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The Effect of Proactive Adaptation on Green Investment

Olivier Bahn **Marc Chesney**

Jonathan Gheyssens

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The effect of proactive adaptation on green investment

O. Bahn[a,1], M. Chesney[b,2,*], J. Gheyssens[c]

[a] *GERAD and MQG, HEC Montreal, Montreal, Canada*
[b] *Institute of Banking and Finance and Swiss Finance Institute, University of Zurich, Zurich, Switzerland*
[c] *Institute of Banking and Finance, University of Zurich and NADEL, ETH Zurich, Switzerland*

Abstract

Climate change is one of the greatest challenges facing our planet in the foreseeable future and despite the urgency of the situation global GHG emissions are still increasing. In this context, and since future climate changes appear now unavoidable to some extent, adaptation measures have recently gained a new political momentum as an important component of climate policies. Contrary to mitigation options, adaptation measures do not reduce emission levels but reduce their impacts. To assess the relationship and effects on the global economy of both mitigation and adaptation, we use in this paper an integrated assessment model (IAM) that includes both proactive adaptation strategies and access to "green" investments (clean technologies) for mitigation. We find that the relationship between adaptation and mitigation is complex and largely dependent on their respective attributes, with weakly effective adaptation acting as a late complement to mitigation efforts. As its effectiveness increases, adaptation becomes more and more a substitute for mitigation. Sensitivity analysis on the potential magnitude of damages also indicates that scientific efforts to better describe GHG impacts will have immediate and important consequences on the sequence of mitigation and adaptation strategies.

Keywords: Adaptation, Climate change, Mitigation, Clean technology, Integrated assessment

1. Introduction

Climate change is one of the greatest challenges facing our planet in the foreseeable future. It is expected, according to the Intergovernmental Panel on Climate Change (IPCC, 2007), to impact

*Principal corresponding author

Email addresses: olivier.bahn@hec.ca (O. Bahn), chesney@isb.uzh.ch (M. Chesney), gheyssens@isb.uzh.ch (J. Gheyssens)

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ecosystems and the environmental services they provide (in terms of food and water in particular) but also human societies (affecting human health and regional economies, for instance). Besides, the IPCC argues that human activities, through the greenhouse gases (GHG) they release in the atmosphere, are responsible for most of the observed increase in global average temperatures up to now, and that they shall continue to do so in the absence of ambitious climate policies to reduce GHG emissions.

Despite the urgency of the situation, global GHG emissions are still increasing, in particular because there is not yet an overall agreement to curb world emissions. In this context, and since future climate changes appear now unavoidable to some extent, adaptation measures have recently gained a new political momentum as an important component of climate polices. Contrary to mitigation options, adaptation measures do not reduce emission levels, but provide strategies to deal effectively with climate change effects by reducing their impacts (Tol, 2005; Adger et al., 2007; Klein et al., 2007b). Adaptation strategies cover a large array of sectors and options, from new agricultural crops, modified urban planning (dikes, sewerage systems), medical preventions against pandemic to controlled migrations of population and activity changes. Depending on the degree of anticipation (and requirement for it), adaptation measures can be reactive or preventive: vaccination campaigns can be made mandatory without any materialized threat (as precautionary principle) or could be offered only in case of pandemic urgency, for instance.

Compared to mitigation strategies, adaptation measures have two main strengths. First, their benefits are often immediate or very short-term, which reduces their exposure to uncertainty and discounting preferences. This immediacy is also beneficial for populations already vulnerable to certain impacts of climate change (Parry et al., 2009). Second, adaptation measures in effect privatize policies against climate changes by largely limiting the benefits of adaptation to those having invested in it. Adaptation avoids the free-riding problem traditionally associated with mitigation[3] and does not require concerted and simultaneous actions, fostering the advancement of regional or local projects. As pointed by Olson (1965), "*only a separate and 'selective' incentive will stimulate a rational individual in a latent group to act in a group-oriented way*" and to that goal, adaptation is effective.

Both international institutions and governments have recognized these strengths and have now started to conceive and finance portfolios of adaptation projects. For instance, the World Bank has initiated a US$500 million Pilot Program for Climate Resilience and prepared in 2009 a new study to assess adaptation costs, areas and applicability in developing countries (Margulis and Narain, 2009). Under the United Nations Framework Convention on Climate Change (UNFCCC), a new adaptation fund has also been launched, financed with 2% of the shares of proceeds coming from the issuances of certified emission reduction units (CERs) under the clean development mechanism (CDM). During the recent Copenhagen conference (COP15), it was also decided to create the Copenhagen Green Climate Fund (CGCF), with a first budget of US$30 billion in the 2010-2012 period to invest in mitigation and adaptation projects. This fund should eventually reach US$100 billion by 2020[4]. In addition to those dedicated projects, adaptation strategies are now more and more blended into more traditional development projects and official development assistances (ODA) (Klein et al., 2007a). They are also pushed forward in developed countries albeit without the kind of targeted recognition used for developing countries.

Considering the simultaneous promotion of adaptation strategies and the relative weaknesses of mitigation policies so far, the question of their respective role should be assessed, both for policy and investment purposes. It could be that adaptation strategies become inexpensive alternatives to mitigation approaches, at least as long as no clear international agreement forces the world's economies to transition into an more efficient economy (in terms of GHG emissions). If

[3]A country say may hesitate to pay for emission reductions that will also impact favorably those who did not participate in any mitigating efforts, thus unbalancing its competitiveness (Olson, 1965; Baumol and Oates, 1988).

[4]Copenhagen Accord, Conference of the Parties (COP-15), December 2009, articles 8 and 11 (http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf).

this is the case, what would be the impact on the transition timing towards such an economy? More importantly, what could be the long run effects, both in terms of GHG concentrations, overall costs and damages and growth trajectories?

To answer these questions, one may use an integrated assessment, an interdisciplinary approach that uses information from different fields of knowledge, in particular socio-economy and climatology. Integrated assessment models (IAMs) are tools for conducting an integrated assessment, as they typically combine key elements of the economic and biophysical systems, elements that underlie the anthropogenic global climate change phenomenon. Examples of IAMs are DICE (Nordhaus, 1994, 2007), MERGE (Manne et al., 1995; Manne and Richels, 2005), RICE (Nordhaus and Yang, 1996) and TIAM (Loulou and Labriet, 2008; Loulou, 2008).

Research incorporating adaptation measures into integrated assessment models has been rare until recently, despite the importance of these models for current policy decisions. Hope et al. (1993) (updated in Hope, 2006) were the first to integrate adaptation as a policy variable in an IAM, the PAGE model. Bosello (2008) uses a FEEM-RICE model with both adaptation and mitigation options. de Bruin et al. (2009b) have proposed to include adaptation as an explicit strategy in the DICE model (AD-DICE). In follow-up studies, de Bruin et al. (2009a) expand this methodology to the RICE model (AD-RICE), Felgenhauer and de Bruin (2009) introduce uncertainty in the climate outcome and finally Hof et al. (2009) test for the effectiveness of the 2% levy proposed to finance the UNFCCC adaptation fund in a combined AD-RICE/FAIR model. Finally, Bosello et al. (2010) have proposed to consider adaptation within the WITCH model (AD-WITCH).

We use in this paper the deterministic version of a simple integrated assessment model (Bahn et al., 2008, 2010, thereafter referred to as BaHaMa) enriched to consider explicitly adaptation options. BaHaMa is in the spirit of the DICE model but distinguishes between two types of economy: the "carbon economy" (our present economy) where a high level of fossil fuels is necessary to obtain output and a so-called "carbon-free" or "clean economy" (an hydrogen economy, for instance) that relies much less on fossil fuels to produce the economic good. Besides, compared to AD-DICE, our approach provides some important distinctions. We do not consider adaptation efforts as costs ("*flow*") but as investments ("*stock*"), a setting considered also by Bosello (2008) and Bosello et al. (2010). As such, we emphasize its proactive component in lieu of its reactive element (see Lecocq and Shalizi, 2007). We can therefore assess the timing of adoption of clean technologies in the presence of adaptation strategies and evaluate the sensitivity of their interactions to specific parameters. This element could be of importance in the current debate about the required incentives to foster adequate "green" R&D investments. Moreover, our model, while being close in certain aspects to the DICE model for comparison purposes, remains largely autonomous in its calibration procedure, allowing us to test a variety of parameter's specifications.

The paper is structured as follows. Section 2 details our IAM with explicit adaptation options, thereafter referred to as Ada-BaHaMa. The section covers also some of the economic rationales behind the modeling choices. Sections 3 and 4 give the model's results and sensitivity analyzes on adaptation effectiveness and climate sensitivity. Finally we conclude in Section 6 and propose some further improvements that provide additional directions for research.

2. BaHaMa with explicit adaptation

2.1. Model description

An overview of Ada-BaHaMa is given in Fig.1.

