Optimal growth with adaptation to climate change

Patrice Dumas, Minh Ha-Duong

To cite this version:

Patrice Dumas, Minh Ha-Duong. Optimal growth with adaptation to climate change. Climatic Change, Springer Verlag, 2013, 117 (4), pp.691-710. 10.1007/s10584-012-0601-7 . halshs-00207621v2

Noname manuscript No.
(will be inserted by the editor)

Optimal growth with adaptation to climate change

Patrice Dumas · **Minh Ha-Duong**

the date of receipt and acceptance should be inserted later

Abstract Many economic sectors, like housing or transportation, are exposed to climate and likely to suffer efficiency losses when climate changes. The global economy is far from being sheltered from climate, these sectors represent a significant fraction of the existing capital stock. Using an optimal growth model with perfect knowledge, we examine the balance between efficiency losses and investment in adaptation measures, which can become sunk costs when climate changes even more. Simulations remind that adaptation should be proactive: protection measures installed today are not designed for today's climate only, but anticipate future warmer conditions over their lifetime: delaying adaptation after damages happen leads to a multiplication by ten of the costs. While there is an additional investment compared with a no climate change baseline, the overall cost to adapt is relatively low in front of the potential losses from misadaptation. This allows to stay almost always well adapted to climate.

Keywords Climate change · adaptation · optimal growth · integrated assessment model

1 Introduction

According to the Intergovernmental Panel on Climate Change (2007), warming of the climate system is unequivocal, and continued greenhouse gases emissions at or above current rates would cause further warming and induce many changes in the global climate system

---

We acknowledge financial support from the Ile de France region, under the R2DS research programme. We would like to thank S. Hallegatte, C. Böhringer and EAERE participants for their useful comments.

Patrice Dumas
Laboratoire de Météorologie Dynamique
Ecole Normale Supérieure, 24 Rue Lhomond, F 75231 Paris Cedex 05
E-mail: dumas@lmd.ens.fr
Tel.: +33 1 43 94 73 79
Fax: +33 1 43 94 73 70

Minh Ha-Duong
Centre International de Recherche sur l'Environnement et le Développement
Campus du Jardin Tropical, 45 bis, avenue de la Belle Gabrielle, 94736 Nogent-sur-Marne Cedex, France

during the 21st century that would very likely be larger than those observed during the 20th century. Because many decision-makers already take into account climate change in their investment choices, some planned adaptation of human activities is occurring now. More extensive adaptation is required to reduce vulnerability to climate change.

Generally, adaptation can be defined as initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. anticipatory and reactive, private and public, and autonomous and planned. Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc. This paper focuses on anticipatory adaptation to expected climate change in one of the most important of all human systems: the economy.

In a changing climate, two sources of impacts on the socio-economic system can be distinguished: an absolute component, associated with an hypothetically stable but warmer climate, and a transient component associated with a changing climate. There is a larger literature on the absolute component (Nordhaus and Boyer, 2000; Stern, 2006) than on the transient component (Kelly et al, 2005; Hallegatte, 2005). The absolute component of adaptation is explicitly studied in De Bruin et al (2007) where adaptation to the absolute level of climate change damages is separated from the absolute damages and the trade-off between mitigation and adaptation is studied. In our view, the existence of adaptation implies that the transient component, associated with transient adaptation costs should receive more attention.

Reilly and Schimmelpfennig (2000) argued that understanding better adaptation is critical to assess the long-term impacts of climate change, and thus the required policy response. Two extreme and opposed views are commonly found in the existing literature on climate impacts: no adaptation, and total adaptation.

- The former assumption, also called “dumb farmer” or “no response”, amounts to say that climate change is too sudden and societies are too inert and shortsighted to adapt. It allows to assess potential vulnerability, which may overestimates really expected impacts.
- The total adaptation assumption amounts to say that economic agents anticipate perfectly future climatic conditions, so that adaptation is rapid and costless. This allows to assess potential adaptability, but may lead to underestimate the really expected impacts.

The specific literature on adaptation recognizes that there is a dynamic trade off to be made between, on the one hand, the productivity loss caused by the changing climate and, in the other hand, the ressources allocated to adaptation. Kelly et al (2005) argued that agents are slowed in their ability to instantly adapt to the changed climate for two reasons: input (e.g., capital) fixity and incomplete knowledge of the climate change. Like most of the other existing studies on adaptation, uncertainty and learning (Schneider et al, 2000; O’Neill et al, 2006; Smit et al, 2000), Kelly et al. focused on the second reason and examined the problem of adaptation to a weak change on a background of a large natural variability. They found that for agriculture in the US midwest, the costs of being not perfectly adapted is lower that expected gains from climate change. For coastal flooding, West et al (2001) found that the costs of not adapting to the risk is small.

Here we explore the other factor limiting adaptation, capital fixity. We consider that there is no uncertainty and that economic agents anticipate perfectly. But investments to be adapted to the climate, adaptation measures, are embodied in specific stocks of long-lived capital, which cannot easily be transformed into consumption goods or other kinds of capital. If climate change is rapid, the capital specific of a climate may become unusable before it is obsolete.

