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**Adapting and Mitigating to
Climate Change: Balancing
the Choice under
Uncertainty**

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Keywords: Climate Change, Mitigation, Adaptation, Uncertainty, Integrated Assessment Model

JEL Classification: C61, D58, Q54

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Abstract

Nowadays, as stressed by important strategic documents like for instance the 2009 EU White Paper on Adaptation or the recent 2009 “Copenhagen Accord”, it is amply recognized that both mitigation and adaptation strategies are necessary to combat climate change. This paper enriches the rapidly expanding literature trying to devise normative indications on the optimal combination of the two introducing the role of catastrophic and spatial uncertainty related to climate change damages. Applying a modified version of the *Nordhaus’* Regional Dynamic Integrated Model of Climate and the Economy it is shown that in both cases uncertainty works in the direction to make mitigation a more attractive strategy than adaptation. When catastrophic uncertainty is concerned mitigation becomes relatively more important as, by curbing emissions, it helps to reduce temperature increase and hence the probability of the occurrence of the event. Adaptation on the contrary has no impact on this. It is also shown that optimal mitigation responses are much less sensitive than adaptation responses to spatial uncertainty. Mitigation responds to global damages, while adaptation to local damages. The first, being aggregated, change less than the second in the presence of spatial uncertainty as higher expected losses in some regions are compensated by lower expected losses in other. Accordingly, mitigation changes less than adaptation. Thus if it cannot be really claimed that spatial uncertainty increases the weight of mitigation respect to that of adaptation, however its presence makes mitigation a “safer” or more robust strategy to a policy decision maker than adaptation.

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1. Introduction

In 1992, 154 nations signed the United Nations Framework Convention on Climate Change at Rio de Janeiro. Its aim was to stabilize GHG concentrations at a level "that would prevent dangerous anthropogenic interference with the climate system". When the battle against climate change started it was thus focused on mitigation measures. Ten years later, the Working Group II contribution to the *IPCC TAR* "Impact, Adaptation and Vulnerability" (*IPCC 2001*) emphasized as fundamental the role of adaptation to "reduce many of the adverse impacts of climate change and enhance beneficial impacts". This was a neat shift in emphasis driven by the increasing awareness that climate change could not be halted irrespectively of the implementation of aggressive mitigation efforts. Indeed, the strong inertias in the climate system will expose modern societies to some degree of warming no matter what they do to curb emissions. Needless to say, the constant difficulties encountered by international climate negotiations, hardly justify optimisms in the effective likelihood to observe the implementation of aggressive mitigation in the short term.

Therefore nowadays, as stressed by important strategic documents like for instance the 2009 EU White Paper on Adaptation or the recent 2009 "Copenhagen Accord", it is amply recognized that both mitigation and adaptation strategies are necessary to combat climate change. Against this background, a rapidly expanding literature is trying to devise normative indication on the optimal combination of the two in a cost efficient policy. This investigation is extremely complex due to the many uncertainties that still surround the climate change issue. Indeed the knowledge of climate dynamics, of the related environmental damages, on their economic relevance and of the costs of climate change policies, especially when adaptation is involved, is still far from conclusive. Decisions however have to be made and, given the abovementioned climatic inertias, they cannot be postponed for too long were they expected to produce some results within the century.

This paper investigates how the presence of uncertainty about climate change damages can shape decision making and, more specifically, the optimal mix between mitigation and adaptation. Two sources of uncertainty are considered: the uncertain occurrence of a catastrophic event - what we define "event uncertainty" - and the uncertainty related to the geographic distribution of climatic damages, what we call "spatial uncertainty". These different uncertainty sources are implemented into an integrated assessment model where mitigation and adaptation are available policy choices for the decision maker.

Section 2 proposes a brief literature review. Section 3 introduces the integrated model, the inclusion of adaptation and uncertainty and describes the calibration process. Section 4 elaborates the results derived from the modeling exercise. Section 5 draws major conclusion.