We next describe the different component of the original BaHaMa model and its new adaptation feature.

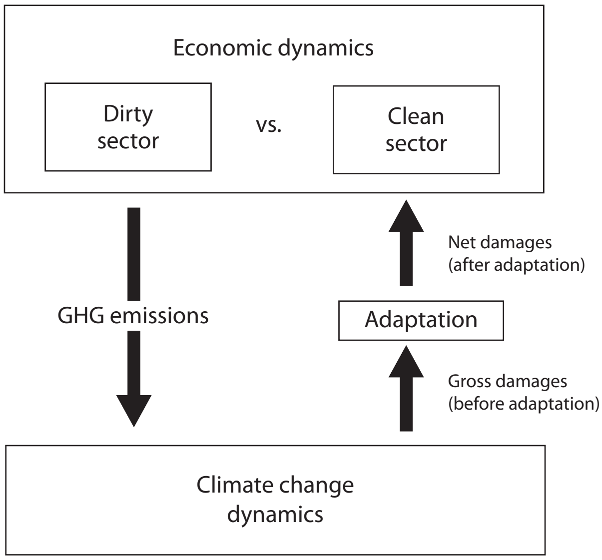

Figure 1: Schematic overview of Ada-BaMaMa.

2.1.1. Production dynamics

Production (Y) occurs in the two types of economy (the carbon economy, referred to by an index 1, and the clean economy, referred to by an index 2) according to an extended Cobb-Douglas production function in three inputs, capital (K), labor (L) and energy (measured through GHG emission level E):

$$
\begin{aligned}
Y(t) = {} & A_1(t)K_1(t)^{\alpha_1}(\phi_1(t)E_1(t))^{\theta_1(t)}L_1(t)^{1-\alpha_1-\theta_1(t)} \\
& + A_2(t)K_2(t)^{\alpha_2}(\phi_2(t)E_2(t))^{\theta_2(t)}L_2(t)^{1-\alpha_2-\theta_2(t)}\,, \qquad (1)
\end{aligned}
$$

where for each economy i ($i = 1,2$): A_i is the total factor productivity, α_i the elasticity of output with respect to capital K_i, ϕ_i the energy efficiency and θ_i the elasticity of output with respect to emissions. Notice that capital stock in each economy evolves according to the choice of investment (I_i) and a depreciation rate δ_{K_i} through a standard relationship:

$$K_i(t+1) = I_i(t) + (1-\delta_{K_i})K_i(t) \quad i = 1,2. \tag{2}$$

Besides, total labor (L) is divided between labor allocated to the carbon economy (L_1) and labor allocated to the carbon-free economy (L_2):

$$L(t) = L_1(t) + L_2(t). \tag{3}$$

2.1.2. Climate change dynamics

Stocks of GHGs are computed using the following dynamic equations from the DICE model (Nordhaus, 2007), that distinguish between three reservoirs, an atmospheric reservoir (M_{AT}), a quickly mixing reservoir in the upper oceans and the biosphere (M_{UP}), and a slowly mixing deep-ocean reservoir (M_{LO}) which acts as a long-term sink:

$$M_{AT}(t+1) = (E_1(t) + E_2(t)) + \psi_{11}M_{AT}(t) + \psi_{21}M_{UP}(t) \tag{4}$$

$$M_{UP}(t+1) = \psi_{12}M_{AT}(t) + \psi_{22}M_{UP}(t) + \psi_{32}M_{LO}(t) \tag{5}$$

$$M_{LO}(t+1) = \psi_{23}M_{UP}(t) + \psi_{33}M_{LO}(t) \tag{6}$$

where $\psi_{i,j}$ are calibration parameters. Relationship between accumulation of GHGs and temperature deviation is also from DICE and is given by the following equations:

$$F(t) = \eta log_2\left(\frac{M_{AT}(t)}{M_{AT}(1750)}\right) + F_{EX}(t) \tag{7}$$

$$T_{AT}(t+1) = T_{AT}(t) + \xi_1\left[F(t+1) - \xi_2 T_{AT}(t) - \xi_3\left(T_{AT}(t) - T_{LO}(t)\right)\right] \tag{8}$$

$$T_{LO}(t+1) = T_{LO}(t) + \xi_4\left(T_{AT}(t) - T_{LO}(t)\right) \tag{9}$$

where F is the total atmospheric radiative forcing, F_{EX} an exogenous radiative forcing term, T_{AT} the earth's mean surface temperature, T_{LO} the average temperature of the deep oceans, and ξ_i and η calibration parameters for an assumed climate sensitivity of 3 °C that corresponds to the best estimate[5] given by the IPCC (Meehl et al., 2007). Accumulation of GHGs increases the earth radiative forcing, warming the atmosphere and then gradually the oceans. This allows for the existence of inertia between GHG concentration and climate change.

2.1.3. Damage and adaptation frameworks

To model climate change damages and their economic impacts, we follow an approach used in the MERGE model (Manne and Richels, 2005). We compute in particular an economic loss factor (ELF) due to climate changes at time t, which is adapted to take into account the effects of adaptation $\mathrm{AD}(t)$ as follows:

$$\mathrm{ELF}(t) = 1 - \mathrm{AD}(t)\left(\frac{T_{AT}(t) - T_d}{cat_T - T_d}\right)^2, \tag{10}$$

where T_d is the temperature deviation (from pre-industrial level) at which damages start to occur and cat_T is the climate sensitivity dependent "catastrophic" temperature level at which the entire production would be wiped out. For the illustrative purposes of this paper and to have a comparable basis with the current literature on IAM with adaptation, T_d and cat_T are calibrated in order to replicate the damage intensity of DICE; see Section 2.2. Notice further that this loss factor applies on production levels, see Section 2.1.4, such that damages are computed as: $\mathrm{AD}(t)Y(t)\left(\frac{T_{AT}(t)-T_d}{cat_T-T_d}\right)^2$.

In our model, adaptation reduces the damaging effects of GHG concentration and for simplification purposes it has neither impact on the total factor productivity (no innovation breakthrough

[5] In Section 4, we test our model for different values of climate sensitivity, using the 'likely' range of 2–4.5 °C given by the IPCC.

is coming from adaptation investment) nor direct correlation with GHG emissions (as in the often cited air conditioned example). Contrary to the recent efforts by de Bruin et al. (2009b) but in a fashion similar to Bosello (2008), we consider adaptation as an investment (stock) instead of a cost (flow), since for a large part adaptation projects will be directed towards infrastructure and medium-to-long-term economic transformations. To use the words of Lecocq and Shalizi (2007), we favor the proactive type of adaptation over the reactive one. This approach gives us greater flexibility over the nature of adaptation policies. By controlling for capital depreciation rate in the model, we can test for proactive effectiveness: if adaptation investments are in line with realized impacts, depreciations should be slow. On the contrary, inadequate strategies or incapacity to predict future damages will force to reinvest frequently, imposing a high deprecation rate on the adaptation capital. At the margin, with an annual depreciation of 100%, the adaption investment corresponds to a cost.

The adaptation dynamics is as follows:

$$\mathrm{AD}(t) = 1 - \alpha_{\mathrm{AD}} \frac{K_3(t)}{K_{3\max}(t)} \tag{11}$$

with α_{AD} representing the maximal adaptation effectiveness, $K_3(t)$ the amount of adaptation capital in period t and $K_{3\max}(t)$ the maximal amount of adaptation capital to be invested in each period to ensure the optimal effectiveness of adaptation strategies.

In our framework, adaptation costs should increase whenever temperature (and therefore damages) broadens. To take this into account, we model $K_{3\max}(t)$ as an increasing function of temperature level:

$$K_{3\max}(t) = \beta_{\mathrm{AD}} \left(\frac{T_{AT}(t)}{T_d} \right)^{\gamma_{\mathrm{AD}}}, \tag{12}$$

where β_{AD} and γ_{AD} are calibration parameters. The behavior of this function is determined by the calibration process. Nonetheless, we force the calibration to be bounded such that $\beta_{\mathrm{AD}} \geq 0$ and $\gamma_{\mathrm{AD}} \geq 1$. Hence, getting the full offsetting potential of adaptation will require more and more investment if mitigation is not also considered jointly.

2.1.4. Welfare maximization

A social planner is assumed to maximize social welfare given by the integral over the model horizon (T) of a discounted utility from per capita consumption $c(t) = C(t)/L(t)$. Pure time preference discount rate is noted ρ and the welfare criterion is then given by:

$$W = \int_0^T e^{-\rho t} L(t) \log[c(t)]\, dt. \tag{13}$$

Consumption comes from an optimized share of production, the remaining being used to invest in the production capital (dirty and/or clean), in the adaptation capital and to pay for energy costs. The presence of damages (defined by the ELF factor) reduces the available production such that:

$$\text{ELF}(t)Y(t) = C(t) + I_1(t) + I_2(t) + I_3(t) + p_{E_1}(t)\phi_1(t)E_1(t) + p_{E_2}(t)\phi_2(t)E_2(t), \tag{14}$$

where I_3 is the investment in the adaptation capital and p_{E_i} are energy prices. Note also that adaptation stock evolves according to a relation similar to Eq. (2):

$$K_3(t+1) = I_3(t) + (1 - \delta_{K_3})K_3(t), \tag{15}$$

where δ_{K_3} is a depreciation rate.