This text is organized as follows. Section 2 roughly assesses how much of the world's capital stock is specifically adapted to the current climate, and therefore exposed to climate change. We do so by disaggregating the global economy into 26 sectors, each more or less vulnerable to climate change. Using GTAP data, we find that a significant share of all the global capital stock appears to be sensitive to climate, about 25%.

Section 3 presents the integrated optimal growth model used to assess optimal adaptation pathways (calibration is discussed in Annex A). The effects of climate change are represented as losses in economic efficiency incurred when the productive system is not in line with the current climate. The model does not include uncertainty, climate change mitigation, or any permanent damages (or benefits) linked with the absolute level of climate change.

Section 4 presents the main results. First, adaptation is proactive: along the optimal investment path, the protection capital installed is not perfectly adapted to the present climate, but anticipates on the future warmer conditions. Second, adaptation is almost complete: additional investment allows to stay almost always well adapted to climate along the optimal path. Third, costs are low: while climate change requires additional investments for adaptation, the overall cost to adapt is relatively low in front of the potential losses from misadaptation, and the overall utility loss is small in the end. Section 5 discusses and concludes.

2 Capital and adaptation to climate

To examine from a macroeconomic point of view when and how much to adapt to a changing climate requires to discuss first the differences between productive, exposed and protection capital. This discussion will be limited to the man-made capital only, preserving natural capital is a different issue.

In some sectors, the efficiency of capital can be impacted by global warming, but this impact can be offset by allocating sufficient specific ressources to adaptation. This leads us to distinguish three kinds of capital stocks, see Figure 1.

The fraction v of the economically productive capital that is potentially impacted by climate change will be called *Exposed capital*. The *Protection capital* represents the accumulation of economic ressources allocated to adaptation. This notion covers more precisely the measures that are long-lived, not directly productive, and specific to a given climate range. A canonical example of that kind of capital could be hail guard nets.

As Figure 1 shows, we defined protection capital as specific to a level of climate change. This implies that protective measures that improve the situation in all climates, like insulation are not included. These are considered to be part of the productive capital.

A first example of protection capital is the set of protections and constructions that must fit with sea or river levels. If the level is too low those constructions have to be moved in the direction of the the sea, while housing and infrastructure have to retreat when the sea level rises, allowing to stay, in the long run, at the best distance to the sea.

Water production and transport have also to be modified when the regimes of precipitation and of temperatures change: at some place the available water does not balance the needs anymore while at other places water may be more abundant. The bulk of the water system does not necessarily need to be changed, the parts that must be adjusted correspond with the protection capital.

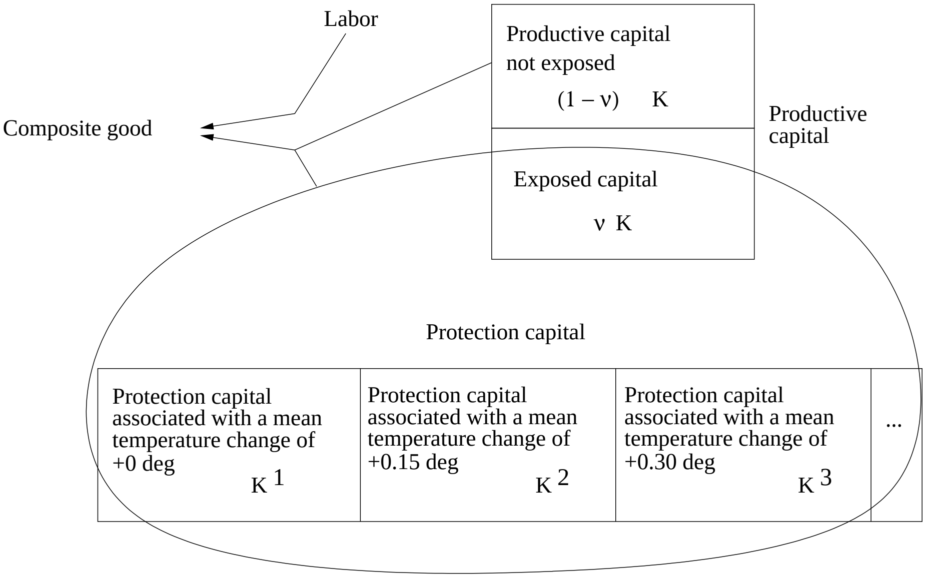

Fig. 1 Three kinds of capital stock involved in adaptation to climate change. Exposed capital is the fraction of economically productive capital that is potentially impacted by climate change. *Protection capital* is the accumulation of specific, long-lived, non-productive ressources allocated to adaptation.

Institutions and habits may also be considered to be like protection capital, although they are not present in national economic accounts. For example the health care system must be adapted to the climate, the season demanding more resources may be winter or summer depending on the climate, as the heat-waves in Europe in 2003 demonstrated (Salagnac, 2007).

The combination of exposed capital and protection capital, as shown with a bubble Figure 1, is called sensitive capital. Its productivity depends on climate.

