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Adaptation can help mitigation: an integrated approach to post-2012 climate policy

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ABSTRACT. This paper analyzes the optimal mix of adaptation and mitigation expenditures in a cost-effective setting, in which countries cooperate to achieve a long-term stabilization target (550 CO_2-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 analyze the optimal portfolio of adaptation measures. Results show that the optimal intertemporal distribution of climate policy measures is characterized by early investments in mitigation followed by large adaptation expenditures a few decades later. Hence, the possibility of adapting does not justify postponing mitigation. Moreover, a climate change policy combining mitigation and adaptation is less costly than mitigation alone. In this sense mitigation and adaptation are shown to be strategic complements rather than mutually exclusive.

1. Introduction

The emission reduction commitments proposed at the end of COP XV in Copenhagen will probably fail to stabilize global warming below or around

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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, which needs careful planning along with mitigation (Fankhauser and Burton, 2011). 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). Environmental irreversibility, market distortions and budget constraints are particularly binding in developing countries that assign planned adaptation a leading role (see, for example, Banerjee and Duflo, 2004).

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 comes from Hope *et al.* (1993) and Hope (2006) 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 were proposed by Bosello (2008), Bosello *et al.* (2010b) and de Bruin *et al.* (2009a, b). All these studies conclude that adaptation and mitigation are strategic complements: namely, 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 the studies also highlight the existence of a trade-off between the two strategies: because resources are scarce, investing more in mitigation implies fewer resources for adaptation (Tol, 2005). Moreover, successful adaptation reduces the marginal benefit of mitigation and a successful mitigation effort reduces the damage to which it is necessary to adapt (Barrett, 2008). 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 to 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 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

[1] On the effectiveness of the Copenhagen pledges, see Carraro and Massetti (2010), and for a comparison of different studies, see 'Adding up the numbers: mitigation pledges under the Copenhagen Accord', [Available at] http://www.pewclimate.org/docUploads/copenhagen-accord-adding-up-mitigation-pledges.pdf.

[2] See Hope *et al.* (1993), Hope (2006), Bosello (2008), de Bruin *et al.* (2009a, b) and Bosello *et al.* (2010b).

the standard damage functions used in most integrated assessment models, i.e., the one from Nordhaus's DICE/RICE models. These damage functions include, at best, extreme but not catastrophic events, and no uncertainty.

This paper analyzes adaptation and the trade-off between adaptation and mitigation in a cost-effective setting. It assumes that a global mitigation policy will successfully manage to stabilize GHG concentrations at 550 ppme (parts per million equivalent) by the end of the century. Although this target is less ambitious than the 2°C target, it is still quite demanding and difficult to achieve. Given this mitigation path, this paper explores how adaptation should be optimally designed to address the damage not eliminated by mitigation, how different adaptation strategies should be combined, and how the equity-adverse impact of climate change should be addressed. It also stresses the different time scale of adaptation and mitigation, and provides some indications on key priorities for adaptation policy.

The paper characterizes the adaptation mix beyond the stock and flow distinction, as in Agrawala *et al.* (2011), and it provides more detailed results on regional adaptation and mitigation costs. In this sense, the analysis proposed in this paper is a nice complement to Agrawala *et al.* (2011), which focused more on the modelling advancements and global results in comparison to the AD-DICE model.

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 implemented.

Results indicate that 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 on all forms of adaptation. However, they devote a relatively larger share of their adaptation expenditure to reactive interventions, whereas OECD countries spend more on anticipatory interventions.

An internationally coordinated mitigation policy partially crowds out adaptation. However, when ambitious mitigation effort is assisted by adaptation interventions, the overall policy mix entails a lower cost since part of the mitigation costs are compensated by the net gains from adaptation. Hence, both mitigation and adaptation should be part of the internationally adopted climate change policy.

The remainder of the paper is organized 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 Appendix A). Section 4 analyzes how a stringent mitigation policy modifies the role and the scope for adaptation. Section 5 summarizes 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, 2009). It is an intertemporal, optimal growth model in which forward-looking agents choose the path of investments to maximize a social welfare function. It features a game-theoretic structure and can be solved in two alternative settings. In the non-cooperative setting, the 12 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 internalize the environmental externality. The cooperative setting describes a first-best world, in which all externalities are internalized because a benevolent social planner maximizes a global welfare function.[4] The benchmark for the present exercise is a non-cooperative setting and in the mitigation scenarios countries only cooperate on climate.