2.2. Model calibration

The different modules of Ada-BaHaMa (adaptation, economy and climate) are basically calibrated on the models DICE (version 2007[6], thereafter referred to as DICE2007) and AD-DICE

[6]See: http://www.econ.yale.edu/ nordhaus/DICE2007.htm.

(de Bruin et al., 2009b).

We start our calibration procedure by the adaptation component which is new the feature in the Ada-BaHaMa model. First, we calibrate ex-ante parameters defining the maximal amount of efficient adaptation capital ($K_{3\max}$). We use for this the most recent report that the World Bank (Margulis and Narain, 2009) issued on the cost of adaptation in developing countries for the period 2005-2055: to fully offset climate change impacts in developing countries, US$ 100 billion should be spent each year until 2055. Despite representing only a small share of the global economy, these adaptation costs, when adjusted for our model, still correspond to high values compared to the AD-DICE estimates. They are also conservatively close to the estimates obtained in Bosello et al. (2010). Second, the maximal adaptation effectiveness (parameter α_{AD}) is set to 0.33 (at most 33% of damages are avoided)[7] following results reported with AD-DICE. Third, to reproduce the magnitude of climate change damages estimated by DICE and AD-DICE, we use values of GHG concentrations, temperatures, gross damages and production from these models in order to calibrate parameters of our damage function (ELF). Damage estimates are presented in Fig. 2. Our calibration is slightly more conservative than the one of de Bruin et al. (2009b) for temperature increase above 1.2 °C.

The other modules of Ada-BaHaMa (economy and climate) are again basically calibrated on DICE2007. In particular, parameters in Eqs. (1), (2) and (4) to (9) are mostly from DICE2007.

Note however that, compared to the dirty economy, production in the clean economy has a better energy efficiency but higher energy costs in the short term. The resulting overall production in Ada-BaHaMa reproduces then the economic output of DICE2007; cf. Fig. 3.

However, compared to DICE2007, the modeling of two types of economies implies an optimal trajectory, conditioned by a transition to the clean economy after 2055 to reduce climate change damages, that involves much less GHG emissions over the long run; cf. Fig. 4.

[7] However and considering its importance in the determination of the optimal mix of strategies, we conduct in Section 4 sensitivity analyses for different–lower and higher–values of α_{AD}.

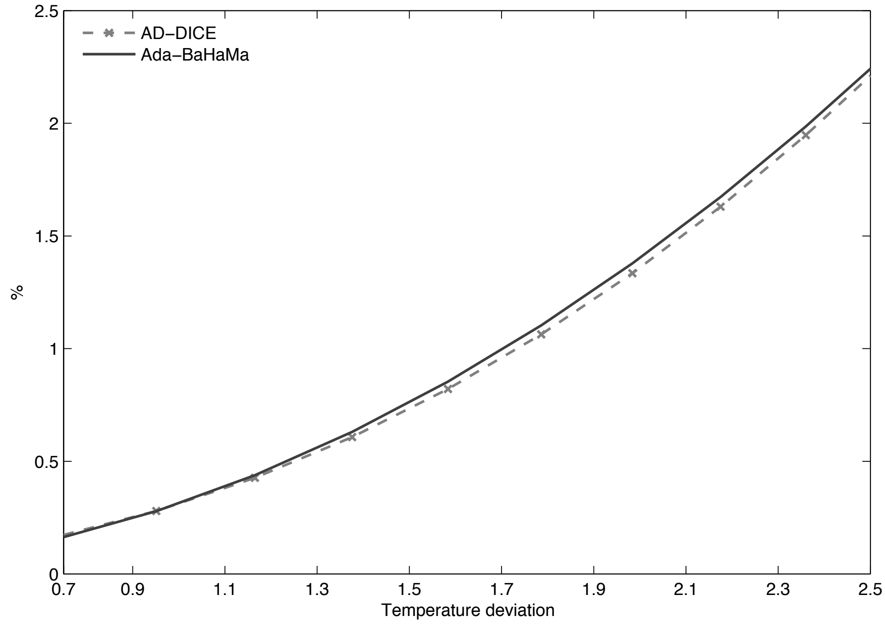

Figure 2: Damage levels (in percentage of production) for different temperature increases in Ada-BaHaMa and AD-DICE (in °C)

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3. Results

In this section, we report on four different scenarios: a counterfactual baseline without any adaptation or mitigation (investments in the clean technology) efforts, an adaptation-only scenario where the clean technology is not available, a mitigation-only scenario where adaptation is not possible and finally a combined scenario with both mitigation and adaptation efforts. More precisely, we first detail impacts of these scenarios on dirty and clean production capital stocks as well as on adaptation capital stocks. We then look at effects on climate change and the corresponding damages. Finally, we detail the overall effects on economic output.

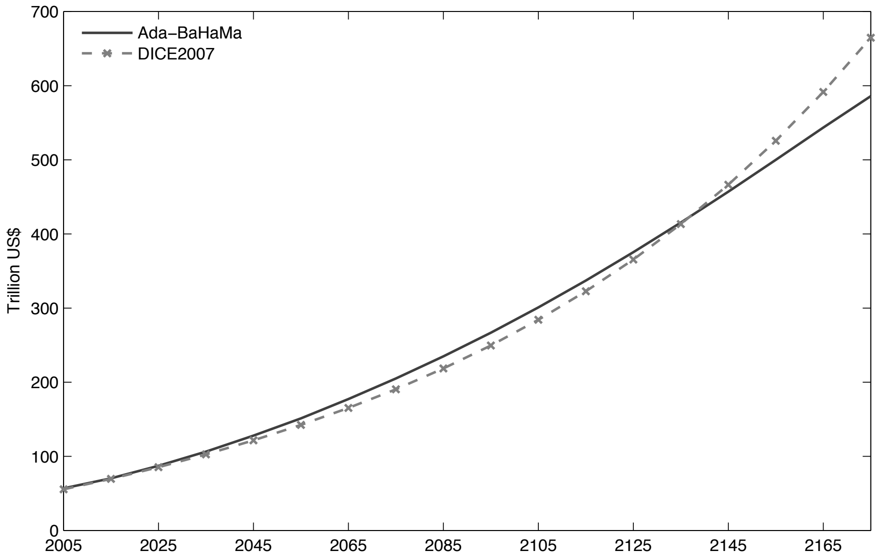

Figure 3: Economic production paths in Ada-BaHaMa and DICE2007.

3.1. Capital accumulation paths

When comparing our scenarios, two important components stand out in the strategies deployed to address climate change: first, the existence and timing of a transition between the dirty and the clean economy (mitigation strategy), see Fig. 5 and 6, and second, the importance awarded to adaptation, especially when the clean technology is not available, see Fig. 7.

When the clean technology is not available (adaptation-only scenario), clean capital does not of course accumulate. In addition, accumulation of dirty capital is slightly higher compared to the baseline scenario, as (net) damages and thus the necessity to limit dirty production are reduced through adaptation. Conversely, when the clean technology is available (mitigation-only and combined scenarios), there is a clear transition between the two economies: dirty capital is rapidly phased out after 2045 or 2055 and completely replaced by clean capital by the end of the century. Discrepancies coming from not allowing adaptation (mitigation-only scenario) are however noticeable, as a transition from dirty to clean capital is done ten years earlier to prevent

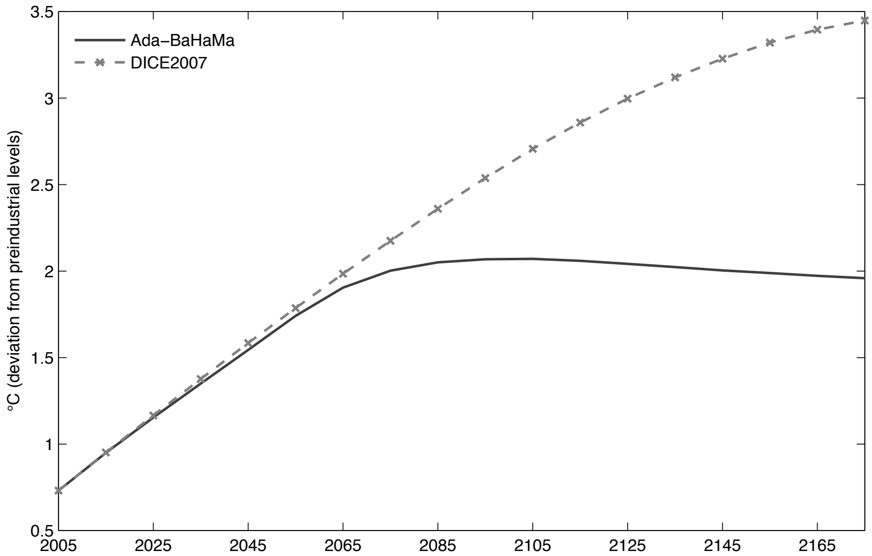

Figure 4: Temperature deviation paths in Ada-BaHaMa and DICE2007 (in °C).

harmful damage levels. In other words, even a low-effective[8] adaptation strategy does delay the adoption of clean technologies and the transition towards a new (cleaner) economy.