We now turn to the question of evaluating the share of economic activity vulnerable to climate that must be protected, and the amount of protection capital. Empirically, this can only be given a rough answer.

We used a coarse disaggregation of the global economy and a qualitative multi-criteria characterization of the sectors mapped into a quantitative scale. The GTAP (1997) database was used as a basis for an aggregation of the global economy in 26 sectors. Each sector was scored using a qualitative scale (—, + and ++) for three criteria:

1. Climate specificity: Is the organization of the sector identical across different climates or not? For example the Water sector is specific because water supply and demand depends on the regional patterns of precipitation and evaporation.
2. Importance of outdoor activity in the sector.
3. Vulnerability to climatic extreme events.

Those criteria are considered to be linked with exposure to climate and a need to be protected by measures specific of the climate. The scores are given in Table 1. Criteria were linearly weighted to translate the qualitative scores into two quantitative indexes, a sensitivity and a defensivity index.

The sensitivity index is used to determine the fraction of sensitive capital over total capital. For each criterion, a + translates to a vulnerability of 20% and a ++ translates to vulnerability of 33%. For example, for the transport, there is no specificity for a climate, so the associated vulnerability is 0%. Transport is mildly vulnerable because it is an outdoor activity, with a + which amounts to a vulnerability of 20%. And transport is sensitive to extreme events that render transport infrastructures unavailable, therefore there is a ++ that translates to vulnerability of 33% associated with extreme events. The resulting sensitivity index for the Transport sector is $0+20+33=53\%$.

The defensivity index is used to determine the fraction of protection capital over total capital. Weights are interpreted as fractions of sensitive capital. We assumed that climate specificity do not imply any need for a protective measures, while sensitivity to extreme events implies a larger amount of protective measures higher than outdoor activity. Thus, the defensivity weights are respectively 0, 15% and 35% for each criteria. For example for the transport this leads to $100\cdot(0\cdot 0+0.2\cdot 0.15+0.33\cdot 0.35)=15\%$.

Sectors were weighted according to their share in the capital revenues and to their share in the added value in order to obtain a global, economy-wide figure. These weights, according to our query of the GTAP database, are shown in the last columns of Table 1 for each of the vulnerable sectors. The result is a global sensitivity index of 24–25%, depending on the weighting used, and a defensivity index of 10%. The share of the sectors is affected by the weighting procedure, but the figures are not qualitatively different. These numbers will be used to calibrate the model in the following.

The whole procedure is heuristic, and a sensitivity analysis on these parameters is conducted later in the assessment. But this is not completely inappropriate for the question at hand given that assessing absolute and relative stocks of capital can only be done imprecisely, and that systems of national accounts are presently not designed to measure climate change adaptation expenditures. Existing assesments of economic sectors impacted by climate change target absolute damages, and not adaptation measures, and therefore omit sectors threatened by extreme events.

While the results indicate order of magnitudes only, they allow for a few comments. First, the significant value of the sensitivity index reminds that even if most of the economic activity in services and industry takes place indoor, and some part of the economy is dematerialized, on the whole a significant fraction of the human activity remains exposed to climate and climate change.

Second, economic sectors appear unequally exposed to climate change. Construction and housing appears to be the most problematic sector, given their weight in the economy, followed by the utilities, and last by the agriculture and recreational services that are vulnerable but don’t weight much overall.

Third, this assessment did not account for system-wide interdependencies between economic actors. When extreme climate events turn catastrophic, the disruption of business networks can be felt across all sectors.

3 An optimal growth model with adaptation

This section presents an optimal growth model with climate change adaptation and no uncertainty. It is inspired from the classical Ramsey/Cass/Koopmans model, as well as from the DICE (Nordhaus, 1994) and RESPONSE (Ambrosi et al, 2003) integrated assessment

Sector	specific of a climate	outdoor activity	sensitive to climatic extreme events	sensitivity index (percent)	defensivity index (percent)	share in capital (percent)	share in added value (percent)
Agriculture	++	++	+	86%	12%	2.02%	3.44%
Wood products	++	+	++	86%	15%	0.97%	0.9%
Transport	—	+	++	53%	15%	2.66%	2.84%
Electricity	+	—	++	53%	10%	1.69%	1.04%
Water	++	—	+	53%	7%	0.24%	0.22%
Construction	++	++	+	86%	12%	4%	5.32%
Communication	—	—	+	20%	7%	0.56%	0.43%
Insurance	—	—	++	33%	10%	0.19%	0.41%
Business services	—	—	+	20%	7%	3%	2.12%
Recreational services	+	+	+	60%	10%	2.88%	2.56%
Public	—	—	+	20%	7%	1.41%	3.28%
Dwellings	+	—	+	40%	7%	5.23%	2.49%
Other[†]	—	—	—				

