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Adaptation Can Help Mitigation: An Integrated Approach to Post-2012 Climate Policy

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SUMMARY The latest round of international negotiations in Copenhagen led to a set of commitments on emission reduction which are unlikely to stabilise global warming below or around 2°C. As a consequence, in the absence of additional ambitious policy measures, adaptation will be needed to address climate related damages. What is the role of adaptation in this setting? How is it optimally allocated across regions and time? To address these questions, this paper analyses the optimal mix of adaptation and mitigation expenditures in a cost-effective setting in which countries cooperate to achieve a long-term stabilisation target (550 CO2-eq). It uses an Integrated Assessment Model (AD-WITCH) that describes the relationships between different adaptation modes (reactive and anticipatory), mitigation, and capacity building to analyse the optimal portfolio of adaptation measures. Results show the optimal intertemporal distribution of climate policy measures is characterised by early investments in mitigation followed by large adaptation expenditures a few decades later. Hence, the possibility to adapt does not justify postponing mitigation, although it reduces its costs. Mitigation and adaptation are thus shown to be complements rather than substitutes.

Keywords: Climate change impacts, mitigation, adaptation, integrated assessment model

JEL: Q54,Q56,Q43

AD-WITCH has been developed by FEEM in cooperation with the OECD. The contribution of all colleagues who worked on the development of the original WITCH model - in particular Valentina Bosetti, Emanuele Massetti, and Massimo Tavoni - is gratefully acknowledged. We are also grateful to Kelly de Bruin who collaborated on the model calibration and to Alice Favero for useful suggestions.

1. Introduction

The emission reduction commitments proposed at the end of COP XV in Copenhagen will probably fail to stabilise global warming below or around the 2°C target. According to most assessments, the proposed emission reductions can lead to a temperature increase above 3°C by the end of the century[1]. In this context, adaptation becomes a necessary measure and must be planned well in advance. Investments in adaptation may indeed be quite costly.

Socio-economic systems have a large potential to adapt to climate change, but market signals might not be sufficient to induce the necessary expenditure (Bosello et al. 2010a). Market-driven adaptation can have a strong damage-smoothing potential at the global level, yet global damages remain positive. This form of market-driven adaptation works well if markets function properly, which is not always the case. Finally, some forms of damage and their distributional implications cannot be addressed by markets (e.g. some biodiversity losses). Hence, policy-driven, or planned adaptation plays a leading role, especially in developing countries.

Most literature has explored the relationship between mitigation and adaptation using a cost-benefit set-up[2]: adaptation is modelled as an aggregated strategy fostered by some form of planned spending, which can directly reduce climate change damage. The pioneering contribution in this field is Hope (1993), who proposed the first effort to integrate mitigation and adaptation into the PAGE Integrated Assessment Model. PAGE, however, defines adaptation exogenously and therefore it cannot determine the optimal characteristics of a mitigation and adaptation portfolio.

The first assessments of the optimal mix of adaptation and mitigation where both mitigation and adaptation are endogenous have been proposed by Bosello (2008), Bosello et al. (2010), de Bruin et al. (2007), and de Bruin et al. (2009). All these studies conclude that adaptation and

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1 On the effectiveness of the Copenhagen pledges see Carraro and Massetti (2010), “Two good news from Copenhagen?” at http://www.voxeu.org/index.php?q=node/4490 and, for a comparison of different studies , “Adding up the Numbers: Mitigation Pledges under the Copenhagen Accord” at http://www.pewclimate.org/docUploads/copenhagen-accord-adding-up-mitigation-pledges.pdf

[2] See Hope (1993), Bosello (2008), Bosello et al. (2010), de Bruin et al. (2007), de Bruin et al. (2009).

mitigation are strategic complements: the optimal policy consists of a mix of adaptation measures and investments in mitigation, both in the short and long-term, even though mitigation will only decrease damages in later periods. All authors also highlight the existence of a trade-off between the two strategies: because resources are scarce, investing more into mitigation implies fewer resources for adaptation. Moreover, successful adaptation reduces the marginal benefit of mitigation and a successful mitigation effort reduces the damage to which it is necessary to adapt. This, again, explains the trade off between the two strategies. However, the second effect is notably weaker than the first one. Mitigation, especially in the short-medium term, only slightly lowers the environmental damage stock and therefore does little to decrease the need to adapt.

Finally, all the aforementioned studies stress that adaptation is a more effective option to reduce climate change damage, especially if agents have a strong preference for the present (high discount rates), or early climate damages are expected. This outcome depends on the cost and benefit functions driving the decision to spend on mitigation and adaptation, which are based on the standard damage functions used in most integrated assessment models, i.e. the one from Nordhaus' DICE/RICE models. These damage functions include at best, extreme, but not catastrophic events, and no uncertainty.

In light of the recent outcomes of international negotiations, this paper analyses adaptation from a novel perspective. It assumes that a global mitigation policy will successfully manage to stabilise GHG concentrations at 550 ppm-e by the end of the century. This target is less ambitious than the 2°C target, but still quite demanding and difficult to achieve. Given this mitigation path, this paper explores the following: how adaptation should be optimally designed to address the damage not eliminated by mitigation, how different adaptation strategies should be combined, and should the equity-adverse impact of climate change be addressed. It also stresses the different time scale of adaptation and mitigation, and gives some indications on key priorities for adaptation policy.

A second novel contribution of this paper is the modelling of adaptation itself. As in Bosello et al. (2010), a macro-perspective describing the interconnections between reactive and anticipatory adaptation and mitigation in an integrated assessment model (AD-WITCH) is assumed. The new element is the inclusion of an additional policy variable, which is adaptive capacity building. This is an essential aspect of the adaptation process, because it ultimately determines the effectiveness of adaptation interventions (Parry et al. 2007, Bapna and McGray 2008, Parry 2009).

The first part of the paper describes the implementation of the adaptation module into the WITCH model, and explores its main features in the absence of mitigation. The second part considers the role of adaptation, its different modalities, and its regional characteristics when a global mitigation policy is enacted.

Results indicate that anticipatory adaptation measures and investments in adaptive capacity building should occur earlier than reactive adaptation interventions. Adaptive capacity building is particularly important in non-OECD countries. Developing countries are more exposed to climatic damages and are therefore forced to spend more than OECD regions in all forms of adaptation. However, they devote a relatively larger share of their adaptation expenditure to reactive interventions, whereas OECD countries spend more for anticipatory interventions.

An internationally coordinated mitigation policy partially crowds out adaptation. However, when ambitious mitigation effort is assisted by adaptation interventions, the GHG stabilisation target can be achieved at a lower cost. Hence, mitigation and adaptation are shown to be complements rather than substitutes.