As far as adaptation capital is concerned, it does not of course accumulate in the mitigation-only scenario (where the adaptation option is not available). Both in the adaptation-only and combined scenarios, adaptation is used after 2045, where the accumulation of adaptation capital (K_3) reaches immediately its maximal level ($K_{3\max}$) and stays at this level afterwards. In this two scenarios, the delay in implementing adaptation measures results from the low-effectiveness of adaptation and signs a trade-off between costs of adaptation and its positive effect on welfare. In Section 4.1, we will test for different values of adaptation effectiveness. Notice also that the maximal level of adaptation capital ($K_{3\max}$) depends on temperature level; cf. Eq. (12). As the latter reaches lower levels in the combined scenario (see Fig. 9) due to the transition to the clean economy, the required amount of capital for a maximal effectiveness of adaptation is significantly reduced in this scenario (compared to the adaptation-only scenario).

[8]Recall that in our standard setting, at most only 33% of damages can be avoided.

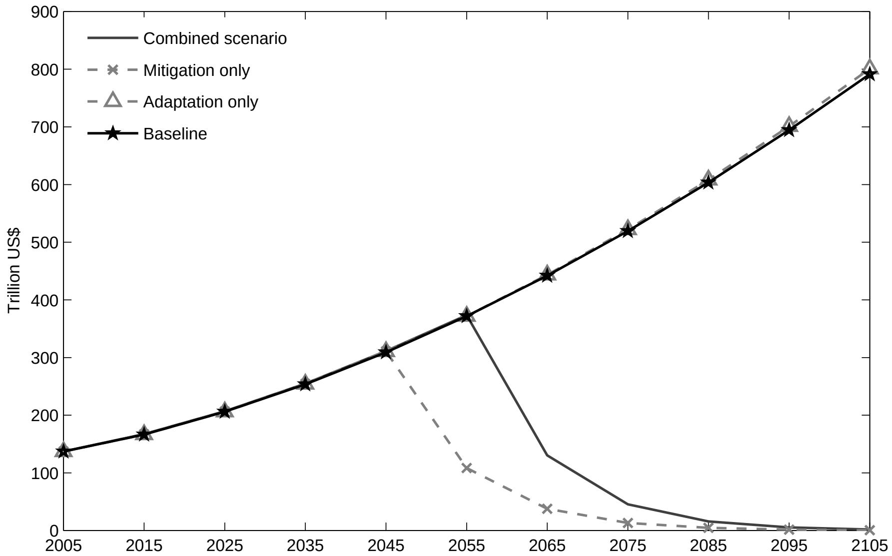

Figure 5: "Dirty" capital K_1 accumulation paths.

3.2. GHG concentration, temperature and net damages

Greenhouse gas concentration in the atmosphere, given in Fig. 8, follows the mitigation efforts detailed in the previous Section 3.1. Thanks to the rapid adoption of clean technologies (after 2045) in the mitigation-only scenario and the corresponding transition toward a cleaner economy, concentrations in the mitigation-only scenario peaks in 2055 and temperature increase (given in Fig. 9) stabilizes by the end of the century below 2 °C. For the combined scenario, the offsetting effect of adaptation, postponing the transition to "green investment" by about 10 years, has for consequence a higher concentration peak (reached in 2065) and temperature increase stabilizes by the end of the century slightly above 2 °C. Conversely in the adaptation-only scenario, the lowest mitigation effort (with dirty production being slightly higher than the "business-as-usual" baseline), concentration keeps always increasing as well as temperature that reaches around 2.75 °C by the end of the century.

Temperature increase translates directly into gross damages; cf. Eq. (10). Hence as reported in Fig. 10, net damages in the mitigation-only scenario (that correspond to gross damages in the

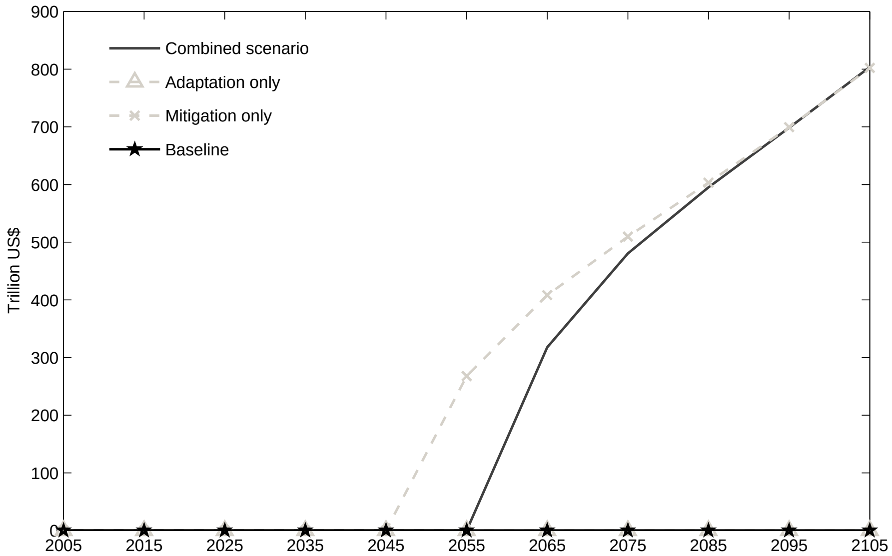

Figure 6: "Clean" capital K_2 accumulation paths.

absence of adaptation) peak in the second half of the century (2075) before gradually decreasing. Gross damages may however be "reduced" through adaptation. In the adaptation-only scenario, net damages are initially reduced (by 2055, compared to the mitigation-only scenario) when adaptation measures start to be implemented. But as they immediately reach their full potential (33% of gross damages avoided) they cannot afterwards compensate for the continuous increase in GHG concentrations and thus in damages. When both adaptation measures and adoption of clean technologies are enacted in the combined scenario, it is interesting to note that exposure to damages is the lowest of all scenarios.

3.3. Economic output paths

Recall that in the combined scenario, economic output (Y) is calibrated on the DICE2007 model; cf. Section 2.2, Fig. 3. Compared to our baseline, we can however note the occurrence of GDP losses due to climate change damages. In Fig. 11, the combined scenario is used as a comparative level. As expected, reducing the choice of policy options to address climate changes yields an

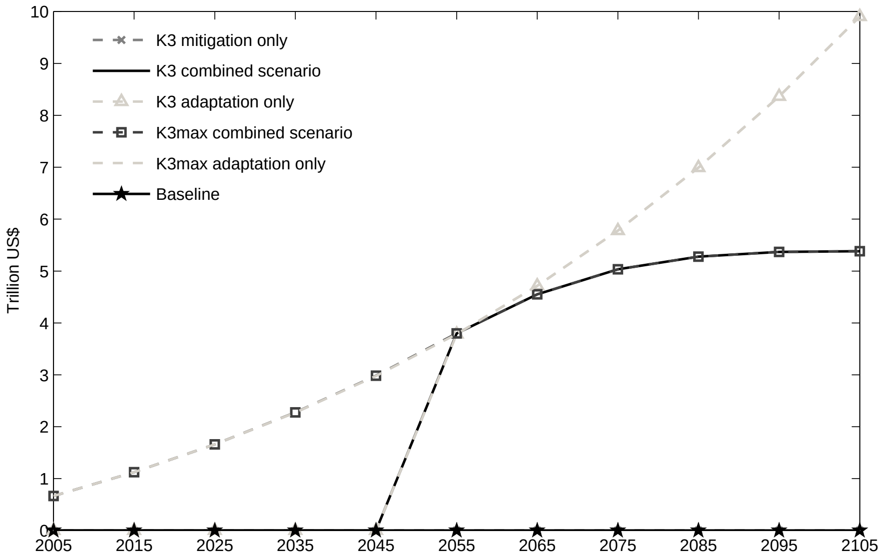

Figure 7: Adaptation capital K_3 accumulation paths and maximal amount of adaptation capital ($K_{3\max}$).

overall decrease in economic output compared to the combined scenario. This is in particular the case in the adaptation-only scenario, where the inability to prevent significant temperature increase (thus significant net damages) yields increasing GDP losses. The decrease in economic output is however not significant in the mitigation-only strategy, where it amounts to an average of 0.095% (per period of 10 years) between 2015 and 2105. The absence of a massive adaptation investment (to the detriment of investments in production capitals) in period 2055 allows for a short-lived production surplus over the combined strategy. In that case, preventing the use of adaptation measures is indeed not very disadvantageous for the economy due to our low setting for adaptation effectiveness (at most only 33% of damages can be avoided).