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, and anticipatory and reactive adaptation.

A well-developed adaptive capacity is key to the success of adaptation strategies. The IPCC defines adaptive capacity as 'the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damage, to take advantage of opportunities, or to cope with the consequences' (IPCC, 2007). 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). AD-WITCH includes this component through two variables: generic and specific adaptive capacity building. Generic adaptive capacity building is broadly linked to the level of economic and social development of a region and includes factors such as income, education, infrastructure, quality of institutions and social capital (Yohe and Tol, 2002; Alberini *et al.*, 2006; Toya and Skidmore, 2007; Dell *et al.*, 2008). Specific capacity refers to the activities specifically targeted at facilitating adaptation to climate change. Examples falling within this category include the following: climate information systems (such as improvement in meteorological services, early warning systems, climate modelling and impact

[3] The 12 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; and 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 internalizes all externalities. For more insights on the treatment of technical change in the WITCH model, see Bosetti *et al.* (2009).

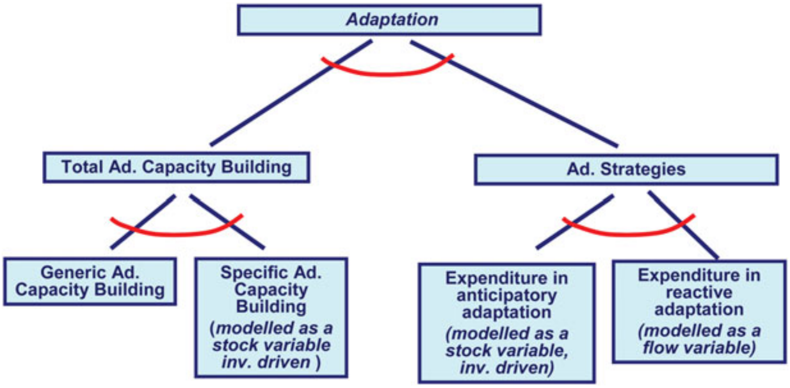

Figure 1. *The adaptation tree in the AD-WITCH model*

assessment), climate change education and awareness campaigns and, most importantly, R&D and technological innovation.

Anticipatory adaptation gathers all the measures where a stock of defensive capital must already be operational when the damage materializes. A typical example of these activities is coastal protection. Anticipatory adaptation is characterized 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 to long term.

By contrast, reactive adaptation describes the actions that are put in place when climate-related damages effectively materialize. 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 the online Appendix, available at http://journals.cambridge.org/EDE, for model equations). This functional form allows great flexibility in the combination of adaptation modes and provides a straightforward interpretation on their substitution/complementarity relationships and the related sensitivity analysis.

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. Since it is subject to economic inertia (initial investments in adaptation takes 5 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 of the expenditure undertaken in previous periods.

Adaptive capacity building and other adaptation activities are modelled as substitutes. Similarly, reactive and anticipatory adaptations 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 prerequisite to facilitate any form of adaptation. In addition, the CES structure with elasticity less than one allows for partial compensation between generic and specific capacity (Yohe and Tol, 2007). 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.*, 2009a, b) or anticipatory measures (Bosello, 2008), and which neglected the role of adaptive capacity building (Bosello *et al.*, 2010b). A second novel feature of the model is an updated calibration of macro-regional adaptation costs and effectiveness. Table 1 summarizes adaptation costs, adaptation effectiveness and total climate change damages, together with the calibrated values, at the calibration point, when CO_2 concentration doubles. The 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. Details on the calibration procedure are described in Agrawala *et al.* (2011).

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 optimizing behaviour of the AD-WITCH model, when a region experiences net gains from climate change, it is impossible to replicate any adaptive behaviour to contrast potential, yet existing, negative impacts and positive adaptation costs in that region.[6] Accordingly, when WITCH data show gains from climate change, we refer to Nordhaus and Boyer's (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

[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.

[6] In fact it is possible to model positive adaptation expenditure with gains from climate change as in de Bruin *et al.* (2009a, b), but then this had to be interpreted as adaptation expenditure to take advantage of the benefit from climate change, which is slightly different from what is mentioned here.

Table 1. *Adaptation costs, adaptation effectiveness, and total climate change damages for a doubling of CO_2 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[a] (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

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

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 recognize that the quantitative assessment of adaptation costs and benefits is still at a pioneering stage and that some areas (for example 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 to be as informative as a perfect replication of the data. The insights provided should then be interpreted more as highlighting trends and qualitative behaviours rather than detailed quantitative indications.

