doing). Therefore, the additional capacity installed in the non-OECD reduces the technology cost in the OECD as well.

As a further experiment (Figure 7 right panel) we examine the effect of adaptation implemented in OECD countries on mitigation and adaptation in non-OECD. The aim, following the ideas put forward by Auerswald et al. (2011) and Marrouch and Chaudury (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 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 adaptation and capacity building, (-0.059% and -0.072%). This seems to

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

confirm Auerswald et al., (2011) intuition and to confute Marrouch and Chauduri (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% (Figure 7, right panel). This raises some caution regarding the practical possibility to use adaptation as a credible signal of low mitigation commitment in a country 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, are not 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. Let us assume this would be possible, neglecting for experimental sake all the transaction costs potentially involved. In a last simulation (Trans M in Figure 7 left panel) we assume that what is available to adaptation is directly invested by OECD to support investment in renewable energy in the non-OECD. The region thus experiences an increase in its investments in renewables from $ 12 to 55 Billion in 2050, from $ 47 to 100 Billion in 2100. Emission reduction in Non-OECD is effectively higher (-0.4%) and, because of the technical change effect - the global cost of renewable energy is 10% lower compared to the case with no transfer - also OECD´s emission reduction is higher (-1%).

In terms of discounted consumption, although developing countries would still be better off with a mitigation transfer than without, they would slightly prefer a support to adaptation (Table 2 third vs. first 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 lacks this perception and therefore under-evaluates 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, 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 $100 billion yearly. When also non-OECD perceive the risk of a catastrophe and global emissions are stabilised, their additional investments in clean energy would reach 100 USD Billion in 2035 and climb to 300 USD Billion in 2080 just to stabilise emission levels.

On the other hand, although the transfer would reduce consumption possibilities in the OECD, in terms of GDP they could experience small gains, especially when the transfer goes to financing renewables (see Table 3, 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 7: CO2 cumulated emissions 2005-2100, percentage change compared to the case without transfer

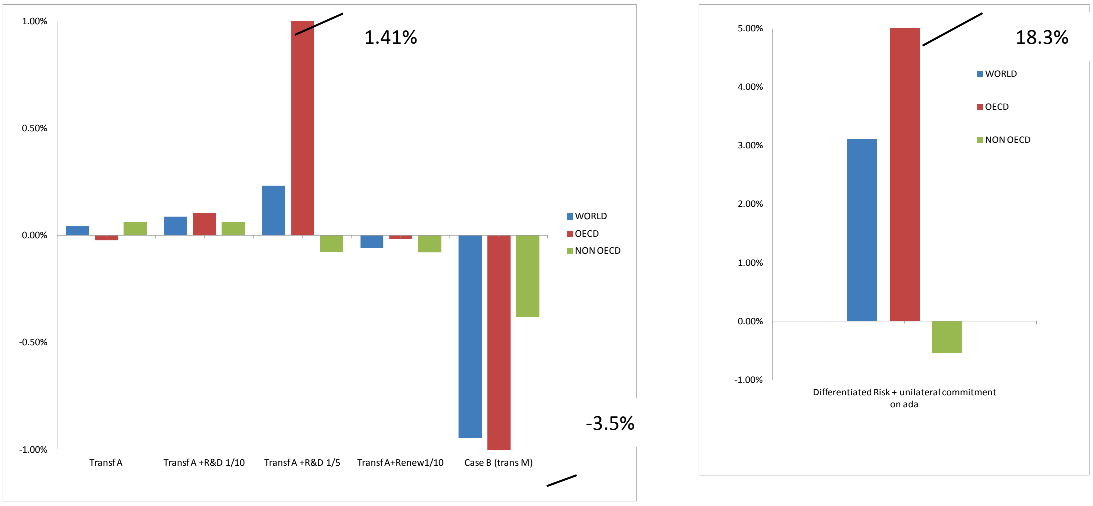


Table 2: Consumption: difference compared to the case with no transfer. Percentage point difference (discounted over the century).

% 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 3: 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

Various official documents, such as the 2009 EU White Paper on Adaptation or the 2010 Cancún Adaptation Framework, acknowledge mitigation and adaptation as necessary strategies to combat climate change. A rapidly expanding scientific literature has provided normative indications regarding the optimal combination of the two. This paper contributes to the normative literature on mitigation and adaptation by framing the question of the optimal policy balance in the context of climate catastrophic risk. The analysis uses an integrated assessment model and it accounts for the endogenous link between the probability of experiencing a climate-change related catastrophic event and the temperature increase caused by GHG emissions.

The presence of catastrophic risk induces substantial mitigation effort even in a non-cooperative setting where global cooperation on climate does not succeed, as the incentive to free ride is greatly weakened. 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 manage the catastrophic probability.

Nonetheless, the strategic complementarity between mitigation and adaptation does not vanish. Even though adaptation does not influence the catastrophic probability, it is still a necessary complement to mitigation to address the residual damage not accommodated by mitigation. 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.

These findings suggest that in a world characterised by catastrophic risk, mitigation is a key policy variable, as it is the only strategy able to reduce the catastrophic probability. Mitigation should be justified on the basis of precautionary considerations and only marginally considering its capacity to reduce the smooth component of climate change damages. Adaptation should be deployed to tackle that part of the climate damage that mitigation fails to accommodate because of time lag between mitigation action and mitigation benefits.

Given these results, we then investigate whether unilateral or partial commitment to adaptation can be used as a leverage to increase abatement effort outside the group in a non-cooperative setting. We find that if the OECD countries financed all adaptation needs of non-OECD up to a ceiling of $ 100 billion, such adaptation funding *per se* would not affect neither abatement nor adaptation. Domestic adaptation expenditure is displaced almost perfectly by the international adaptation aid and mitigation remains unchanged. If the adaptation fund were conditional on additional mitigation, than the adaptation funding can foster additional mitigation in developing countries, though the effectiveness of this strategy is very limited. On the one hand, the resources needed by developing countries to significantly de-carbonise their production and energy system are much higher than $100 billion yearly. On the other hand, in the chosen non-cooperative setting any additional abatement effort in non-OECD is strategically balanced by an increase in emissions in the OECD, which therefore erodes part of the benefit of the non-OECD mitigation. 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.

We also evaluate whether a unilateral commitment to adapt by the OECD countries can induce more abatement in other countries. As a reaction, abatement in non-OECD regions effectively increases. However, the effect on overall abatement is negative, as world cumulated emissions increase.

Summarising, adaptation funds and strategic commitments to adaptation do appear efficient and effective ways of buying emission reduction in non-OECD countries. Needless to say that adaptation funding remains important, but for other purposes, such as addressing the adverse distributional implications of climate change impacts. 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 and 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. 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 could offer partly different insights.

DISCLAIMER

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