4. Sensitivity analysis

The influence played by adaptation measures on the timing of adoption of clean technologies is largely dependent on certain key parameters, like the degree of adaptation effectiveness or the

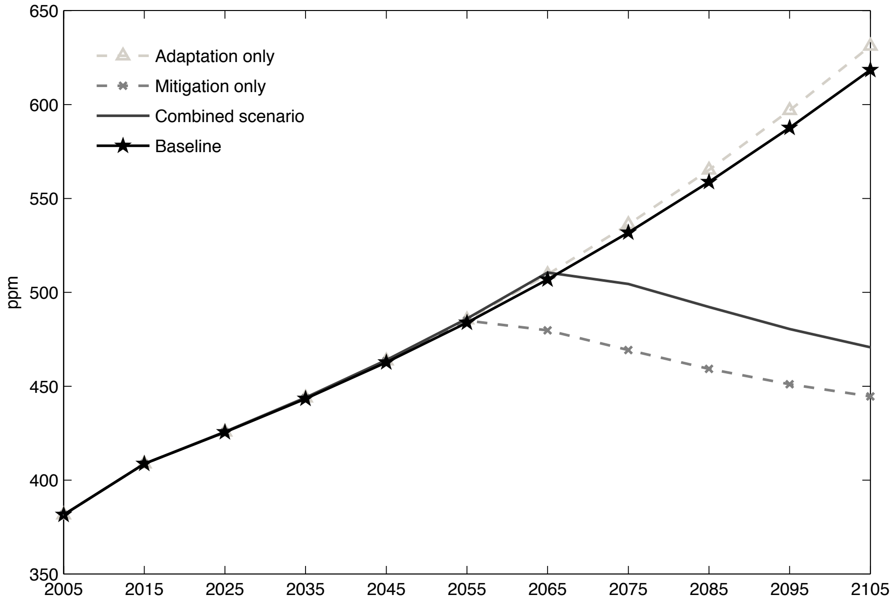

Figure 8: GHG concentration paths.

climate sensitivity assumed in the model. In sections 4.1 and 4.2, we test for different levels for these two key parameters.

4.1. Sensitivity analysis on adaptation effectiveness

According to past and current research on adaptation policies, it seems indisputable that the effectiveness of adaptation measures will be highly influenced by geographical, political and societal idiosyncrasies, as well as by the quality and reliability of preventive efforts which in turns largely depend on the accuracy of damage predictions. Considering the high level of uncertainty surrounding damage assessments, our basic parameter setting uses a relatively low level of effectiveness for adaptation. As such, it penalizes regions for which adaptation could be both

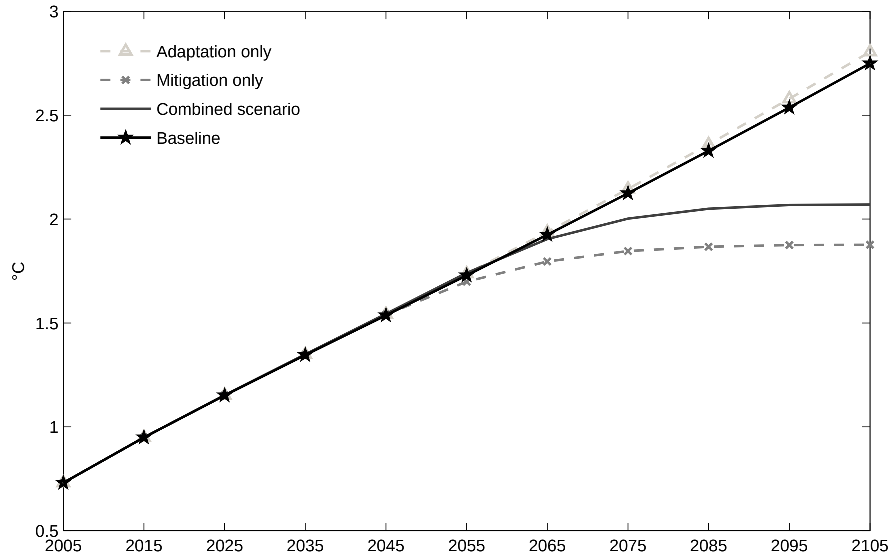

Figure 9: Temperature deviation paths from preindustrial levels (in °C).

inexpensive and efficient[9]. The World Bank[10] (Margulis and Narain, 2009) indeed reports that adaptation in developing countries could be completely effective and offset climate change damages in full. Although possibly over-optimistically, an effectiveness level of 100% ($\alpha_{\mathrm{AD}} = 1$) can thus be also envisioned (if only to test the view of Margulis and Narain, 2009).

When increasing the adaptation effectiveness, we observe a strong substitution effect between increasingly efficient adaptation measures and adoption of clean technologies. As reported in Fig. 12 and 13, the adoption of clean technologies is delayed by a few decades and its preventive role against climate change damages is replaced by adaptation measures.

Note that a stronger reliance on adaptation has the drawback of pushing temperature to much higher levels; see Fig. 14. For instance, with a value of 100% for the adaptation effectiveness, temperature increase reaches by 2105 3 °C (compared to around 2.1 °C under our standard

[9]For instance, Bosello et al. (2010) found that adaptation effectiveness was closer to 38% for the Middle East and the Latin and South America regions.

[10]which provides our cost estimates for the calibration of the maximal amount of efficient adaptation capital $K_{3\max}$.

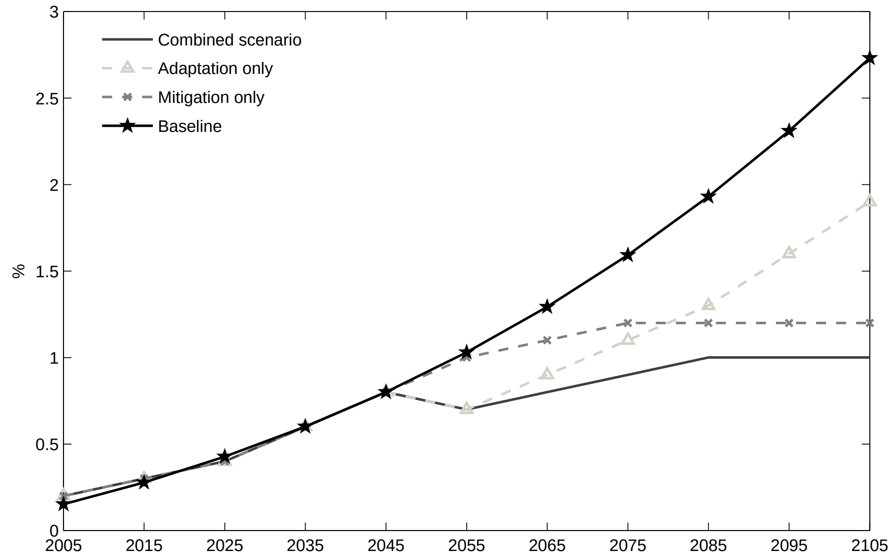

Figure 10: Evolution of net damages.

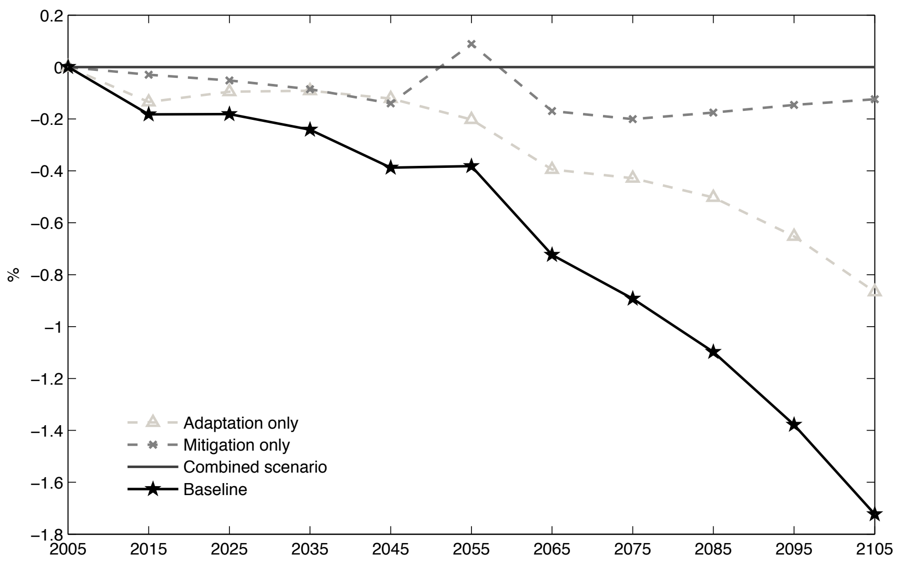

Figure 11: Economic output difference (in %) relative to the combined scenario.

setting). By shielding the world's economy from (most of) climate change damages, improvement in adaptation effectiveness favors more polluting practices and delays a transition toward a cleaner economy.