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. CO_2 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.[7] 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 equalizes regional marginal costs and benefits is substantial. In 2100, for the world as a whole, adaptation roughly halves damages from US$13 trillion (3.8% of GWP) to 6 trillion (1.8% of GWP). The US$7 trillion of avoided damages in 2100 represents about 2 per cent of GWP. Adaptation becomes sizeable only after 2040, when climate change damage is sufficiently high as to justify strong adaptation expenditure.[8] Despite

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

[8] This empirical result is very close to the theoretical finding reported by Millner and Dietz (2011). They show that in a Ramsey model with adaptation capital, under standard conditions, the latter grows faster than vulnerable physical capital. In our model, stock adaptation (anticipatory adaptation and specific capacity building) responds to damage and thus increases faster than the stock of physical capital.

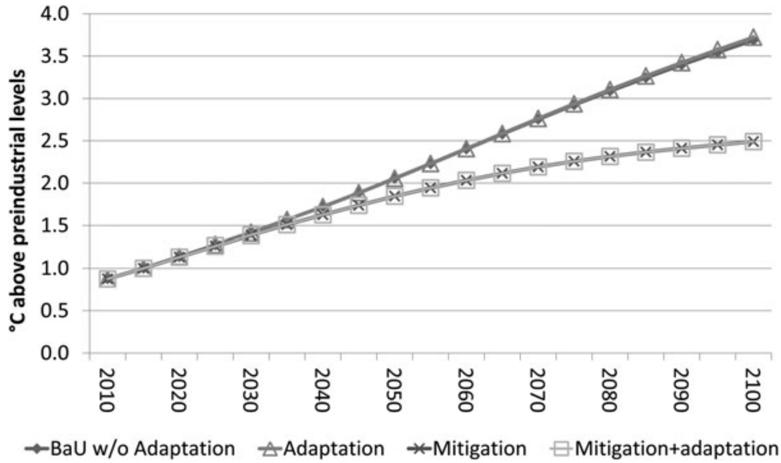

Figure 2. *Decomposition of climate change costs: residual damage, adaptation expenditure, total damages and avoided damage*

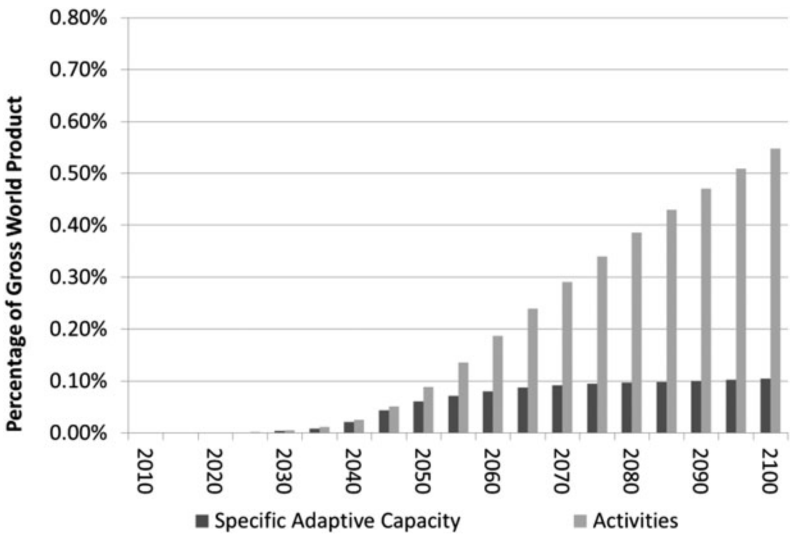

Figure 3. *Adaptation strategy mix. Capacity building and adaptation activities*

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

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.