Table 1 Vulnerability to climate change by economic sectors. The first three columns are qualitative assessments by the authors, they are used to derive the columns “Sensitivity index” and “defensivity index”. The sensitivity index determines the share of the sector that needs climate adaptation, and the “defensivity capital” determines the fraction of protection capital. Column “share in capital” presents the proportion of sensitive capital in this sector over total capital across all sectors. Similarly, column “share in added value” presents the proportion of sensitive added value in this sector over total added value across all sectors.[†]Other sectors are: Textile, Processed food, Minerals, Oil Products, Coal, Gas, Paper, Plastic, Vehicles, Electronic, Machinery, Manufacture, Trade, Financial

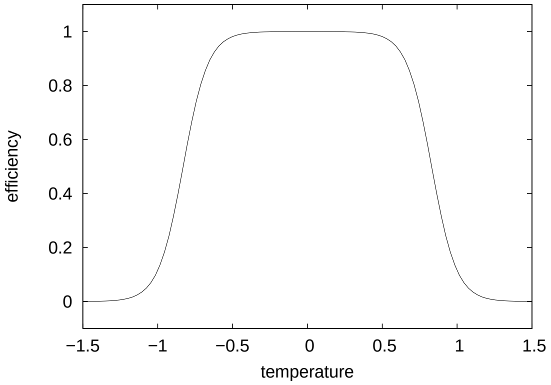

Fig. 2 Efficiency of the protection capital as a function of the difference between the actual temperature and the temperature associated with the protection capital.

models. The originality is that in addition to the productive capital, protection capital is introduced.

The objective is to maximize the intertemporal sum of the discounted utility of consumption. Economic output is a function of exogenous labor and capital. Economic production lead to CO_2 emissions, then climate change through a simple carbon cycle and global warming submodel. Climate change penalizes the productivity of the aggregate economy. Adaptation is introduced as follows (see Figure 1 again).

We assume that there are different categories of protection capital. Each is designed for a specific climate, and becomes abruptly inefficient when climate changes too much. This is inspired from the concept of coping range discussed for example by Smit et al (2000). Since in the model climate change is represented by an amount of global warming, this modeling structure can be translated into a temperature scale.

A category of protection capital K_j is defined by the global average temperature θ^j for which it is best adapted. Denoting θ_t the realized temperature in the model at date t, we use an efficiency function $g(\theta_t - \theta^j)$ such that $g(0) = 1$ and g becomes small when the temperature difference becomes large, see Figure 2.

For analytical convenience, we assume that g is symmetric, with warming and cooling equally similarly harmful. Taking the example of sea-level rise this hypothesis amounts to equivalent costs for sea-level rise and sea-level fall, corresponding with the costs of relocating at an optimal distance from the sea. The function is specified with two parameters, parameter w controls the width $g(w/2) = g(-w/2) = 1/2$, while parameter z controls the abruptness of the efficiency change. More precisely:

$$g(x) = \frac{1+e^{-zw}}{\left(1+e^{-z(x+w/2)}\right)\left(1+e^{-z(x+w/2)}\right)} \tag{1}$$

We assume that different kinds of adaptation measures can be superposed to protect the productive exposed capital. Thus, protection capital stocks are perfect substitutes. A better adaptation could also be achieved by augmenting the range of temperatures that a given cpital can handle (increasing w), or by the use of capital that becomes obsolete faster (Fankhauser et al, 1999). Here we do not consider those opportunities, nor their cost.

The total protection capital is computed by summing up the different stocks of protection capital, each with its own efficiency:

$$\text{Protection capital stock } = \sum_j g(\theta_t - \theta^j) K_j \tag{2}$$

Protection capital is needed even in absence of climate change, in order to be adapted to the current climate. In the no-climate change run (BAU), there is only one type of protection capital, K^{BAU} with an efficiency of 1.

A fraction νK of productive capital is exposed to climate and must be combined with the protection capital to enter the production function. It is assumed that the exposed capital and the protection capital have a constant elasticity of substitution and are complements: they are not useful taken separately.

The capital available for the production is the sum of the non-vulnerable capital $(1-\nu)K$ and the previous combination of exposed and protection capital. Capital and labor are combined using a Cobb-Douglas function. The production Y may be used for investment in productive capital I, investment in protection capital I^j and consumption C. Labor is equal to the population P multiplied by an geometrically increasing technical progress factor $\mu(1+\kappa)^t$.

Denoting the variables per labor unit with lower case letters, for example $c = \frac{C}{P\mu(1+\kappa)^t}$, the production function is:

$$y_t = \left[(1-\nu)k_t + \left(\eta \left(\nu k_t \right)^\rho + \gamma \Big(\sum_j g(\theta_t - \theta^j) k_t^j \Big)^\rho \right)^{\frac{1}{\rho}} \right]^\alpha \tag{3}$$

The remainder of the model is classical. Denote u the utility function with constant inter-temporal elasticity of substitution: $u'(C) = C^{-\tau}$. The objective is:

$$\max_{i_t^j, i_t, c_t} \sum_{t=0}^{140} \beta^t P_t u \left(c_t \mu (1+\kappa)^t \right) \tag{4}$$

Such that:

$$y_t = c_t + i_t + \sum_j i_t^j \tag{5}$$

$$k_{t+1} = \frac{P_t}{P_{t+1}(1+\kappa)} ((1-\delta)k_t + i_t) \tag{6}$$

$$k_{t+1}^j = \frac{P_t}{P_{t+1}(1+\kappa)} ((1-\delta)k_t^j + i_t^j) \quad \forall j \tag{7}$$

$$\frac{E_t}{E_0} = \xi_t \, e^{\psi t} \, \frac{y_t P_t (1+\kappa)^t}{y_0 P_0} \tag{8}$$

In the emission dynamics, the factor ξ_t corresponds to the transition from the current trend to the projected trend. The other factor is an exogenous energy efficiency improvement, used in Nordhaus (1994) for example. The carbon cycle and temperature equations are the same as in Nordhaus and Boyer (2000) (not shown here).