The remainder of the paper is organised as follows. Section 2 describes the modelling of adaptation and the calibration of the enhanced AD-WITCH model. Section 3 presents the baseline “no mitigation” scenario and describes its main characteristics (a sensitivity analysis is presented in Annex II). Section 4 analyses how a stringent mitigation policy modifies the role and the scope for adaptation. Section 5 summarises our main results and their policy implications.

2. Adaptation modelling and calibration

The AD-WITCH model links adaptation, mitigation, and climate change damage within an integrated assessment model of the world economy, where the energy and climate system are carefully described. AD-WITCH builds on the WITCH model (Bosetti et al. 2006, Bosetti et al. 2009). It is an intertemporal, optimal growth model in which forward-looking agents choose the path of investments to maximise a social welfare function. It features a game-theoretic structure and can be solved in two alternative settings. In the non-cooperative setting, the twelve model regions[3] behave strategically with respect to all major economic decision variables, including adaptation and emission abatement levels, by playing a non-cooperative game. 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[4]. The benchmark for the present exercise is a non-cooperative setting and countries can only cooperate on mitigation investments.

The AD-WITCH model separates residual damage from adaptation expenditures, which become policy variables. Adaptation is chosen optimally, with all other variables in the model, e.g. investments in physical capital, in R&D and in energy technologies. To make adaptation comparable to mitigation, a large number of possible adaptive responses are aggregated into four broad expenditure categories: generic and specific adaptive capacity building, anticipatory and reactive adaptation.

A well-developed adaptive capacity is key to the success of adaptation strategies. AD-WITCH includes this component through two variables: generic and specific adaptive capacity building. Generic adaptive capacity building is linked to the overall level of economic and social

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[3] The twelve macro regions are: USA, WEURO - Western Europe, EEURO - Eastern Europe, CAJAZ - 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, TE - Transition Economies, EASIA - South East Asia, MENA - Middle-East and North Africa.

[4] AD-WITCH, as well as the WITCH model, also 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).

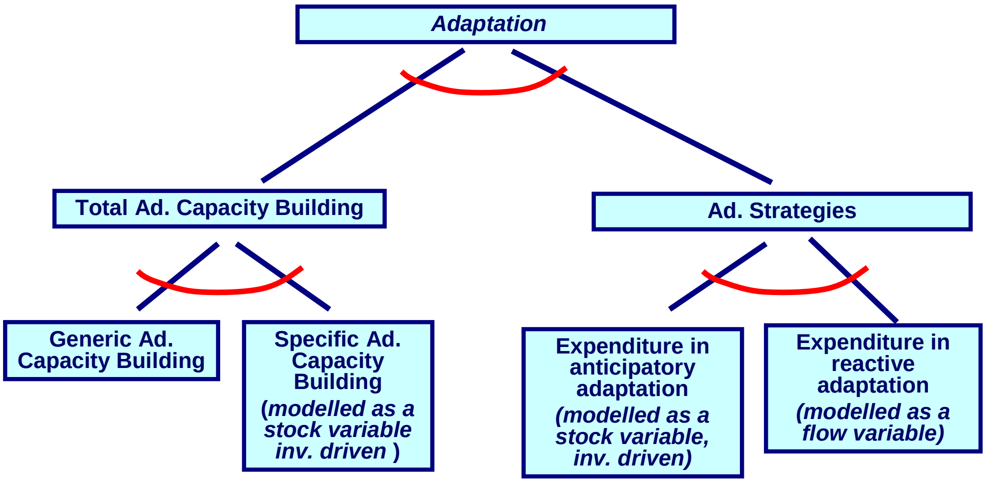
development of a region. The degree of economic development affects the final impact of climate change on the economic system: for example, a high-population-growth and low-income-per-capita region is more prone to suffer from climate change than a low-population, high-income-per-capita region (Parry et al. 2007, Parry 2009). Specific adaptive capacity building refers to all dedicated investments that are specifically targeted at facilitating adaptation activities. Examples falling within this category are the improvement of meteorological services and of early warning systems, the development of climate modelling and impact assessment, and, above all, technological innovation for adaptation purposes.

Anticipatory adaptation gathers all the measures where a stock of defensive capital must already be operational when the damage materialises. A typical example of these activities is coastal protection. Anticipatory adaptation is characterised by some economic inertia as investments in defensive capital take some time before translating into effective protection capital. Therefore, investments must begin before the damage occurs, and, if well designed, become effective in the medium, long-term.

By contrast, reactive adaptation describes the actions that are put in place when climate related damages effectively materialise. Examples of reactive actions are expenditures for air conditioning or treatments for climate-related diseases. These actions must be undertaken period by period to accommodate damages not avoided by anticipatory adaptation. They need to be constantly adjusted to changes in climatic conditions.

An “adaptation tree” (Figure 1) assembles these adaptation strategies into a sequence of nested CES functions (see Annex I for all model equations).

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



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 variable, which accumulates over time with adaptation-specific investments. In the second nest, anticipatory adaptation is also modelled as a stock of defensive capital. Because it is subject to economic inertia (initial investments in adaptation takes five years to accrue to the defensive stock), anticipatory adaptation must be planned in advance. Once it has been built up, 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 climate damage in each period, and it is independent upon the expenditure undertaken in previous periods.

Adaptive capacity building and other adaptation activities are modelled as substitutes. Similarly, reactive and anticipatory adaptation are also modelled as substitutes. After a careful sensitivity analysis, we chose a mild substitution degree (substitution elasticity is 1.2 in both cases). 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 to facilitate any form of adaptation.

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

The integration of these adaptation strategies into a unified framework is a first major contribution to the literature, which previously focused either on reactive (de Bruin et al. 2009) or anticipatory measures (Bosello 2008), and which neglected the role of adaptive capacity building (Bosello et al. 2010). A second novel feature of the model is an updated calibration of macro-regional adaptation costs and effectiveness. Table 1 summarises adaptation costs, adaptation effectiveness, and total climate change damages, together with the calibrated values, at the calibration point, when CO2 concentration doubles. Details on the calibration procedure are described in Agrawala et al. (2010).

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[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.