2. Literature Review

The consequence of climate change can be grouped into two categories: changes in average conditions and changes in extreme conditions (*IPCC TAR 2001*). The former induce impacts which are gradual and continuous, often within the coping range of systems; the latter are discontinuous events bringing about, potentially, a sharp decline of social welfare outside the coping range. The collapse of North Atlantic Thermohaline Circulation (THC), a "runaway" greenhouse effect (climate change could be much greater and occur much faster than the common consensus indicated), the disintegration of West Antarctic Ice Sheet (WAIS), are all examples of such discontinuity (*Pearce et al. 1996; Guillerminet and Tol 2008*). Catastrophic events are usually associated with very low probability, but, once materialized, with great and sudden harm (*Posner 2004*). This "event uncertainty" is obviously expected to influence the decision making process. In the climate change impact literature there is indeed a consolidated research showing that it induces higher mitigation rates (*Clark and Reed 1994; Yohe, 1996; Gjerde et al. 1998; Bosello and Moretto 1999; Ingham et al. 2005b*) and earlier action of emission control (*Baranzini et al. 2003; Guillerminet and Tol 2008*). These studies however do not push the investigation to analyze the consequences of these uncertainties on the optimal mix between mitigation and adaptation strategies.

Conversely, a very recent stream of research does analyze the optimal mix between adaptation and mitigation using applied Integrated Assessment Model (IAM) (*De Bruin, et al. 2007, 2009; Bosello 2010; Bosello et al. 2010*). The robust outcome of these studies is that adaptation and mitigation are strategic complements: the optimal policy consists of a mixture of adaptation measures and investments in mitigation, this is also true in the short term even though mitigation will only decrease damages in later periods as emission cuts can slow down temperature increase and the related damages with a delay of 50-80 years.

All the authors also highlight the existence of a trade off between strategies: being resources scarce, more on one means less on the other. Moreover, successful adaptation reduces the marginal benefit of mitigation and a successful mitigation effort reduces the damage to which it is necessary to adapt. However this second effect is notably weaker than the first. Indeed mitigation especially in the short-medium term lowers only slightly environmental damage stock and therefore does little to decrease the need to adapt.

In addition, in all these studies the bulk of resources are devoted to adaptation especially when discount rates are high and when investment in adaptation can build a cumulating stock of "defensive" infrastructures. In these cases adaptation appears far more effective than mitigation, especially in the short term, to contrast climate change damages.

These researches however are based on integrated assessment models which exclude irreversible, low-probability extremely damaging climatic events. They perform what *Weitzman (2009)* defines in a debated paper (*see also Nordhaus 2009*) a "standard" cost benefit analysis. As shown by *Weitzman (2009)* the cost of a future irreversible event in the presence of uncertainty might be infinite. Accordingly, also the willingness to pay to avoid the risk of it can become infinite. This, translated into the context of deciding how much it is worth to mitigate or adapt, (and assuming that adapting to a catastrophe even though physically possible can be extremely costly), would implicitly support the idea that

uncertainty can shift the burden of climate change damage reduction from adaptation to mitigation. This analysis is not performed by Weitzman though.

A notable exception in this debate is *Ingham et al. (2005)*. They compound in a theoretical model mitigation adaptation and catastrophic outcomes. However they assume that adaptation can reduce the damage induced by catastrophic events and show that “event uncertainty” pulls up both the mitigation and adaptation investment. Thus mitigation and adaptation remain economic substitutes and the optimal mix between the two depends on their relative cost.

Another form of uncertainty can influence the mix between adaptation and mitigation: that of the geographical distribution of climatic damages. Damages are obviously region and site specific. However, even though some general regional patterns and dynamics are well understood (for instance higher vulnerability of low than mid, high latitudes, identified hot spots for sea-level rise or droughts and floods risk etc.) an exact prediction of where and with which intensity a given impact is going to hit is not possible. This is particularly concerning for some anticipatory adaptation practices entailing huge and almost irreversible upfront investments. Typical examples are coastal or river hard defenses. In these circumstances the private good nature of adaptation comes into play. Its benefits are fully appropriable by the community that implements adaptation, but the whole burden of a planning mistake also falls on the adapting community. Thus, in the presence of huge spatial uncertainty, anticipatory adaptation could be an unattractive option.