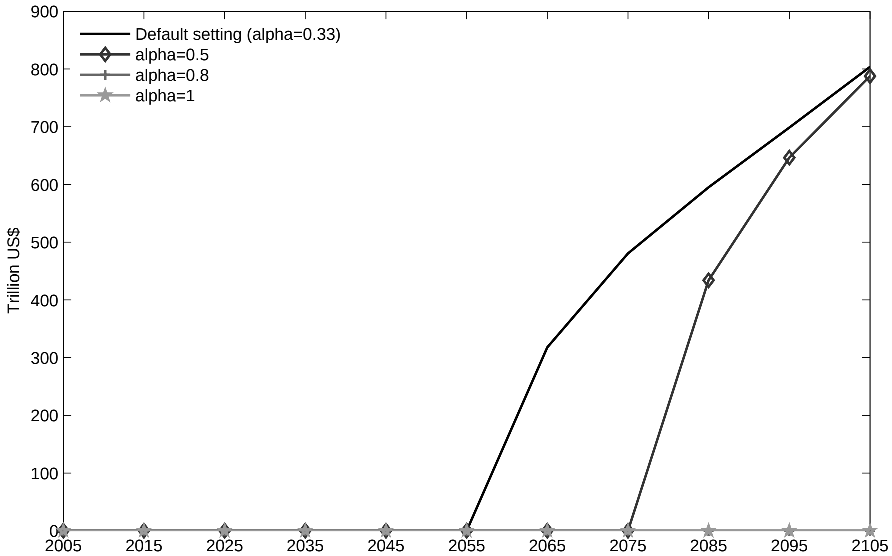

Figure 12: "Clean" capital K_2 accumulation paths for different levels of adaptation effectiveness.

This could however turn out to be a risky policy, especially in presence of uncertainty about climate change effects, which may include "abrupt" changes[11] (see for instance Lenton et al., 2008), which in turn could hinder the capacity to successfully–and continuously–provide efficient adaptive solutions in the future.

4.2. Sensitivity analysis on climate sensitivity

According to the IPCC (2007), the equilibrium impact of doubling atmospheric CO_2 concentration may in average lead to an increase in temperature from pre-industrial levels of about 3 °C, recognizing "*an upper bound of likely range of climate sensitivity of 4.5 °C and lower bound of likely range of climate sensitivity of 2 °C*". To account for this level of uncertainty, which has a direct and immediate impact on damages, we conducted a sensitivity analysis on our combined

[11]Examples of such extreme events include a melting of the West Antarctic ice sheet and a collapse of the Atlantic thermohaline circulation.

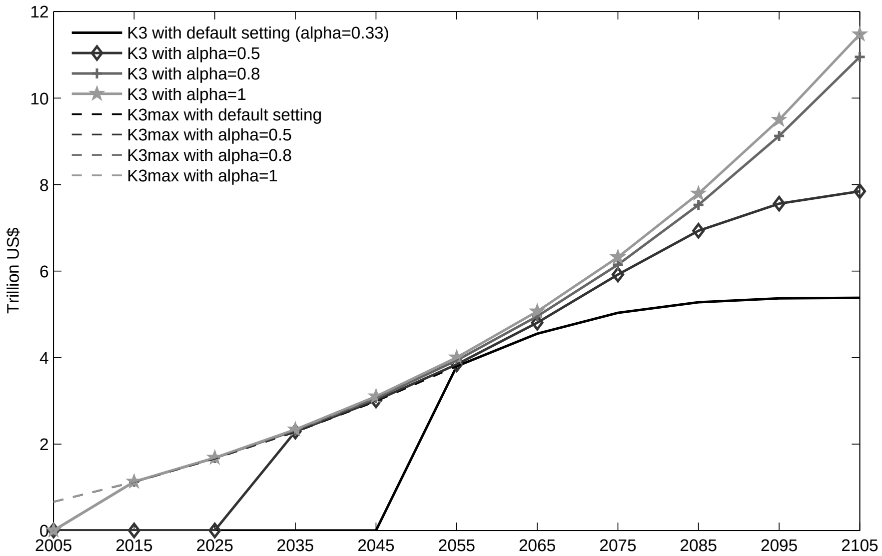

Figure 13: Adaptation capital K_3 accumulation paths and maximal amount of adaptation capital ($K_{3\max}$) for different levels of adaptation effectiveness.

strategy (mitigation and adaptation) for a low (2 °C), medium (3 °C) and 'high'[12] (4.5 °C) levels of climate sensitivity. As expected, a low climate sensitivity, yielding lower damages, postpones dramatically "green" investments and the transition to clean energy. In our simulation, a climate sensitivity of 2 °C delays transition by 40 years, a larger impact than any possible improvement in adaptation efficiency. When the sensitivity to climate is high, we obtain an opposite effect, speeding up the transition by 20 years; see Fig. 15 and 16.

Adaptation plays here a complementary role, with an identical timing for the three scenarios (2055) but with different investment levels; see Fig. 17. Again, higher climate sensitivity yielding larger damages forces a larger investment in adaptation. The cross-over observed towards the end of the century between the low and medium climate sensitivities can be explained by a similar pattern in temperature increase; see Fig. 18: a medium climate sensitivity, provoking an earlier transition towards clean production, has the effect of limiting temperature increase and thus

[12]It must be emphasized that the range of possible values of climate sensitivity may be much wider than those used here; see for instance (Stainforth and et al, 2005).

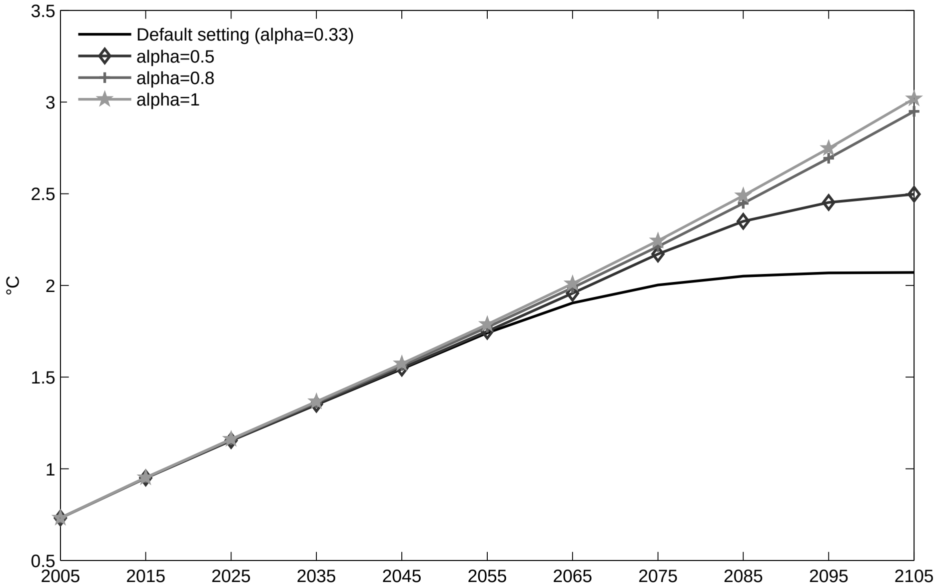

Figure 14: Temperature deviation from preindustrial levels in °C for different levels of adaptation effectiveness.

damages at the end of the century. Conversely, for a low climate sensitivity, the continuous emission from "dirty" production until 2095 produces temperature (and thus damages) increase, to the point where the two temperature curves intersect.

In our sensitivity analysis, it appears clearly that a change of scientific consensus on the climate sensitivity will have major effects on the best policy mix to deploy and on its timing. However and due to a relatively high level of uncertainty surrounding this parameter, promoting a "lower bound" strategy poses the risk that if wrong, no adaptation policy will be able to offset the irreversible effect of a large increase in GHG concentration. Mitigation strategy, in the words of Bosello et al. (2010), could be "*the starting point. Its characteristics should be determined on the basis of the precautionary principles and independently from adaptation because adaptation cannot avoid irreversibility*".