Table 1: Adaptation costs, adaptation effectiveness, and total climate change damages for a doubling of CO2 concentration. Extrapolation from the literature and calibrated values

	Estimated Adaptation Costs (% of GDP)	Estimated Adaptation Effectiveness (% of reduced damage)	Calibrated Adaptation Costs in AD-WITCH (% of GDP)	Calibrated Adaptation Effectiveness in AD-WITCH (% of reduced damage)	Residual Damages in AD-WITCH (% of GDP)	Total Damage in AD-WITCH (% of GDP)	Total Damages in Nordhaus and Boyer* (2000) (% of GDP)	Total Damages in the WITCH Model (% of GDP)
USA	0.09	0.18	0.10	0.22	0.40	0.50	0.45	0.41
WEURO	0.18	0.13	0.27	0.13	1.63	1.95	2.84	2.79
EEURO	0.37	0.30	0.18	0.27	0.72	0.90	0.70	-0.34
KOSAU	0.48	0.16	0.19	0.18	0.81	0.98	-0.39	0.12
CAJANZ	0.09	0.20	0.06	0.11	0.14	0.25	0.51	0.12
TE	0.28	0.12	0.15	0.12	0.55	0.67	-0.66	-0.34
MENA	1.06	0.34	0.81	0.46	1.99	2.80	1.95	1.78
SSA	0.70	0.21	0.62	0.19	3.58	4.23	3.90	4.17
SASIA	0.49	0.19	0.68	0.23	3.72	4.38	4.93	4.17
CHINA	0.20	0.15	0.11	0.21	0.49	0.56	0.23	0.22
EASIA	0.40	0.18	0.45	0.21	1.75	2.20	1.81	2.16
LACA	0.13	0.38	0.24	0.25	0.96	1.24	2.43	2.16

* The regional disaggregation adopted by Nordhaus and Boyer (2000) does not perfectly correspond to the one used in WITCH and AD-WITCH.

In the calibration procedure, this paper integrates the original database of the WITCH model with Nordhaus and Boyer (2000) and Agrawala and Fankhauser (2008), which provide the most recent and complete assessment on costs and benefits of adaptation strategies.

Three major points deserve to be mentioned. First, we gather new information on climate change damages consistent with the existence of adaptation costs and calibrate AD-WITCH on these new values and not on the original values of the WITCH model. Second, due to the optimising behaviour of the AD-WITCH model, when a region gains from climate change, it is impossible to replicate any adaptive behaviour and positive adaptation costs in that region. Accordingly, when WITCH data show gains from climate change, we refer to Nordhaus and Boyer (2000) results. If both sources report gains (as in the case of Transition Economies, TE) we impose a damage level originating an adaptation cost consistent with the observations. Third, the calibrated total climate change costs are reasonably similar to the reference values. The main explanation is that consistency needs to be guaranteed across three interconnected items: adaptation costs, total damage, and protection levels. Adaptation costs and damages move together. For instance, it is not possible to lower adaptation costs in Western Europe (WEURO) to bring them closer to their reference value without decreasing total damage, which is already lower than the reference. Although we are fully aware of these shortcomings, we also recognise that the quantitative assessment of adaptation costs and benefits is still at a pioneering stage and that some areas (e.g. agriculture and health) and regions (especially developing countries) still lack reliable data.

This study respects the observed ordinal ranking of adaptation costs and effectiveness which, given the overwhelming uncertainty, can be considered as informative as a perfect replication of the data.

3. Model baseline with endogenous adaptation strategies

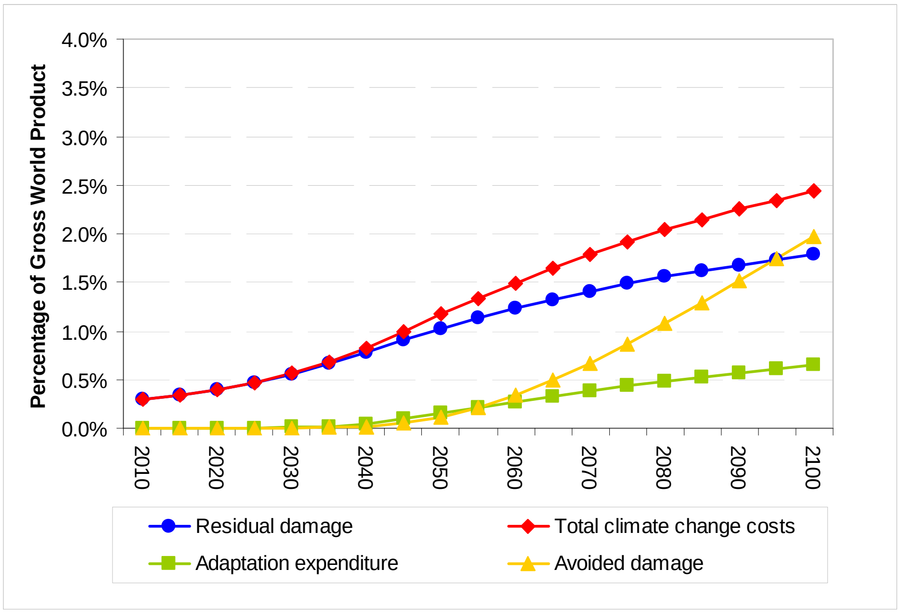
Economic growth in the AD-WITCH baseline scenario closely replicates the Gross World Product (GWP) path of the B2 IPCC SRES scenario. Population peaks in 2070, at almost 9.6 billion, slightly decreasing thereafter to reach 9.1 billion in 2100. CO2 emissions are more similar to the A2 IPCC SRES scenario until 2030. Afterwards they grow at a lower rate, reaching 23 billion tons in 2100.

The baseline scenario endorses a non-cooperative view of international relationships, which implies that no cooperative mitigation effort is undertaken. In a non-cooperative world, the public good-nature of mitigation features a free riding incentive that reduces mitigation activity to almost zero. By contrast, adaptation is a private good whose benefits are fully appropriable, at least within the macroeconomic region where it is implemented[6]. Accordingly, it is also a viable strategy in a non-cooperative setting.

As Figure 2 shows, according to our results, the optimal level of adaptation that equalises regional marginal costs and benefits is substantial. In 2100, for the world as a whole, adaptation roughly halves damages from US$13 (3.8% of GWP) to 6 Trillion (1.8% of GWP). Those 7 US$ Trillion of avoided damages in 2100, represent about 2% of GWP. Adaptation becomes sizeable only after 2040, when climate change damage is sufficiently high to justify strong adaptation expenditure.

Despite adaptation, residual damage remains high throughout the century, and in 2100, climate damage is almost 2% of world GDP. In 2100, residual damages accounts for 73% of total climate change costs, while the remaining 27% is the cost of adaptation.

Figure 2: Decomposition of climate change costs: residual damage, adaptation expenditure, total damages, and avoided damage



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[6] However, there might be market failures that lead to under-provision of adaptation measures, but these issues are typically confined within the border of a region and can therefore be dealt with by using national or local policies.