Mitigation on the contrary is a global public good: in principle one ton of CO₂ abated benefits the world as a whole irrespectively of where it is abated. When a planner decides to mitigate she knows that the damage will be reduced independently upon the location where it is going to manifest. In this sense mitigation is more mistake-free than adaptation.

This issue has not received great attention. In our knowledge it has been tackled just by *Lecocq and Shalizi (2007)*. Developing a simple theoretical model they conclude that spatial uncertainty enhances the importance of mitigation with regards to adaptation, as the first is global and accordingly only marginally determined by the local dimension of climate change damages, while, the second is more sector- and site- specific and thus extremely influenced by damage local specificities. This is the other topic we would like to investigate with our applied model.

3. Adaptation and Uncertainty Modeling

The modeling tool used to analyze mitigation, adaptation and uncertainty is an improved version of the basic Nordhaus and Yang (1996) RICE model. RICE-96 is a climate-economic hard-linked integrated assessment tool originally designed to find the optimal abatement effort under different cooperative or non-cooperative setting, in six major geo-political blocks: the United States (USA), Japan (JPN), the European Union (EEC), China (CHN), the Eastern Europe and Russia (FSU), and the rest of the world (ROW). The economic component is a standard Ramsey-Keynes growth model. It is linked to climate dynamics through the emission flow, by product of economic activity, which induces temperature increase. This on its turn impacts the economic system through a damage function translating warming into GDP losses. The model is fully dynamic: regional (or global) decision makers maximize aggregated

inter-temporal utility from consumption deciding investment and abatement rates. This structure has been enriched including the adaptation policy option building upon *Bosello (2010)*, then coupled in two different experiments with the risk of a catastrophic event, whose occurrence is uncertain to the policy makers, and with spatial uncertainty.

The complete structure of the model is reported in the Appendix. Below the description of the implementation of adaptation and of the two forms of uncertainty follows.

3.1 Adaptation Modeling and Calibration

Adaptation is modeled as a dedicated investment (IA), which cumulates over time subjected to a depreciation rate (the same of physical capital).

$$\mathbf{SAD}(\mathbf{n}, \mathbf{t}) = (1 - \delta_{IA}) * \mathbf{SAD}(\mathbf{n}, \mathbf{t} - 1) + \mathbf{IA}(\mathbf{n}, \mathbf{t}) \quad (1)$$

The resulting stock of adaptation capital (SAD) reduces climate damages decreasing the multiplicative coefficient $(1-\Omega)$ in the model climate change damage function.

$$\Omega = \mathbf{a}_1(\mathbf{n}, \mathbf{t}) * \frac{[1 - \mathbf{b}_1(\mathbf{t}) * \mathbf{b}_2(\mathbf{n}) * \mu(\mathbf{n}, \mathbf{t})^{\mathbf{b}_3(\mathbf{n})}]}{\left\{1 + 1/[1 + \mathbf{SAD}(\mathbf{n}, \mathbf{t})^2]\right\}} * \left[\frac{\mathbf{T}(\mathbf{t})}{2.5}\right]^{\mathbf{a}_2(\mathbf{n})} \quad (2)$$

According to (2) adaptation shows decreasing marginal returns to scale by construction. Adaptation investment competes with investment in physical capital, consumption and mitigation expenditure in the income budget constraint (3).

$$\mathbf{Y}_n(\mathbf{n}, \mathbf{t}) = \mathbf{C}(\mathbf{n}, \mathbf{t}) + \mathbf{I}(\mathbf{n}, \mathbf{t}) + \mathbf{IA}(\mathbf{n}, \mathbf{t}) \quad (3)$$

Mitigation costs, adaptation investments and the residual damage form the climate bill, which is the total cost of climate change.