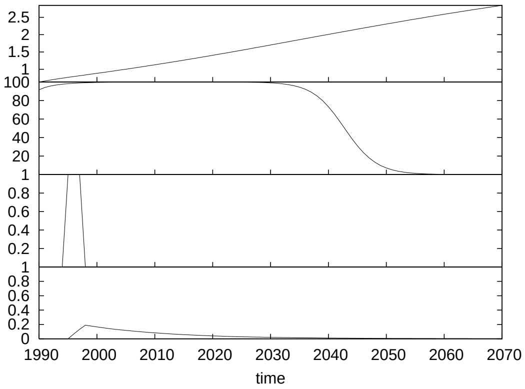

Fig. 3 Evolution of the type 10 protection capital, associated with a temperature increase of 1.26°C. From top to bottom: global temperature increase θ_t, efficiency of the capital $g(\theta_t - \theta^{10})$, investment in that type of capital scaled by the total amount of investment in protection capital $\frac{i_t^{10}}{\Sigma_j i_t^j}$ and capital 10 stock scaled by the total amount of protection capital.

4 Results and sensitivity analysis

The model was implemented in GAMS. We used Section 2 estimates and a SRES A1 scenario trajectory to calibrate the parameters, see appendix A.

The model results are best explained by looking first at a specific type of protection capital. Consider for example the capital associated with $j = 10$. This corresponds to adaptation measures designed to work optimally for a temperature increase of $\theta^{10} = 1.26$°C above the pre-industrial era. This capital becomes inefficient only when global warming goes over $\theta^{10} + w = 2.9$°C.

Figure 3 shows how the global temperature, this capital efficiency $g(\theta_t - \theta^{10})$, the optimal investment in this capital i_t^{10} and the capital stock K_t^{10} evolve over time. The investment I_t^{10} is scaled by the total amount of protection investment, and the capital K_t^{10} is scaled with the total protection capital.

The third panel in Figure 3 shows a pulse of investment in type-10 protection capital. This class of protection investment is used only 1995, 1996, 1997, but during these three years only this class is used.

Looking now at the second and fourth panel in the figure, we see that investment occurs at a time when the efficiency is already high, but not 100% yet. Full capital efficiency is reached only about ten years after the investment and lasts approximately two decades. At the tail end, when the efficiency begins to decrease due to excessive global warming, most of the protection capital stock has decayed.

Thus, along the optimal trajectories sunk costs are sustained in the beginning and in the end of the capital lifetime, when capital is not fully efficient. The climate change speed is too high to allow for the use of a capital as efficient as in the baseline. The replacement has to be performed before new capital is fully efficient and still some inefficient capital remains.

At its peak, the capital of type 10 represents only 20% of the total protection capital. Along the optimum trajectory, the model adapts every 2 to 3 years to global warming by

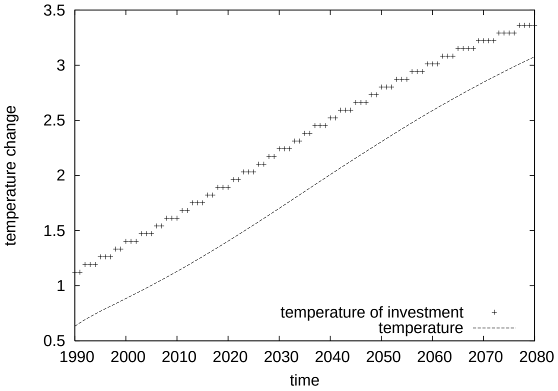

Fig. 4 Optimal investment in protection capital (++ line) anticipates the atmospheric temperature (dashed line) by about two decades, or half a degree.

calling in a different kind of protection capital. Consequently, the total protection capital stock is made from a variety of different kind of capital.

This can also be seen on Figure 4. The figure shows the realized temperature θ_t and the temperature θ^j associated with the kind of investment I_t^j (in proportion of the different kinds of investment made at this period). It shows that investment anticipates by about two decades the temperature increase. Said otherwise, at any time protection investment is designed for a temperature about half a degree higher than current temperature.