Figure 3 shows how adaptation expenditure is allocated between adaptive capacity-building and adaptation activities. Both increase in response to the increasing climate damage. Thus, they behave like normal goods. They are mild economic substitutes and accordingly strategic complements. Specific adaptive capacity building absorbs a smaller and declining fraction of the adaptation budget. Its share decreases from 44% in 2030, (US$ 4 Billion out of 8.4), to 16% in 2100 (US$ 374 Billion out of 2331). This result indicates that building specific adaptive capacity is initially more important, because it enables the economic system to effectively develop and exploit adaptation strategies thereafter. Once the required capacity has been developed, even though capacity building continues to grow, there is more room to direct actions against climate damages.

Figure 3: Adaptation strategy mix. Capacity building and adaptation activities

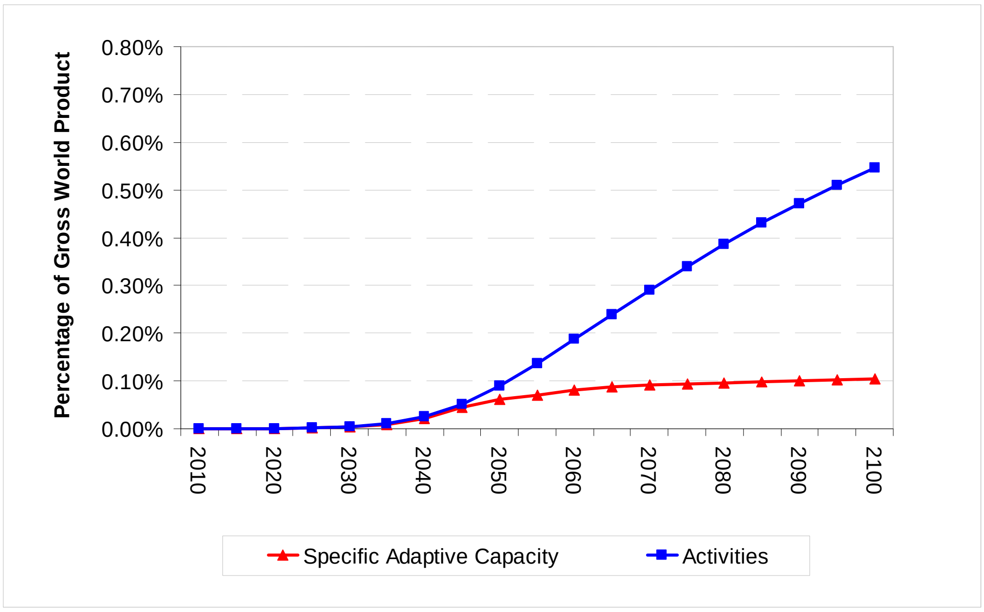


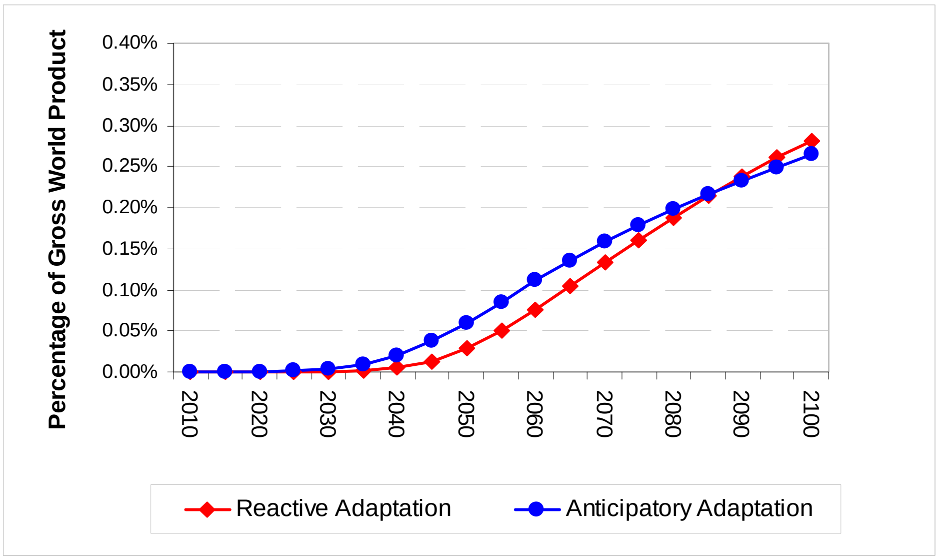
Figure 4 describes the composition of anticipatory and reactive adaptation strategies. Again they are both increasing throughout the century, but anticipatory adaptation starts earlier. This is because defensive capital must be ready when the damage materialises, and it faces at least a five-year economic inertia. On the contrary, reactive adaptation by definition alleviates the damage instantaneously and can be put in place immediately after the damage occurs.

Note also that anticipatory adaptation is the main adaptation strategy until 2085. Reactive adaptation prevails afterwards. This reflects the convex-in-temperature climate damage. As time goes by, damages increase at a rate that requires a growing support of reactive measures, which become the main options in the long-run.

Due to the local nature of adaptation and the differences in regional vulnerability, regional adaptation patterns may differ substantially from what the global picture suggests. Such diversity is shown in Figure 5, which emphasises the different size, timing, and composition of adaptive behaviour across developing and developed countries.

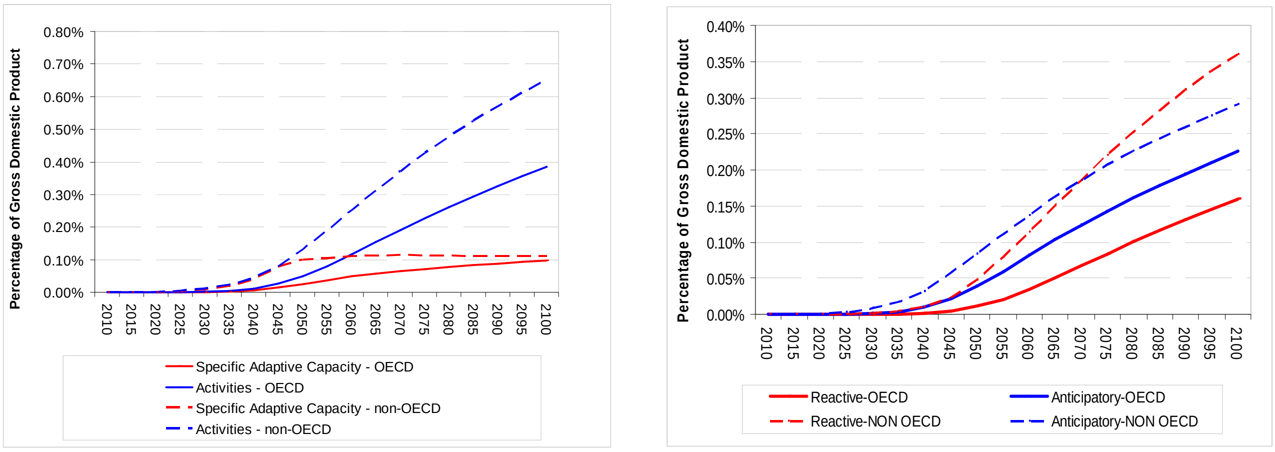
Developing countries are more exposed to climatic damages, therefore they are forced to spend more than OECD regions in all forms of adaptation either in percent of GDP (Figure 5) or in absolute terms (Table 2). In 2100, adaptation expenditure in non-OECD countries more than doubles that of OECD regions. Not surprisingly, adaptation effort is particularly large in more vulnerable regions, namely Sub-Saharan Africa (SSA), South-Asia (SASIA), Middle East ant North Africa (MENA).