Calibrating adaptation costs and benefits is problematic. Firstly it is not clear if the original RICE damage function includes optimal adaptation costs. If so, this would require to disentangle adaptation costs from that damage function as done for instance by *De Bruin et al. (2007, 2009)*; *Bosello et al. (2009)*. Even if it were so however, and this is the second problem, estimates of climate change damages and of adaptation costs are so uncertain that, given the present knowledge, it is very hard to justify any assumptions on the size of this optimal adaptation. What could be done is at best indicate some order of magnitude (*Agrawala and Fankhauser 2008*; *Nordhaus 2009*; *Parry 2009*). Thus in the present work rather than engaging into complex calculations to extrapolate from a basically unknown damage another unknown optimal adaptation expenditure, it is assumed that adaptation costs are not included in the original damage specification of the *RICE-96* model. Then the model is allowed to define its optimal adaptation level responding to local damages, but within some imposed reasonable “boundaries”. The reference point for the definition of these boundaries is a doubling of CO₂ concentration. When this happens, following *Tol et al. (1998)* and *De Bruin et al. (2007)* it is imposed that global adaptation expenditure ranges between 0.1 and

0.5% of GDP, and that the effectiveness of adaptation ranges between 30% - 80% of total damage.

Figure 1 displays the calibrated adaptation expenditure and effectiveness.

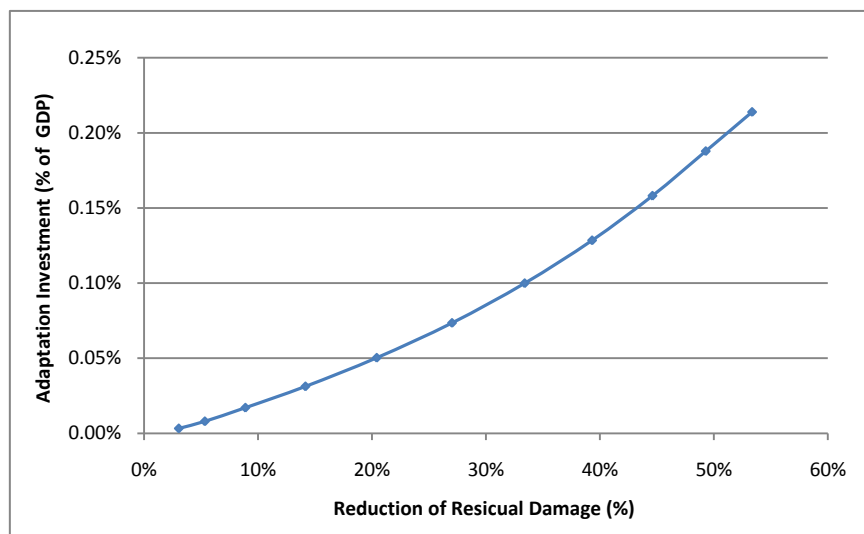


Figure 1 Effectiveness of Adaptation Investment

3.2 Event Uncertainty Modeling and Calibration

“Event uncertainty” is implemented through a failure distribution function of the duration of the climatic system i.e. the probability of the occurrence of the catastrophic event. It is denoted by a hazard rate which assumes a Weibull form (*Kiefer 1988*), a simple generalization of the exponential distribution.

$$P(t) = 1 - \exp\left(-\int_{T(0)}^{T(t)} \varphi_0 \eta [TE(t) - TE(0)]^{\eta-1} dTE\right) \quad (4)$$

(4) shows that the maintenance of the atmospheric temperature at the original level $T(0)$ eliminates the possibility of the occurrence of catastrophic events. Then, the higher the temperature increase, the higher the probability. This depends upon the two parameters φ_0 and η .

To keep the convexity of the hazard rate function, we assign η the value of 2.5 (*Gjerd et al. 1998*). φ_0 is calibrated in order to have a 7% probability to experience a catastrophe, i.e. a GDP loss equaling the 25% for a temperature increase of 3 °C above pre-industrial period. In our model this happens in 2100. The 7% probability is an upward revision of the 4.8% value proposed by *Nordhaus (1994)*, in view of more recent studies on the likelihood of catastrophic outcomes proposed by *Hadley Center (2005)* and *Tyndall Center (2005)*. According to both the probability of climate-induced catastrophes within this century are much higher: 30% for the shutdown of THC according to the first and 4% to 75% for a collapse of the Greenland ice sheet according to the second. This suggested us to increase by roughly 50% the initial *Nordhaus*’ estimate, leading us to a still “optimistic” catastrophic probability estimate of the 7%.