Examining now the results from the costs perspective, the model balances two costs:

- The economic inefficiencies caused by climate change. In our setting this damage is associated with a protection capital efficiency lower than in the baseline (BAU) without climate change. Denoting the BAU protective capital amount as K^{BAU}, this damage is therefore present when
$$\sum_j g(\theta_t - \theta^j) K_t^j < K^{BAU}$$
- Over-investment in protection capital relative with the baseline. This happens if
$$\sum_j K_t^j > K^{BAU}$$

Figure 5 shows the protection capital efficiency and the protection capital amount change relative to the BAU protection capital (without climate change). This figures shows that most of the cost corresponds with an additional investment peaking at about 7%. It seems to be preferable to bear sunk costs than to suffer from ill-adaptation.

Turning to the net costs of climate change, figure 6 shows the consumption losses over time. An interesting result is that in the very first periods the consumption is higher in case of climate change. Investment is directed to a capital associated with a higher temperature right from the beginning, but the amount of investment is lower than in the baseline. A possible explanation of this trajectory is linked with discounting and cost. Indeed there is a net loss incurred with climate change. To lower the overall cost, consumption is augmented in the first years, when discounting is not too strong.

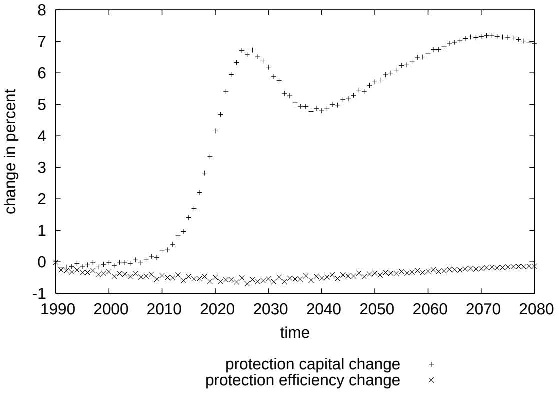

Fig. 5 The balance of costs. Compared to the BAU, the optimal trajectory invests more in protection capital, but the efficiency losses stay small.

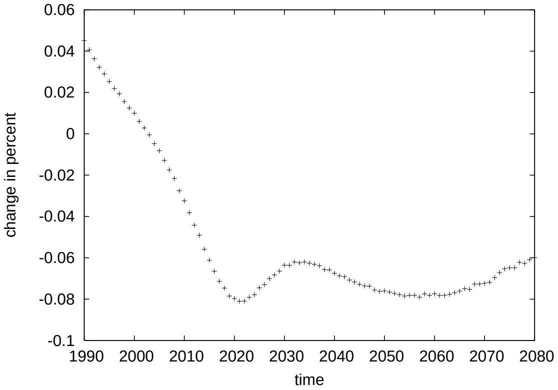

Fig. 6 Consumption change over time in percent.

On figure 6 and 5 a bulge happens near the year 2025. Most of this bulge is caused by the non-optimality of the preexisting protection capital stock available in the first period. Indeed the initial protection capital is composed of only one type of capital, without anticipation over the future climate change. If the initial protection capital is instead a mix of capitals with a structure similar with the structure resulting from the optimization, the bulge almost disappears. A little increase remains, certainly because the speed of climate change is the highest around this year.

Three sensitivity analysis were performed. The first deals with *w*, the efficiency range of the protection capital, a very uncertain parameter. In the second one a best and worst case scenario are compared. The last analysis is devoted to the consequences of a delay in implementation of adaptation measures, which could be explained if adaptation was reactive rather than with perfect anticipations.

The total intertemporal utility increases when *w* increases: having protection capital that remains efficient longer is better. For the studied values of climate change speed (a few tenth

scenario	w	π_p	π_s	$T_{2\times}$	result
worst case	1.44	0.15	0.5	4.5	0.044
central case	1.66	0.1	0.24	3.5	0.005
best case	2.66	0.05	0.12	2.5	0.00005
reactive	same as central case				0.03

Table 2 Sensitivity analysis parameter values and results. Result is the total intertemporal utility loss, compared to the no climate change baseline, in percent. The key parameters in columns are the efficiency range of protection capital w, the fraction of protection capital π_p, the fraction of exposed capital π_s and the climate sensitivity $T_{2\times}$. The *reactive* scenario only allows adaptation to start when efficiency loss in vulnerable sectors has reached 2%.

of a °C per decade), and capital depreciation rate (3% annually), at the simulated efficiency ranges of 1.5–2.5°C the utility loss remains modest in all cases. It is practically zero when w is more than 2.5°C.

To analyze the results further, two extreme cases were examined, a worst case and a best case scenario. These were defined by changing the climate sensitivity $T_{2\times}$, the protection efficiency range w, the fraction of vulnerable capital π_s and the fraction of protection capital π_p as Table 2 shows. In the best case, protection capital has a wide efficiency, climate sensitivity is low, the fraction of capital exposed climate is low and not much protection capital is needed. The order of magnitude of the utility loss changes, but remains relatively modest even in the worst cases scenario. The optimal investment strategy remains qualitatively the same: a sequence of pulses in protection capital, anticipating to remain adapted.