Figure 4: Adaptation strategy mix. Composition of adaptation activities



The effective availability of resources to meet adaptation needs in developing regions is particularly concerning. In 2050, developing countries are expected to spend around US$ 200 Billion (already twice the current flow of official development assistance), but approximately US$ 1.6 Trillion in 2100. On an annuitized base computed throughout the century, climate change adaptation would cost non-OECD countries approximately US$ 500 Billion (or 0.48% of their GDP) against US$ 200 Billion (or 0.22% of GDP) in OECD countries. This would call for international aid and cooperation on adaptation.

Figure 5: Regional adaptation strategy mix. Adaptive capacity building versus adaptation activities (left panel) and reactive adaptation versus anticipatory adaptation (right panel)



In developing countries damage is not only higher, but also occurs earlier. For this reason, adaptation starts earlier than in OECD. The case of adaptive capacity building is interesting. Non-OECD countries should first build up a stock of adaptive capacity, an essential prerequisite for successful adaptation. In doing so, they face a development gap with developed countries. Therefore, investments in specific adaptive capacity in developing countries are larger and grow faster during the first half of the century with respect to investments in developed countries.

Table 2: Regional components of damage and adaptation costs from 2005 to 2100 in Net Present Values (3% discounting, 2005 US$ Billion except GDP in Trillion)

	Total damage	Total adaptation expend.	Expenditure on reactive adaptation	Investment in anticipatory adaptation	Investment in specific adaptive capacity	Residual damage	GDP	Total damage (% of GDP)
USA	3079	563	158	283	122	2516	884	0.3%
WEURO	10362	1216	308	555	353	9146	801	1.3%
EEURO	519	83	28	45	10	436	70	0.7%
KOSAU	739	145	44	79	23	594	117	0.6%
CAJAZ	220	128	36	70	22	92	323	0.1%
TE	540	154	5	124	25	386	134	0.4%
MENA	3707	941	278	414	249	2766	162	2.3%
SSA	3230	537	239	236	61	2693	85	3.8%
SASIA	12075	1987	821	803	363	10088	298	4.1%
CHINA	2691	550	304	63	183	2142	535	0.5%
EASIA	2804	512	175	188	148	2292	163	1.7%
LACA	3908	611	204	192	215	3297	361	1.1%
GLOBAL	43874	7424	2600	3051	1774	36450	3932	1.1%
OECD	14919	2134	573	1032	529	12785	2194	0.68%
NON OECD	28955	5290	2026	2019	1245	23665	1737	1.67%

Finally, the composition of the adaptation portfolio also differs across countries. In OECD regions anticipatory adaptation clearly prevails, whereas in non-OECD countries anticipatory and reactive adaptation are almost equal. This difference depends on two factors: the regional characteristics of climate vulnerability and the level of economic development. In OECD countries, the higher share of climate change damages originates from loss of infrastructure and coastal areas, whose protection requires a form of adaptation that is largely anticipatory. In non-OECD countries, climate change affects agriculture, health, and the use of energy for space heating and cooling.

These damages can be accommodated more effectively through reactive measures. As OECD countries are richer, they can easily give up their present consumption to invest in adaptation measures that will become productive in the future. By contrast, non-OECD countries are compelled by resource scarcity to act in emergency.

4. Adaptation and mitigation: a portfolio approach to climate change policy

Having characterised baseline adaptation patterns, we now analyse how this picture may change in the presence of a mitigation policy. We assume that a global agreement aimed at stabilising GHG concentrations at 550 ppme (or 3.7 W/m2) is successfully reached. This stabilisation target is less ambitious than the 2°C target, but still quite difficult to achieve. We also assume that all regions have unlimited access to an international carbon market to maximise cost effectiveness. Permits are allocated on an equal emission per capita basis. Under these conditions, is there still room for adaptation? How much adaptation? Where? When? Can adaptation reduce the costs of mitigation?

Our main results are summarised by Table 3, which breaks down the components of climate change costs, now including also mitigation investments, in three cases: the baseline (i.e. adaptation without mitigation), mitigation policy without adaptation, and mitigation policy with adaptation. The last case characterises the mitigation-adaptation mix and is the center of our investigation.

Note (fourth column) that mitigation expenditure is initially much higher than adaptation. Mitigation must start immediately, even though initial climate damage is very low, because it works against the inertia of the carbon cycle and of the energy system. In AD-WITCH, emission reduction is accomplished by decarbonising the power generation and the transport sector and by improving energy efficiency through innovation. Mitigation options require substantial long-term investments to become competitive and deployed on a large scale, therefore, they must occur earlier. By contrast, adaptation measures work "through" a much shorter economic inertia, and can be postponed until damages are effectively high. This, consistently with the AD-WITCH damage structure, occurs after 2030. Consequently, investments and expenditure in mitigation remain larger than those on adaptation throughout the century.

Mitigation lowers the need to adapt and crowds out adaptation expenditure (second versus fourth column). The crowding-out is particularly prominent after mid-century, when it reaches about 50%. Nonetheless, adaptation remains substantial and it still exceeds US$ 1 Trillion in 2100. As for geographical distribution, adaptation is particularly concentrated in developing countries (Table 4).