Catastrophic uncertainty affects decision making as the planner now maximizes an (intertemporal) expected utility function (5)

$$\begin{aligned} U = & \mathbf{P}(\mathbf{t}) * \sum_{\mathbf{t}} \sum_{\mathbf{n}} \left\{ (\mathbf{1} + \mathbf{R})^{10*(1-\mathbf{t})} * \boldsymbol{\omega}(\mathbf{n}) * \mathbf{L}(\mathbf{n}, \mathbf{t}) * \log \left[0.75 * \frac{\mathbf{C}(\mathbf{n}, \mathbf{t})}{\mathbf{L}(\mathbf{n}, \mathbf{t})} \right] \right\} \\ & + [\mathbf{1} - \mathbf{P}(\mathbf{t})] * \sum_{\mathbf{t}} \sum_{\mathbf{n}} \left\{ (\mathbf{1} + \mathbf{R})^{10*(1-\mathbf{t})} * \boldsymbol{\omega}(\mathbf{n}) * \mathbf{L}(\mathbf{n}, \mathbf{t}) * \log \left[\frac{\mathbf{C}(\mathbf{n}, \mathbf{t})}{\mathbf{L}(\mathbf{n}, \mathbf{t})} \right] \right\} \end{aligned} \quad (5)$$

In (5) utility is a weighted sum of its catastrophic and non catastrophic realizations, with weights given by the probability of the event occurrence. By mitigating the planner can lower the temperature increase and thus the probability of the catastrophic event, but of course it costs. In this formulation adaptation does not play any direct role in decreasing the catastrophic probability. It neither plays a role in decreasing the post catastrophic penalty on utility. The explicit assumption here is that a catastrophe is by definition beyond the adaptive capacity of the social economic system.

3.3 Spatial Uncertainty Modeling and Calibration

The second source of uncertainty considered is spatial uncertainty. It is modeled assigning to each of the model's region a vector of different possible damage parameters. For simplicity these are the six region specific damage parameters of the model. Thus each region is assigned a given probability to experience its own damage or that of each of the other five regions for a total of six possible states of the world. For simplicity it is also assumed that all the damage parameters are equally probable.

This replicates a situation in which the world planner (or the group of fully cooperating regional planners) does not know exactly with which intensity climate change damages are going to hit in the different regions. Accordingly she has to maximize an expected utility which averages across the six possible outcomes choosing one investment in physical capital, one investment in adaptation and one abatement level.

The utility function thus becomes:

$$U = \left(\frac{1}{6} \right) * \sum_{\mathbf{t}} \sum_{\mathbf{n}} \sum_{\mathbf{i}} \left\{ (\mathbf{1} + \mathbf{R})^{10*(1-\mathbf{t})} * \boldsymbol{\omega}(\mathbf{n}) * \mathbf{L}(\mathbf{n}, \mathbf{t}) * \log \left[\frac{\mathbf{C}_i(\mathbf{n}, \mathbf{t})}{\mathbf{L}(\mathbf{n}, \mathbf{t})} \right] \right\} \quad (6)$$

4. Results

Even though RICE is a regional model, results for the “event uncertainty” are displayed and analyzed for the world as a whole. The choice to focus on world results is motivated by their ability to convey the main messages coupled with the simplicity of exposition. Results for the “spatial uncertainty” are shown by region, but still assuming full world cooperation on climate policy. The choice of the cooperative setting is necessary to observe some mitigation effort (and thus to have the possibility to compare mitigation and adaptation with and without uncertainty). In a non-cooperative environment the public good nature of emission reduction and the associated free riding incentive imply an almost null abatement, unless a possible

catastrophe is imposed.

The BAU chosen for the simulation is that of the no policy A2 IPCC SRES scenario. On the one hand its storyline seems more plausible, even though rather pessimistic: it assumes the persistence of regional differences and an almost neutral technical change not too biased toward decarbonization of the economic systems. On the other hand current GHG emission trends are closer to that of the A2 IPCC SRES scenario than to other IPCC scenario family. Data for the benchmarking have been extracted from *CIESIN (2002)*, its GDP growths are reported in Figure 2.