The importance of the initial situation highlights the possible costs arising from delays in implementing adaptation methods to keep up with the climate change speed. This is an important issue since, as reported in Schneider et al (2000) or Tol et al (1998) adaptation to climate change is often reactive.

To examine the costs of late adaptation, we constrained the model such that adaptation is only allowed when the vulnerable sectors production has been reduced by 2%. This happens in 2019 in the central case. The costs significantly change in that simulation: production is reduced in the years preceding 2019, and additional investment becomes substantial. Overall, as can be seen in table 2 bottom row, with late adaptation the utility loss is an order of magnitude larger than in the central case. Reactive adaptation would be costly.

5 Discussion and concluding remarks

Many assumptions were made in the macroeconomic model of adaptation used above: the sensitivity index remains fixed (the model economy cannot adapt structurally by moving towards less sensitive sectors), emission reduction are not considered; there are no direct climate damage function; and anticipations are perfect without uncertainty.

Real-world climate policies should consider both adaptation and mitigation, which in theory could be seen as substitutes. However, one should not neglect the differences in timescales. Adaptation brings short-term benefits because climate has already changed unequivocally, and further global warming of 0.2°C per decade can be expected. The benefits of emission mitigation are best assessed within a timeframe much larger than a decade.

While the model used above do not have a direct climate damage function, this is not to claim that the full effects of climate change can be captured as a preventable marginal decline in the aggregate economic production function. There is also a social aversion for climate change in itself, which may ultimately be even more difficult to measure than capital stocks, as it involves too much controversial value judgments and individual preferences. In a changing climate, the absolute component of climate damages and the adaptation costs allowing to limit those damages are also important. Combining those components, and combining adaptation and mitigation is left for future research.

Along the optimal pathway, adaptation is pro-active, with an anticipation of about twenty years. Some studies show that pro-active adaptation already occurs, but we are hardly seeing a systematic shift in protection investment as suggested by the optimization. Uncertainty may be part of the explanation, the range of possible climate changes, especially at the local level is very broad (Hallegatte et al, 2007). Another part of the explanation is that perfect foresight is an idealization rarely found in reality, even when scientific knowledge allows to reasonably expect an increasing climate change in the near future. How to implement the desirable investment policy is a question that can not be answered here. A sensitivity analysis where adaptation only starts after vulnerable sectors are impacted shows a multiplication by ten of the costs, stressing the issue of reactive versus pro-active adaptation.

To sum up the results, we assessed that about a quarter of the world's productive capital is sensitive to climate. While nowadays the majority of economic activity occurs sheltered indoors, a large number of economic sectors like housing and infrastructures must still be adapted to local climatic conditions or is directly exposed to extreme weather events.

There is a dynamic trade off to be made between the costs of adaptation and the economic productivity losses due to climate change. We presented a stylized macroeconomic growth model to examine this trade off. It shows that along an optimal investment path, the protection capital installed is not designed to the current climate but anticipates on the future warmer conditions. Also, while there is an additional investment compared to a no climate change baseline, the overall cost to adapt is relatively low in front of the potential losses from misadaptation. Over-investment in protection capital allows to stay almost always well adapted to climate and avoid transient misadaptation costs.

Although there is an additional investment in protection capital by several percentage points, the consumption losses remain below one tenth of a percent annually in the model. This mainly because the share of protection investment in total investment is small: we assessed that a low amount of protection capital, less than ten percent of the sensitive capital, was needed to be adapted to a changed climate. Another reason for this result is that we assumed separability between protection and exposed capital. This hypothesis could be challenged in the case of infrastructures and housing: when the protection capital is embedded in an infrastructure, changing the climate specificity may be so costly that rebuilding the whole infrastructure may prove to be cheaper. The balance between mitigation and transient adaptation costs is an interesting issue, however, in the model proposed here, the adaptation costs are so low that they should not trigger additional mitigation efforts.

Adaptation measures are sunks costs, and may become inefficient when climate changes more in the long run. Thus, there is an interplay between the speed of climate change and the natural replacement cycle of protection capital. Our results allow to stress that letting climate change accelerate may well lead to situations where many adaptation measures become obsolete and need to be replaced before they reach their expected lifetime. Finally, our analysis reminds that it is optimal to adapt early and suggests that in a “perfect” world aggregate adaptation costs could be low. Since studies of specific sectors are less optimistic, modelling the effect of uncertainty and delays in adaptation measure implementations at scales that allow to take those issues into account remains important.