Table 3: Building-up of climate costs in the mitigation scenario with and without adaptation in 2030, 2050, 2100 and in Net Present Value (2005-2100)[7]

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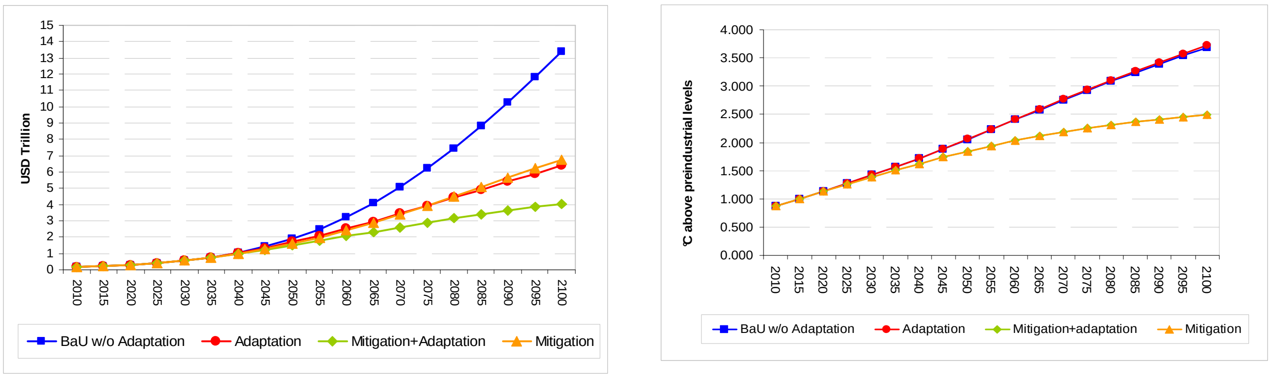
[7] Mitigation expenditure includes additional investments compared to the baseline in zero carbon technologies for power generation (nuclear, renewables, coal plants with CCS, backstop technology), investments in energy efficiency and backstop R&D, and expenditure in biofuels.

Annual Average Costs - WORLD (US$ Billion)			
2030	**Baseline**	**Mitigation W/O adaptation**	**Mitigation + adaptation**
Mitigation expenditure	0	1098	1149
Adaptation expenditure	8	0	6
Residual damage	562	550	548
Total Costs	571	1648	1703
2050			
Mitigation expenditure	0	1551	1590
Adaptation expenditure	250	0	136
Residual damage	1705	1601	1494
Total Costs	1955	3152	3221
2100			
Mitigation expenditure	0	2097	2133
Adaptation expenditure	2331	0	1021
Residual damage	6376	6775	4065
Total Costs	8707	8873	7219
Discounted costs – WORLD (US$ Billion)			
2005-2100 (Discount rate 3%)			
Mitigation expenditure	0	29623	32322
Adaptation expenditure	7424	0	3544
Residual damage	36450	36088	29579
Total Costs	43874	65711	65444
Discounted costs – OECD (US$ Billion)			
2005-2100 (Discount rate 3%)			
Mitigation expenditure	0	13374	15806
Adaptation expenditure	2134	0	725
Residual damage	12785	11137	10227
Total Costs	14919	24511	26758
Discounted costs - non-OECD (US$ Billion)			
2005-2100 (Discount rate 3%)			
Mitigation expenditure	0	16249	16515
Adaptation expenditure	5290	0	2818
Residual damage	23665	24951	19351
Total Costs	28955	41200	38684

Adaptation slightly increases the mitigation effort required to comply with the stabilisation target (fourth versus third column). Indeed, the possibility to adapt increases the amount of damage that can be endured, and thus the level of tolerable emissions. Therefore, reaching the GHG concentrations target requires a slightly higher abatement effort.

Figure 6 provides further information. The left panel shows that in terms of damage reduction, the effect of the optimal adaptation investments identified in the baseline and of the optimal mitigation investment to reach the chosen stabilisation policy is roughly of the same order. However, in terms of costs, the first is much cheaper than the second. Therefore, if the target were simply damage reduction with only one policy instrument at hand, adaptation would be preferred. However, when the goal is to reduce the probability of climate change-induced catastrophes, by controlling temperature increase, adaptation is nearly useless (see Figure 6, right panel) and only mitigation is effective.

Figure 6: Contribution of adaptation and mitigation to damage reduction (left panel) and global temperature increase above pre-industrial levels (right panel)



A portfolio of strategies brings welfare improvements as compared to using only one strategy. Thus this cost effectiveness framework replicates the typical first-best efficiency rule according to which two instruments can do no worse than one. Bosello et al. (2010) demonstrates that this also applies to optimal mitigation and adaptation policies.

Although a fairly ambitious mitigation policy target is adopted internationally and mitigation reduces climate damages, there is still room for adaptation. Again geographic differences are important. OECD regions experience lower damages under global mitigation than they would under optimal domestic adaptation (Table 3) and indeed they greatly reduce adaptation expenditure when both mitigation and adaptation are implemented (Table 4)[8]. In non-OECD regions the opposite occurs: residual damages are higher under the mitigation policy than under optimal domestic adaptation, thus mitigation reduces the need to adapt by a lower margin.

The net effect of combining adaptation and mitigation is a welfare improvement in the long-term. Initially, the additional expenditure on adaptation and the increased costs of mitigation are not compensated by the reduced damage, but as long as climate related damages increase, adaptation becomes more useful. Mitigation and adaptation confirm their mild substitutability and this justifies their joint use in a cost-effective portfolio of climate policies.

Table 4: Composition of adaptation expenditure with and without mitigation (2005 US$ Billion, NPV 3% discounting)

Adaptation	**WORLD**	**OECD**	**non-OECD**
Reactive Adaptation	2600	573	2026
Anticipatory Adaptation	3051	1032	2019

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[8] An interesting result shown by Table 4 is that a small adjustment in favour of reactive adaptation and investment in specific adaptive capacity is recognisable within the adaptation mix. Both adaptation classes, being “stocks”, are more similar to mitigation among adaptation options. They suffer the strongest crowding out. The time and composition profile of adaptation remain almost unchanged with a moderate tilting toward reactive measures and capacity building.

Specific Adaptive Capacity Building	1774	529	1245
Mitigation + adaptation	**WORLD**	**OECD**	**non-OECD**
Reactive Adaptation	1220	198	1022
Anticipatory Adaptation	1362	349	1013
Specific Adaptive Capacity Building	962	179	783
Percentage change	**WORLD**	**OECD**	**non-OECD**
Reactive Adaptation	-53%	-65%	-49%
Anticipatory Adaptation	-55%	-66%	-50%
Specific Adaptive Capacity Building	-46%	-66%	-37%

5. Discussion and conclusions

This paper has investigated the relationship between mitigation and adaptation, as well as the interactions between capacity building and different adaptation measures. By adopting a macroeconomic perspective, it addressed issues of strategic planning and optimal public resource management in a cost-effective setting.

The analysis carried out in this paper emphasises the strategic differences between mitigation and adaptation. In contrast to mitigation, adaptation does not generate international externalities. Its benefits are appropriable domestically and it is not affected by free riding incentives that typically undermine the provision of public goods. As a consequence, adaptation is the main strategy to cope with climate change in a strictly non-cooperative framework.