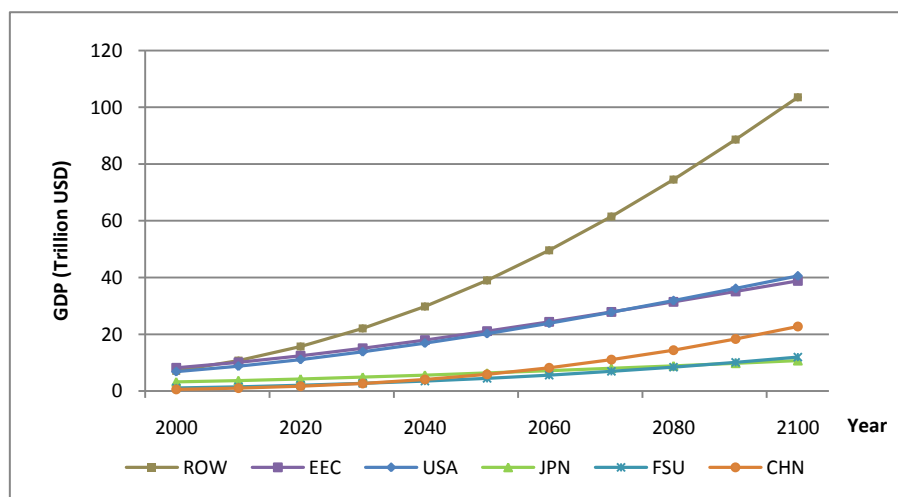


Figure 2 Regional GDP Projections

In addition to the BAU (denoted by (i) in figures) three other scenarios are proposed: mitigation adopted alone (denoted by (ii) in figures); adaptation adopted alone (denoted by (iii) in figures); joint implementation of mitigation and adaptation (denoted by (iv) in figures). Each of them is discussed first in a context of catastrophic and then of spatial uncertainty compared with the certainty case.

4.1 Mitigation and Adaptation under Event Uncertainty

Figures 3 and 4 show the effect of catastrophic uncertainty on mitigation and adaptation effort respectively.

In a certain world mitigation and adaptation confirm their strategic complementarity: both are used in an optimal climate change strategy as the possibility to introduce mitigation (adaptation) does not eliminate the need to adapt (mitigate). They also confirm, in line with the theoretical and empirical literature in the field (*Tol 2005; De Bruin et al. 2007, 2009; Bosello 2010*) the existence of a trade-off. The presence of adaptation reduces the need to mitigate whereas a successful mitigation reduces the amount of damage one needs to adapt to. Moreover mitigation and adaptation compete for scarce funding, thus more placed on one decreases the amount available to the other