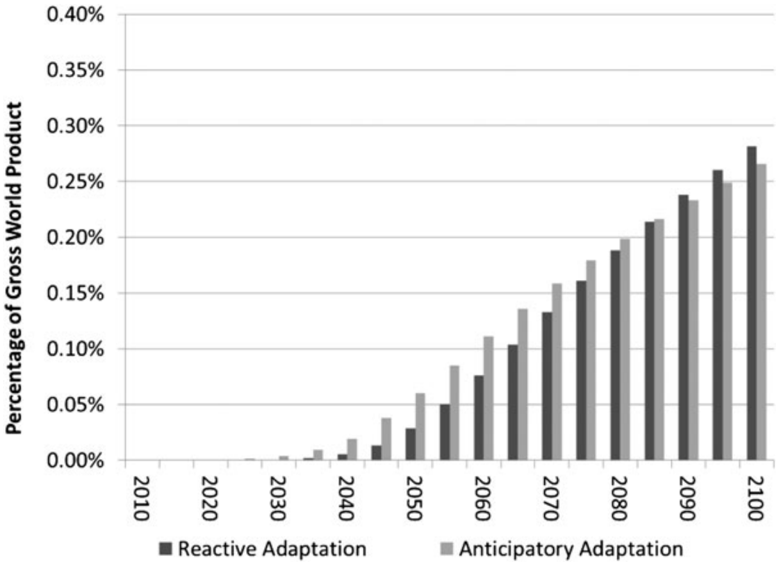

Figure 4. *Adaptation strategy mix. Composition of adaptation activities*

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 per cent in 2030 (US$4 billion out of 8.4 billion), to 16 per cent in 2100 (US$374 billion out of 2331 billion). 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 4 describes the composition of anticipatory and reactive adaptation strategies. Again they are both increasing throughout the century and of course anticipatory adaptation starts earlier. This is because defensive capital must be ready when the damage materializes, and it faces at least a 5-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 emphasizes the different size, timing and composition of adaptive behaviour across developing and developed countries.

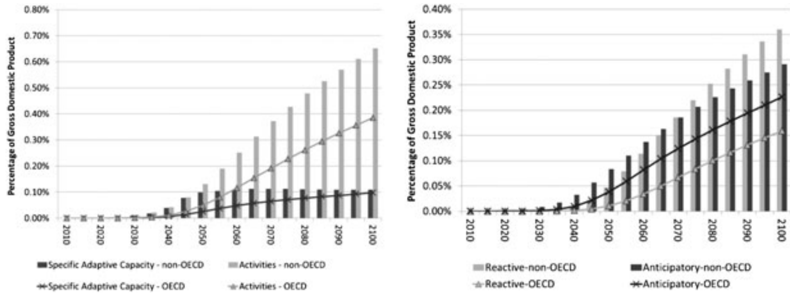

Figure 5. *Regional adaptation strategy mix. Adaptive capacity building vs. adaptation activities (left panel) and reactive adaptation vs. anticipatory adaptation (right panel)*

Developing countries are more exposed to climatic damages; therefore, they are forced to spend more than OECD regions on all forms of adaptation either in percentage of GDP (figure 5) or in absolute terms (table 2). In 2100, adaptation expenditure in non-OECD countries is more than double 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 and North Africa (MENA).[9]

The effective availability of resources to meet adaptation needs in developing regions is of particular concern. 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 per cent of their GDP) compared to US$200 billion (or 0.22 per cent of GDP) in OECD countries. This would call for international aid and cooperation on adaptation.

In developing countries, damage is higher and therefore adaptation starts earlier than in OECD countries. 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. It can also be appreciated that in non-OECD countries adaptive capacity remains as important as adaptation measures up to 2050, while in the OECD countries the two drift apart immediately.

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

[9] Note, however, that these are aggregated results. Therefore they may not be valid for each single developing country.

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 expenditure*	*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

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 characterized baseline adaptation patterns, we now analyze how this picture may change in the presence of a global stabilization policy. We assume that a global agreement aimed at stabilizing GHG concentrations at 550 ppme (or 3.7 W/m^2) is successfully reached.[10] This stabilization 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 maximize 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 summarized by table 3, which breaks down the components of climate change costs, including mitigation investments, in three cases: the baseline (adaptation without mitigation); mitigation policy without adaptation; and mitigation policy with adaptation. The last case characterizes the mitigation–adaptation mix and is the centre 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 decarbonizing 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 to be 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, consistent with the AD-WITCH damage structure, occurs after 2030. Consequently, investments and expenditure on mitigation remain larger than those on adaptation throughout the century.

[10] Regions still optimize their own welfare, but taking into account the GHG emissions constraint.

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)*[a]

Annual average costs: WORLD (US$ billion)	*Baseline*	*Mitigation without adaptation*	*Mitigation + adaptation*
2030			
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

[a]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.