Reactive and anticipatory adaptation measures are shown to be strategic complements that, together with investments in adaptive capacity, should belong to the optimal adaptation strategy. Anticipatory adaptation measures become effective with a delay and should be implemented first. They are the main adaptation strategy in the first half of the century, while reactive adaptation prevails afterwards. Investing in specific adaptive capacity building is also an early strategy, because capacity is a prerequisite for effective adaptation actions.

Adaptation needs largely differ across world regions. In developing countries, the size of adaptation investments that would be optimal on the basis of cost-benefit considerations might not be achievable. Both the rate of growth and the level of adaptation expenditures are far higher in poorer countries. The magnitude of resources needed is likely to be unavailable in these regions. Therefore international cooperation efforts are needed to address distributional issues and financial constraints.

The optimal composition and timing of the adaptation portfolio also varies across regions. Because of the heterogeneous distribution of climate change damages and of different resource endowments, non-OECD countries devote a relatively larger share of expenditure to reactive interventions, whereas OECD countries devote their expenditure to anticipatory interventions. Adaptive capacity building is, however, particularly important in non-OECD countries. Again, international cooperation and financial and technological transfers are needed to fill this gap.

When mitigation policy is internationally coordinated and enforced, adaptation efforts are partly crowded-out. This result is consistent with previous studies that analysed the relationship between adaptation and mitigation in a cost-benefit setting (Bosello 2008, Bosello et al. 2010, de Bruin et al. 2007, de Bruin and Dellink 2009). Two additional considerations are worth mentioning. Notwithstanding the success of mitigation to reduce climate change damages, as long as damages are positive and marginal costs of adaptation are increasing, there is still room for adaptation. Optimal adaptation efforts remain substantial (above US$ 1 trillion in 2100) even in the presence of a GHG concentration stabilisation policy.

The integration of mitigation and adaptation is welfare improving. Total climate change costs are indeed lower in the presence of adaptation. On the other hand, mitigation should start immediately, even though initial climate damage is very low. The reason for early mitigation action is its long-term dimension. First, emission reductions today lead to lower temperature and damages only in the far future. Second, ambitious emission reductions require major changes in the energy infrastructure system, which has a slow capital turnover. Consequently, in the short-run, the optimal allocation of resources between adaptation and mitigation should be tilted towards mitigation. Adaptation becomes increasingly important in the longer-run. Therefore, if the aim is to reduce the probability of catastrophic and possibly irreversible climate related damages, aggressive mitigation actions need to be implemented soon.

Annex I. Introducing adaptation into the Witch model

Four different adaptation expenditures have been considered in the present study. Expenditure in adaptive capacity building is divided into a generic and a specific component. Expenditure in adaptation activities includes anticipatory and reactive adaptation. The starting point for the implementation is the original WITCH climate change damage function:

$$YN_{n,t} = \frac{1}{1 + CCD_{n,t}} \cdot YG_{n,t} \tag{1}$$

In (1) damage from climate change (time and region specific) indicates a GDP loss measured by a gap between gross *YG* and net output *YN*. As in Nordhaus and Boyer (2000), the climate change damage function, $CCD_{n,t}$ is a reduced form relationship between temperature and output :

$$CCD_{n,t} = \theta_{1n} \cdot T_t + \theta_{2n} T_t^{\gamma_n} \tag{2}$$

Its parameters have been calibrated to replicate a percentage change in GDP loss in response to a 2.5°C temperature increase above pre-industrial levels. The exponent γ is set to 2, to model a convex-in-temperature damage. The calibration of (2) compounds two components of climate change damage: adaptation costs and residual damages. We changed this in two ways. We specify the role of adaptation in reducing damage in (2). We then separated the cost component of adaptation from (2). The climate change damage function with adaptation becomes:

$$CCDA_{n,t} = f(ADAPT_{n,t}, CCD_{n,t}) = \frac{1}{1 + ADAPT_{n,t}} \cdot CCD'_{n,t} \tag{3}$$

In equation (3), an increase in adaptation activities as a whole ($ADAPT_{n,t}$) reduces the negative impact from climate change on gross output. We have chosen the simplest functional form that presents, by construction, two agreeable properties: it is bounded between 0 and 1; an infinite amount of resources allocated to adaptation can reduce the residual climate change damage to 0 at the maximum. Adaptation exhibits decreasing marginal productivity, thus additional resources to adaptation become less and less effective in reducing damage.

As mentioned before, different methods of adapting can be chosen. Total adaptation, $ADAPT_{n,t}$ is decomposed into its different forms by a sequence of Constant Elasticity of Substitution (CES) nests. The choice of the CES specification is determined by its great flexibility in representing the different degrees of substitutability and complementarity among its components. By simply adjusting the CES exponents, alternative assumptions about the relationships between different adaptation strategies can easily be tested.

A first CES nest allocates resources to adaptive capacity-building (*TCAP*) or to adaptation activities (*ACT*) according to:

$$ADAPT_{n,t} = (\alpha_{1,n} TCAP_{n,t}{}^{\rho_{ADA}} + \alpha_{2,n} ACT_{n,t}^{\rho_{ADA}})^{1/\rho_{ADA}} \tag{4}$$

Adaptive capacity-building (*TCAP*) is a CES combination of generic (*G_CAP*) and specific (*S_CAP*) adaptation capacity:

$$TCAP_{n,t} = (\alpha_{3,n} G\_CAP_{n,t}{}^{\rho_{cap}} + \alpha_{4,n} S\_CAP_{n,t}^{\rho_{tcap}})^{1/\rho_{tcap}} \tag{5}$$

Generic capacity captures every component that is not necessarily related to adaptation itself but to the economic development of a region. The underlined assumption is that the richer a region the more adaptable it is. Specific capacity depends not only on other forms of investment such as R&D for adaptation purposes and early warning systems, but also on institutional capacity. *G_CAP* follows an exogenous trend mimicking the growth rate of total factor productivity. The initial value is an indicator of local capacity based on human capital and knowledge stock:

$$G\_CAP_{n,t} = G\_CAP_{n,0} * TFP(n,t) \tag{6}$$

Specific adaptive capacity building is modelled as a stock , which accumulates over time with adaptation-specific investments, $IS\_CAP_{n,t}$ according to a standard discrete-time law of motion:

$$S\_CAP_{n,t} = (1-\delta_{CAP}) \cdot S\_CAP_{n,t-1} + IS\_CAP_{n,t} \tag{7}$$

The stock depreciates at a rate of δ_{CAP}, which has been set equal to 3% per year. Investments in specific capacity have been set to be approximately 1% of world expenditure on education and total R&D in the calibration year. In absolute terms this amounts to US$ 164 Billion in 2060. This global amount has been distributed across different regions proportionally to the normalised share of education expenditure over GDP. This criteria corrects the otherwise uneven distribution of R&D investments highly concentrated in developed countries. Total adaptive capacity increases the effectiveness of adaptation activities. Adaptation activities, proactive or reactive, compose another CES nest according to:

$$ACT_{n,t} = \beta(\alpha_{6,n} PAD_{n,t}{}^{\rho_{ACT}} + \alpha_{5,n} RAD_{n,t}^{\rho_{ACT}})^{1/\rho_{ACT}} \tag{8}$$