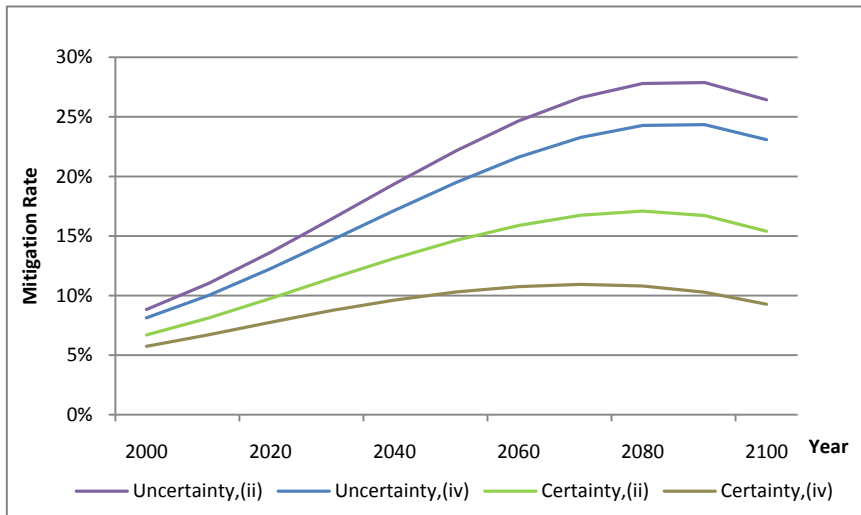


Figure 3 Optimal Mitigation Rate

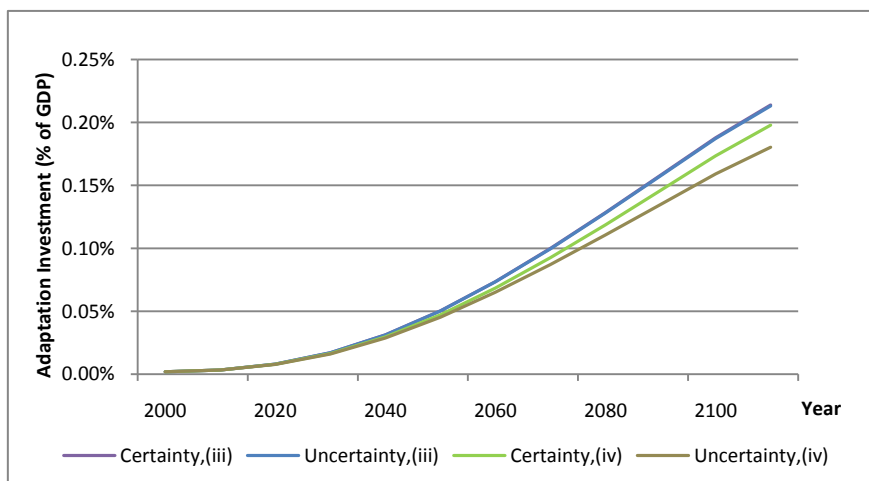


Figure 4 Optimal Adaptation Investment

When event uncertainty is introduced it pulls up, as expected, the optimal mitigation rate (by 51%, Fig. 3). On the contrary adaptation investment remains almost unchanged (Fig. 4). Since mitigation helps to reduce the probability of catastrophic events and adaptation can only control the non-catastrophic damage, a “catastrophic world” would require more mitigation, but not more adaptation. More mitigation reduces the probability of the catastrophic outcomes (Fig. 5) from the 7.2% to the 5.4%, which means that the temperature increase will be curbed from 3.2 °C to 2.7 °C in 2090.