References

Ambrosi P, Hourcade JC, Hallegatte S, Lecocq F, Dumas P, Ha-Duong M (2003) Optimal control models and elicitation of attitudes towards climate change. Environmental Modeling and Assessment 8(3):135–147, DOI 10.1023/A:1025586922143

De Bruin KC, Dellink R, Tol RSJ (2007) AD-DICE: An implementation of adaptation in the DICE model. Nota di Lavoro 51.2007, FEEM

Fankhauser S, Smith JB, Tol RS (1999) Weathering climate change: some simple rules to guide adaptation decisions. Ecological Economics 30:67–78

GTAP (1997) Global Trade Analysis Project. URL `https://www.gtap.agecon.purdue.edu/default.asp`

Hallegatte S (2005) The long time scales of the climate-economy feedback and the climatic cost of growth. Environmental Modeling and Assessment 10(4):277–289

Hallegatte S, Hourcade JC, Ambrosi P (2007) Using climate analogues for assessing climate change economic impacts in urban areas. Climatic Change 82(1–2):47–60, DOI 10.1007/s10584-006-9161-z, URL `http://www.centre-cired.fr/spip.php?article238`

Intergovernmental Panel on Climate Change (2000) Special Report on Emissions Scenarios. Cambridge University Press, URL `http://www.ipcc.ch/ipccreports/sres/emission/index.htm`

Intergovernmental Panel on Climate Change (2007) Climate Change 2007: Synthesis Report. URL `http://www.ipcc.ch/ipccreports/ar4-syr.htm`

Kelly DL, Kolstad CD, Mitchell GT (2005) Adjustment costs from environmental change. Journal of Environmental Economics and Management 50:468–495, DOI 10.1016/j.jeem.2005.02.003

Nordhaus WD (1994) Managing the Global Commons: The Economics of Climate Change. MIT Press

Nordhaus WD, Boyer J (2000) Warming the World: Economics Models of Global Warming. MIT press, URL `http://www.econ.yale.edu/~nordhaus/homepage/dice_section_I.ht%ml`

O'Neill BC, Crutzen P, Grübler A, Ha-Duong M, Keller K, Kolstad C, Koomey J, Lange A, Obersteiner M, Oppenheimer M, Pepper W, Sanderson W, Schlesinger M, Treich N, Ulph A, Webster MD, Wilson C (2006) Learning and climate change. Climatic Change 6(5):585–589

Reilly J, Schimmelpfennig D (2000) Irreversibility, uncertainty and learning: Portraits of adaptation to long-term climate change. Climatic Change 45:253–278, DOI 10.1023/A:1005669807945

Salagnac JL (2007) Lessons from the 2003 heat wave: a French perspective. Building Research and Information 35(4):450–457

Schneider SH, Easterling WE, Mearns LO (2000) Adaptation: Sensitivity to natural variability, agent assumptions and dynamic climate changes. Climatic Change 45:203–221, DOI 10.1023/A:1005657421149

Smit B, Burton I, Klein RJ, Wandel J (2000) An anatomy of adaptation to climate change and variability. Climatic Change 45:223–251, DOI 10.1023/A:1005661622966

Stern N (2006) The Economics of Climate Change. The Stern Review. Cambridge University Press

Tol RSJ, Fankhauser S, Smith JB (1998) The scope for adaptation to climate change: what can we learn from the impact literature? Global Environmental Change 8(2):109–123, DOI 10.1016/S0959-3780(98)00004-1

West JJ, Small MJ, Dowlatabadi H (2001) Storms, investor decisions, and the economic impacts of sea level rise. Climatic Change 48:317–342, DOI 10.1023/A:1010772132755

A Calibration

The emission function parameters and the technical change rate are determined by fitting on the SRES A1 scenario trajectory from the AIM model (Intergovernmental Panel on Climate Change, 2000). The initial protection capital is only constituted of one type of capital, the capital associated with the initial temperature. It is assumed that at the starting point the economy is on the balanced growth path. To scale the production function, it is assumed that

$$K_0^T = (1-\nu)K_0 + \left(\eta\,(\nu K_0)^{\rho} + \gamma\big(K_0^1\big)^{\rho}\right)^{\frac{1}{\rho}} \tag{9}$$

The number of different protection capital types is chosen high enough such that it does not influence the result. In the central case, model parameters are defined as in table 3 below:

τ	inter-temporal elasticity of substitution	1
δ	capital depreciation rate	0.03
P_t	population	follows SRES A1
κ	technical progress growth rate	calibrated on SRES A1
β	discount factor	0.96
$\frac{C_0}{Y_0}$	initial consumption ratio	75%
K_0^T	Total initial capital	$Y_0\,\frac{1-\frac{C_0}{Y_0}}{1-\delta-y_1/y_0}$
π_s	sensitive capital in capital	$\frac{K_0^1+\nu K_0}{K_0^T} = 0.24$
π_p	protection capital in sensitive capital	$\frac{K_0^1}{K_0^1+\nu K_0} = 0.1$
K_0^1	initial protection capital	$\pi_s \pi_p K_0^T$
K_0	initial productive capital	$K_0^T - K_0^1$
νK_0	sensitive productive capital	$\pi_s K_0^T - K_0^1$
α	share of capital	initial value
μ	labor parameter	initial value
ψ	energy efficiency improvement	calibrated on SRES A1
ξ_t	production emission intensity	calibrated on SRES A1
ρ	protection CES parameter	-4
η	protection CES parameter	$(1-\pi_p)^{1-\rho}$
γ	protection CES parameter	$\pi_p^{1-\rho}$
w	width of protection (°C)	1.66
z	protection efficiency slope	12
$T_{2\times}$	climate sensitivity	3.5

Table 3 Model parameters, central case.