Reactive adaptation $RAD_{n,t}$ is a flow of expenditure undertaken period by period. It deals specifically with residual damage. It indicates that the damage reduced in one period does not influence what has to be achieved in the next. On the contrary, proactive adaptation $PAD_{n,t}$ is modelled as a stock of capital. It accumulates over time with adaptation-specific investments, $IPAD_{n,t}$, according to a standard law of motion:

$$PAD_{n,t} = (1 - \delta_{PAD}) \cdot PAD_{n,t-1} + IPAD_{n,t} \tag{9}$$

The stock depreciates at a rate δ_{PAD} that equals the depreciation rate of physical capital, 10% per year. Expenditure in the three adaptation measures (generic capacity is an exogenous trend) is accounted in the national income identity:

$$YN_{n,t} = C_{n,t} + I_{n,t} + IR\&D_{n,t} + \sum_{J} I_{j_{n,t}} + IS\_CAP_{n,t} + RAD_{n,t} + IPAD_{n,t} \tag{10}$$

In equation (10) expenditure in reactive adaptation, proactive adaptation, and specific adaptive capacity compete with the alternative uses of income: consumption $C_{n,t}$, investment in physical capital $I_{n,t}$, investment in other forms of innovation $IR\&D_{n,t}$ and in energy technologies $I_{j_{n,t}}$.

Only residual damage remains in the climate change damage function. Accordingly, the damage function must be defined by a new parameterisation of equation (2), which excludes adaptation costs. The calibration process of (3) and the other equations of the AD-WITCH model is described in Annex II. Residual damage is defined as the difference between gross and net output. From equation (1) we have:

$$YG_{n,t} - YN_{n,t} = CCD_{n,t} YN_{n,t} = RD_{n,t} \tag{11}$$

Using equation (2) and equation (3), residual damage can be defined as follows:

$$RD_{n,t} = YN_{n,t} \frac{1}{1 + ADAPT_{n,t}} (\theta_{1n} T_t + \theta_{2n} \cdot T_t^{\gamma 3n} + \theta_{3n}) \tag{12}$$

Annex II: Sensitivity Analysis

The robustness of our baseline results is tested against changes in two key parameters: the size of climatic damage and the pure rate of time preference (PRTP). Climate change damage estimates have always been uncertain, but the most recent literature (Parry et al. 2007, Stern 2007, UNFCCC 2007, and Hanemann 2008) has revised upward initial assessments. Furthermore AD-WITCH, like most IAMs, abstracts from very rapid warming and large-scale changes of the climate system (system surprises), thus its proposed damage estimates are likely to underestimate the real magnitude of the phenomenon. PRTP is expected to have major influences on the adaptation mix as it governs the perception of present and future as well as the incentives to choose one option or the other.[9]

In addition to our baseline damage, we also analyse a high-damage case, about twice the former. In addition to our baseline PRTP, which is 3% declining over time in line with Nordhaus and Boyer (2000), a lower PRTP equal to 0.1% declines in line with Stern (2007). Table AII.1 and AII.2 summarise the results of the four cases originated by the different combination of damages and PRTPs.

As expected, when damages increase or the PRTP decreases, all adaptation options are fostered. There are also changes in their relative weight within the adaptation mix. A higher damage slightly favours reactive adaptation, which increases by 105% in 2100, as opposed to 97% of anticipatory adaptation and 57% of specific capacity. A lower PRTP favours anticipatory adaptation and adaptive capacity building (respectively +37% and +49% in 2100). Although it shows the highest percentage increase, it still absorbs a minor fraction of total adaptation expenditure (between 13 to 20%). When high damage is combined with low PRTP, the discounting effect tends to prevail and the optimal mix is slightly tilted toward stock measures, namely anticipatory adaptation and specific adaptive capacity. This indicates that higher damages are contrasted *relatively* better with reactive measures which perform indifferently well in the short-term and the long-term. Higher *future* damages that are implicitly associated to a lower PRTP, can be contrasted *relatively* better with anticipatory measures which requires more time to be put in place, but can be more effective in the future.

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[9] There is a longstanding controversy regarding the PRTP (Weitzman 2001). In line with a long line of economists (Ramsey 1928, Harrod 1948, Solow 1974), Stern (2007) argues on ethical grounds for a near-zero PRTP, while others dismiss this argument because it is inconsistent with actual individual behaviour (Nordhaus 2007; Weitzman 2007a).

Table AII.1: Adaptation under different discounting and damages in 2100

	Average annual costs (2005 US$ Billion). In brackets the % change wrt baseline			
2100	**Low damage- high PRTP (Baseline)**	**High damage- high PRTP**	**Low Damage- low PRTP**	**High damage-low PRTP**
Anticipatory Adaptation	950	1871 (97)	1306 (37)	2510 (164)
Reactive Adaptation	1007	2068 (105)	1070 (6)	2138 (112)
Specific Adaptive Capacity Building	374	589 (57)	558 (49)	837 (124)

Lower PRTP and higher impacts from climate change also anticipate optimal adaptation expenditure (Table AII.2). A higher damage imposes spending on adaptation US$ 0.8 Billion already in 2010. This surpasses US$ 3 Billion if high damage is coupled with a low PRTP. Adaptation expenditure increases exponentially thereafter.

Table AII.2: Adaptation expenditure in the short-run (2005 US$ Billion)

Adaptation Activities	**Low damage- high PRTP (Baseline)**	**Low Damage- low PRTP**	**High damage-high PRTP**	**High damage-low PRTP**
2010	0.00	0.01	0.55	2.02
2015	0.02	0.14	2.76	8.98

2020	0.19	1.04	9.88	26.13
2025	1.17	4.83	26.85	60.53
2030	4.64	14.63	60.59	121.34
Specific Adaptive Capacity Building	**Low damage-high PRTP (Baseline)**	**Low Damage-low PRTP**	**High damage-high PRTP**	**High damage-low PRTP**
2010	0.00	0.01	0.28	1.33
2015	0.02	0.14	1.42	6.12
2020	0.16	1.09	5.18	18.89
2025	0.97	5.06	15.16	46.84
2030	3.72	14.74	36.01	95.92

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