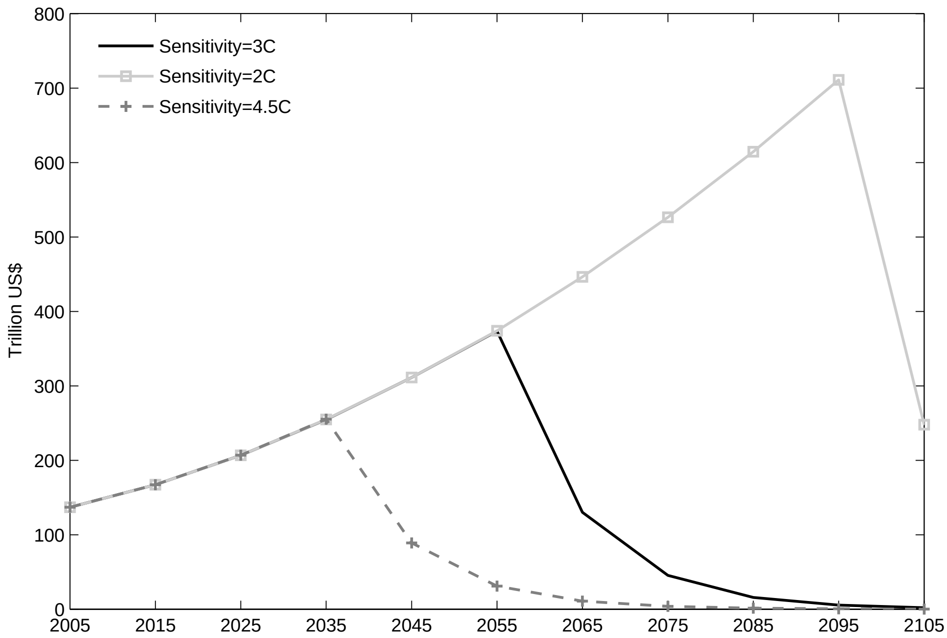

Figure 15: "Dirty" capital K_1 accumulation paths for different climate sensitivity.

5. Comparison to previous studies

In our Ada-BaHaMa model, we have introduced both a reactive adaptation option using an adaptive capital and a mitigation strategy taking the form of clean technology. To the best of our knowledge, this is the first time such a configuration has been used in an IAM. Besides, as already mentioned in the introduction, only few IAMs model explicitly adaptation options. We can however compare our results to the ones of de Bruin et al. (2009b) and Bosello (2008).

Similarly to de Bruin et al. (2009b) which incorporates adaptation as a cost option (reactive adaptation) within a DICE structure, we find that in our initial setting mitigation and adaptation act as strategic complement. However, whereas they use a separable model for mitigation and adaptation, we use an interdependent model, in which adaptation costs increase with carbon concentration (and higher temperature deviation). As a result, where they report that "*mitigation decreases the benefits of adaptation*", our results tend to indicate that mitigation could increase

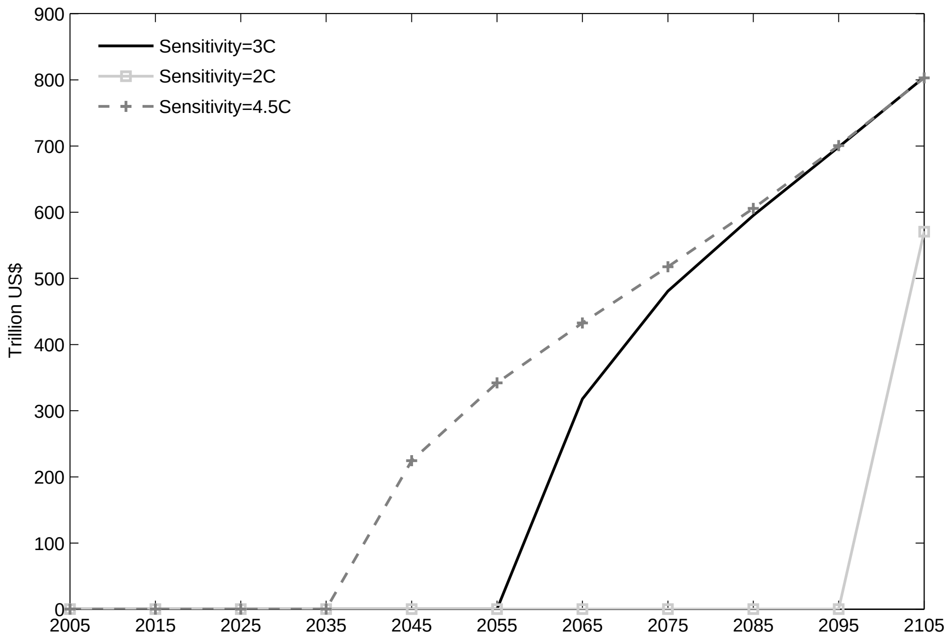

Figure 16: "Clean" capital K_2 accumulation paths for different climate sensitivity.

adaptation effectiveness by reducing the investments required for its deployment.

Bosello (2008) uses proactive adaptation with a dedicated investment variable, therefore modeling the adaptation strategy in a fashion similar to our own. Besides, the efficiency of adaptation depends on the current temperature deviation level, as in our model. It does not however include a maximum investment in adaptation K_{3max}, therefore expanding the potential of adaptation to offset damages. In our initial setting adaptation efficiency is capped at 33%, while Bosello (2008) obtains "*damage [after 2040] reduced by 14% - and booms afterward - when damage is reduced up to the 50%*". As a result and contrary to Bosello's conclusions, our model finds that adaptation with weak efficiency is triggered *before* mitigation, and never starts after, even in scenarios of high efficiencies or high climate sensitivity. Adaptation having decreasing marginal benefits through time (with a linear efficiency and an increasing investment burden), it is beneficial to use the option sooner rather than later.

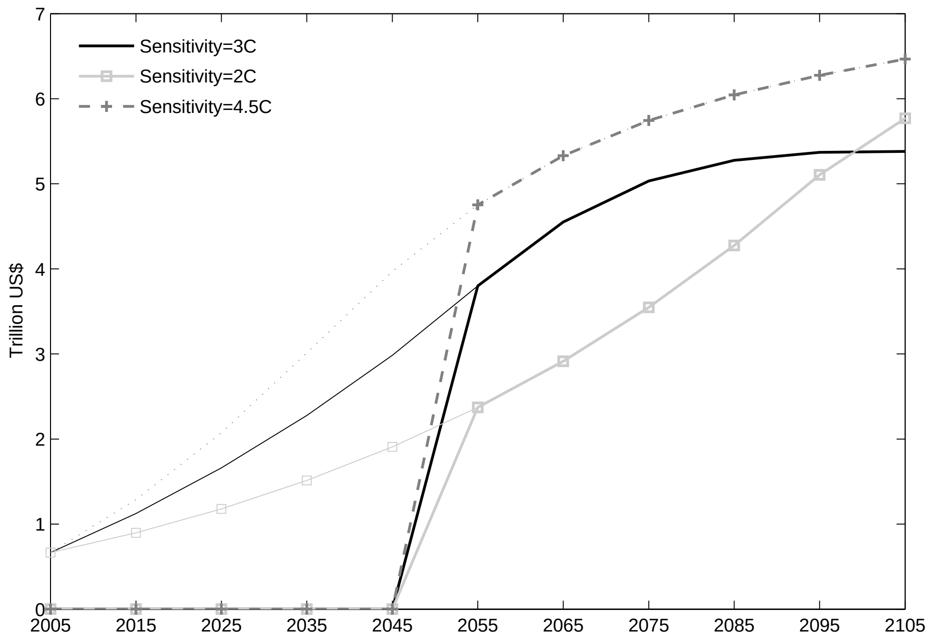

Figure 17: Adaptation capital K_3 accumulation paths and maximal amount of adaptation capital ($K_{3\max}$) for different climate sensitivity.

6. Conclusion

In this paper, we introduce both adaptation and mitigation strategies as decision variables in an integrated assessment model and assess their respective economic and environmental impacts as well as their influence on each other.

Our model presents several differences with the current literature on adaptation and mitigation in IAM. First, we consider adaptation as a proactive policy requiring investment in (an adaptation) capital, which is a richer framework than the reactive cost seen in the literature except in Bosello (2008) and Bosello et al. (2010). Second, and contrary to the approach retained in particular by de Bruin et al. (2009b) in which adaptation and mitigation decisions are separable, our framework allows for interaction between them. Indeed, we model the required adaptation investment as being dependent on the carbon concentration level and thus on the mitigation strategy deployed. And third, we model mitigation as a costly transition towards clean production