Mitigation lowers the need to adapt and crowds out adaptation expenditure (second vs. fourth column). The crowding-out is particularly prominent after mid-century, when it reaches about 50 per cent. Nonetheless,

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
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%

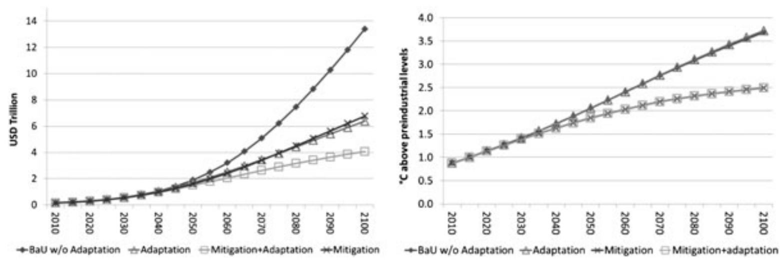

Figure 6. *Contribution of adaptation and mitigation to damage reduction (left panel) and global temperature increase above pre-industrial levels (right panel)*

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).

Adaptation slightly increases the mitigation effort required to comply with the stabilization target (fourth vs. third column). Indeed, the possibility to adapt indirectly reduces the damages produced by emissions, which in an optimization framework increases 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 stabilization 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.

A portfolio of strategies brings welfare improvements as compared to using only one strategy. Thus the cost-effectiveness framework replicates the typical first-best efficiency rule according to which two instruments can do no worse than one, at least globally.[11] Bosello *et al.* (2010a, 2010b) 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).[12] 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 for 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.

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 has addressed issues of strategic planning and optimal public resource management in a cost-effective setting.

The analysis carried out in this paper emphasizes 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,

[11] Note that regionally in the case of OECD countries the joint mitigation and adaptation policy is more costly than mitigation alone. But this depends on how the costs and benefits of the mitigation policy are distributed across participants. Locally, abatement costs can be higher than benefits.

[12] 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.

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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 as well as 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 analyzed the relationship between adaptation and mitigation in a cost-benefit setting (Bosello, 2008; de Bruin *et al.* 2009a, b; Bosello *et al.* 2010a, b). 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 stabilization 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.

Supplementary material and methods

The supplementary material referred to in this paper can be found online at journals.cambridge.org/EDE.

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Appendix A: Sensitivity analysis

The robustness of our baseline results is tested with respect to two key parameters: the size of climatic damage and the pure rate of time preference (PRTP). Climate change damage estimates remain largely uncertain, but the most recent literature (Parry *et al.*, 2007; Stern, 2007; UNFCCC,

Table A1. *Adaptation under different discounting and damages in 2100*

	Average annual costs (2005 US$ billion)			
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)

Note: The percentage change with regard to the baseline appears in parentheses.

2007; Hanemann, 2008) has considered higher damages compared to the early estimates of Nordhaus and Boyer (2000). Furthermore, AD-WITCH, like most IAMs, abstracts from rapid warming and large-scale changes of the climate system (system surprises). PRTP can also affect the adaptation mix. By governing the perception of future damages, it can influence the incentives to choose one option or the other.[13]

We consider a high-damage case where world damage is twice the baseline damage. We combine the assumptions on damages with variations in the PRTP. We consider a high value of 3 per cent declining in the baseline case and a lower value equal to 0.1 per cent declining. Tables A1 and A2 summarize the results of the four cases originated by the different combination of damages and PRTPs. When damages increase or the PRTP decreases, the expenditure on all forms of adaptation increases. The mix is also slightly affected. A higher damage slightly favours reactive adaptation, which increases more (+105% in 2100) than anticipatory adaptation (+97%) and specific capacity (+57%). A lower PRTP favours anticipatory adaptation and adaptive capacity building (+37% and +49% in 2100, respectively). When a high damage is combined with a low PRTP, the discounting effect tends to prevail and the optimal mix is to some extent tilted toward the stock measures, namely anticipatory adaptation and specific adaptive capacity. To summarize, higher damages are contrasted relatively better by reactive measures, which perform just as well in the short and in the long term. The perception of higher damages in the far future instead is contrasted relatively better by anticipatory measures, which require a time lag of 5 years to become effective, but can be more effective in the future.

[13] 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, 2007).

Table A2. *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

Lower PRTP and higher impacts from climate change also anticipate optimal adaptation expenditure (table A2). A higher damage requires spending on adaptation between US$0.8 billion (high PRTP) and US$3 billion (low PRTP) already in 2010. Adaptation expenditure increases exponentially thereafter.