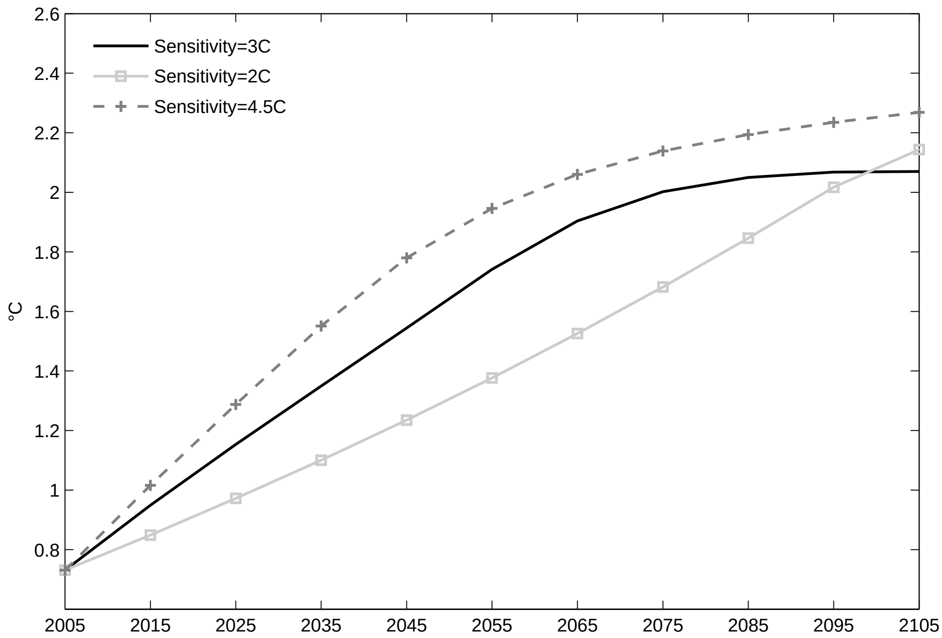

Figure 18: Temperature deviation from preindustrial levels in °C for different climate sensitivity.

systems. This sheds light on trade-offs between existing (fossil) technologies and new cleaner (renewable or fossil with carbon capture and sequestration) production systems.

We find that interaction between adaptation and mitigation is complex and largely dependent on their respective attributes. Our results show that adaptation, when weakly effective, is used as a complement to mitigation strategies. Investment in adaptation is simultaneous to investment in clean production systems and do not hinder the transition from dirty to clean technologies (in our combined scenario). However, resorting to an adaptation-only strategy causes significant temperature increase and thus significant net damages that yield increasing GDP losses. Sensitivity analysis reveals however that this situation changes with increasing adaptation effectiveness. In particular, highly effective adaptation acts as a medium- to long-term substitute to mitigation efforts, that could even prevent long-term investments in clean production systems (in the extreme case of perfectly efficient and certainly unrealistic adaptation measures). Analysis on the climate sensitivity indicates also that the choice of a climate sensitivity parameter is certainly not innocuous on the policy recommendations and represents a crucial element for our mitigation/adaptation model. In our framework, higher climate sensitivity has in particular the effect of accelerating mitigation efforts while increasing adaptation investments. On the opposite end of the sensitivity spectrum, a low sensitivity value hinders significantly the mitigation efforts and reduces adaptation investments.

We view this paper has an essential (first) step for implementing adaptation in the BaHaMa model. But we do envision several other steps to enrich the modeling framework of Ada-BaHaMa, to be carried out in future research. On the one hand, an important step will be to introduce uncertainty, for instance on climate sensitivity and the magnitude of climate change damages, on the adaptation effectiveness or on a technological breakthrough that would provide access to the clean economy. As in Bahn et al. (2008), the resolution of uncertainty will be model as a stochastic control problem. On the other hand, we also acknowledge that the choice of adaptation and mitigation policies has to take into account heterogeneity in regional costs, exposures and achievable benefits. A further improvement of our model will be the development of a multi-regional version of Ada-BaHaMa, building on the two-region version of BaHaMa reported in Bahn et al. (2010).

References

Adger, W., Agrawala, S., Mirza, M., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B., Takahashi, K., 2007. Assessment of adaptation practices, options, constraints and capacity, in: Parry, M., Canziani, O., Palutikof, J., van der Linden, P., Hanson, C. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 717–743.

Bahn, O., Haurie, A., Malhamé, R., 2008. A stochastic control model for optimal timing of climate policies. Automatica 44, 1545–1558.

Bahn, O., Haurie, A., Malhamé, R., 2010. A stochastic control/game approach to the optimal timing of climate policies, in: Filar, J., Haurie, A. (Eds.), Uncertainty and Environmental Decision Making. Springer. volume 138 of *International Series in Operations Research and Management Science*, pp. 211–237.

Baumol, W., Oates, W., 1988. The Theory of Environmental Policy. Cambridge University Press, Cambridge, MA.

Bosello, B., 2008. Adaptation, Mitigation and "Green" R&D to Combat Global Climate Change – Insights from an Empirical Integrated Assessment Exercise. CMCC Research Paper 48. Centro Euro-Mediterraneo per i Cambiamenti Climatici. Lecce, Italy.

Bosello, F., Carraro, C., de Cian, E., 2010. Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage. Sustainable Development Series 32.2010. Fondazione Eni Enrico Mattei. Venice.

de Bruin, K., Dellink, R., Agrawala, S., 2009a. Economic Aspects of Adaptation to Climate Change: Integrated Assessment Modelling of Adaptation Costs and Benefits. Environment Working Papers 6. OECD. Paris, France.

de Bruin, K., Dellink, R., Tol, R., 2009b. AD-DICE: An implementation of adaptation in the DICE model. Climatic Change 95, 63–81.

Felgenhauer, F., de Bruin, K., 2009. The optimal paths of climate change mitigation and adaptation under certainty and uncertainty. International Journal of Global Warming 1, 66–88.

Hof, A., de Bruin, K., Dellink, R., den Elzen, M., van Vuuren, D., 2009. The effect of different mitigation strategies on international financing of adaptation. Environmental Science & Policy 12, 832–843.

Hope, C., 2006. The marginal impact of CO_2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. The Integrated Assessment Journal 6, 19–56.

Hope, C., Anderson, J., Wenman, P., 1993. Policy analysis of the greenhouse effect: An application of the PAGE model. Energy Policy 21, 327–338.

IPCC, 2007. Climate Change 2007: Synthesis Report. Cambridge University Press, Cambridge, UK.

Klein, R., Eriksen, S., Næss, L., Hammill, A., Tanner, T., Robledo, C., O'Brien, K., 2007a. Portfolio screening to support the mainstreaming of adaptation to climate change into development assistance. Climatic Change 84, 23–44.

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

Lecocq, F., Shalizi, Z., 2007. Balancing Expenditures on Mitigation of and Adaptation to Climate Change: An Exploration of Issues Relevant to Developing Countries. Policy Research Working Paper Series 4299. The World Bank. Washington, DC.

Lenton, T., Held, H., Kriegler, E., Hall, J., Lucht, W., Rahmstorf, S., Schellnhuber, H., 2008. Tipping elements in the Earth's climate system. Proceedings of the National Academy of Sciences 105, 1786–1793.

Loulou, R., 2008. ETSAP-TIAM: The TIMES integrated assessment model. Part II: Mathematical formulation. Computational Management Science 5, 41–66.

Loulou, R., Labriet, M., 2008. ETSAP-TIAM: The TIMES integrated assessment model. Part I: Model structure. Computational Management Science 5, 7–40.

Manne, A., Mendelsohn, R., Richels, R., 1995. MERGE: A model for evaluating regional and global effects of GHG reduction policies. Energy Policy 23, 17–34.

Manne, A., Richels, R., 2005. MERGE: An integrated assessment model for global climate change, in: Loulou, R., Waaub, J.P., Zaccour, G. (Eds.), Energy and Environment. Springer. volume 3 of *GERAD 25th Anniversary Series*, pp. 175–189.

Margulis, S., Narain, U., 2009. The Costs to Developing Countries of Adapting to Climate Change: New Methods and Estimates. Global Report of the Economics of Adaptation to Climate Change Study. The World Bank. Washington, DC.

Meehl, G., Stocker, T., Collins, W., Friedlingstein, P., Gaye, A., Gregory, J., Kitoh, A., Knutti, R., Murphy, J., Noda, A., Raper, S., Watterson, I., Weaver, A., Zhao, Z., 2007. Global climate projections, in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Miller, H. (Eds.), Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, UK. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 747–845.

Nordhaus, W., 1994. Managing the Global Commons. The MIT Press, Cambridge, MA.

Nordhaus, W., 2007. The Challenge of Global Warming: Economic Models and Environmental Policy. Working Paper. Yale University. New Haven, CT.

Nordhaus, W., Yang, Z., 1996. A regional dynamic general-equilibrium model of alternative climate-change strategies. The American Economic Review 86, 741–765.

Olson, M., 1965. The Logic of Collective Action: Public Goods and the Theory of Groups. Harvard University Press, Cambridge, MA.

Parry, M., Arnell, N., Berry, P., Dodman, D., Fankhauser, S., Hope, C., Kovats, S., Nicholls, R., Satterthwaite, D., Tiffin, R., Wheeler, T., 2009. Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates. International Institute for Environment and Development and Grantham Institute for Climate Change, London, UK.

Stainforth, D.A., et al, 2005. Uncertainty in predictions of the climate response to rising levels of greenhouse gases. Nature 433, 403–406.

Tol, R., 2005. Adaptation and mitigation: Trade-offs in substance and methods. Environmental Science and Policy 8, 572–578.