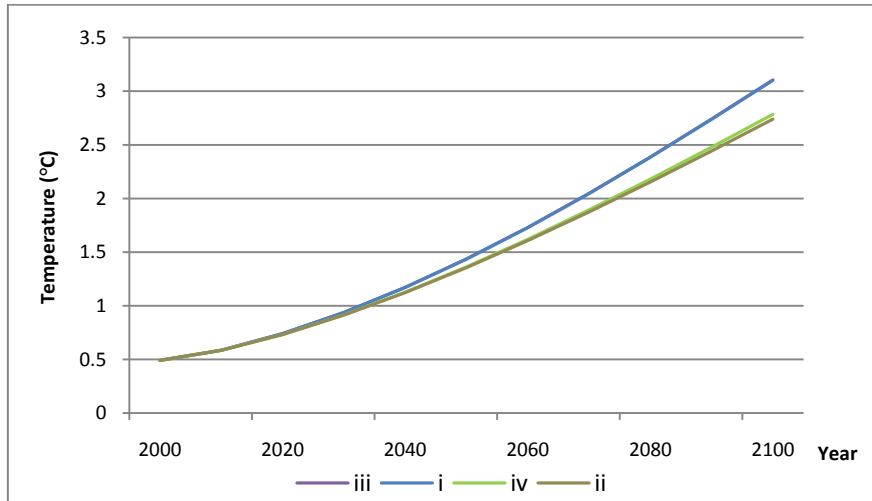


Figure 5a Temperature Increase

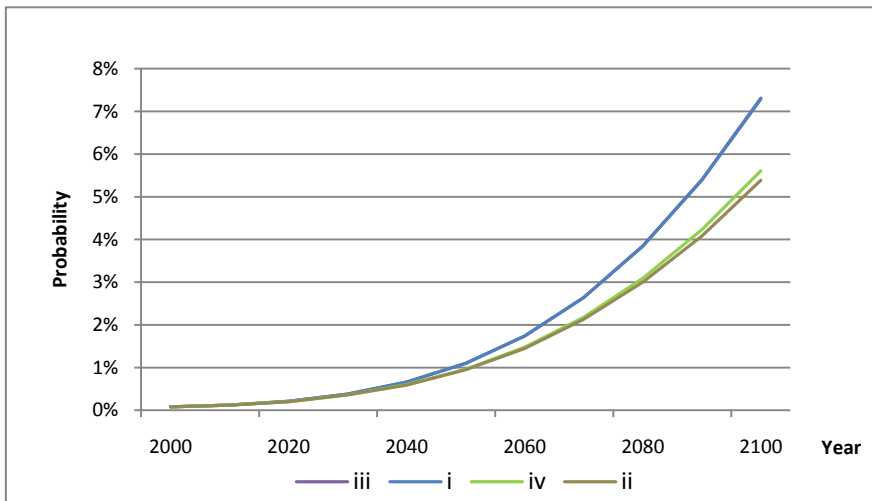


Figure 5b Probability of the Occurrence of Catastrophic Event

Even in the presence of an uncertain catastrophic event a certain degree of crowding out of adaptation on mitigation (and vice versa) still remains. Indeed part of mitigation effort still works to reducing the “smooth” damage component, and this action keeps on being influenced by adaptation activity. However, compared to the certainty case, the crowding out of adaptation on mitigation is greatly reduced (it is the 68% smaller in 2100), while that of mitigation on adaptation is amplified. This result is quantified also in Table 1 which computes the elasticity of mitigation with respect to adaptation and vice versa. Table 1 shows that the elasticity of mitigation to adaptation is smaller in the uncertainty than in the certainty case while that of adaptation to mitigation is larger.

Table 1 Elasticity between Mitigation and Adaptation

	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2010
<i>Certainty Case</i>											
Twice the Mitigation cost											
$\Delta IA/IA(\%)$	0	0.68	1.28	1.74	2.08	2.32	2.48	2.58	2.63	2.61	2.57
$\Delta\mu/\mu(\%)$	-30.94	-31.08	-31.24	-31.43	-31.66	-31.91	-32.18	-32.46	-32.74	-33.02	-33.33
Elasticity of IA to μ	0	-0.02	-0.04	-0.06	-0.07	-0.07	-0.08	-0.08	-0.08	-0.08	-0.08
Twice the Adaptation Cost											
$\Delta IA/IA(\%)$	-69.94	-65.76	-59.22	-50.98	-42.15	-33.66	-25.97	-19.16	-13.16	-7.89	-3.45
$\Delta\mu/\mu(\%)$	8.48	10.26	12.06	13.78	15.38	16.86	18.18	19.41	20.44	21.27	22.10
Elasticity of μ to IA	-0.12	-0.16	-0.20	-0.27	-0.36	-0.50	-0.70	-1.01	-1.55	-2.70	-6.41
<i>Uncertainty Case</i>											
Twice the Mitigation cost											
$\Delta IA/IA(\%)$	0	0.94	1.87	2.64	3.31	3.89	4.42	4.89	5.29	5.58	5.80
$\Delta\mu/\mu(\%)$	-30.62	-30.67	-30.73	-30.81	-30.93	-31.08	-31.26	-31.42	-31.61	-31.81	-31.99
Elasticity of IA to μ	0	-0.03	-0.06	-0.09	-0.11	-0.13	-0.14	-0.16	-0.17	-0.18	-0.18
Twice the Adaptation Cost											
$\Delta IA/IA(\%)$	-69.95	-65.79	-59.31	-51.17	-42.46	-34.09	-26.50	-19.79	-13.87	-8.68	-4.29
$\Delta\mu/\mu(\%)$	4.39	4.84	5.14	5.28	5.30	5.22	5.08	4.96	4.78	4.57	4.39
Elasticity of μ to IA	-0.06	-0.07	-0.09	-0.10	-0.12	-0.15	-0.19	-0.25	-0.34	-0.53	-1.02

This outcome highlights that in the presence of an uncertain catastrophic event, more adaptation offers a weaker incentive to reduce mitigation. Indeed even though adaptation decreases the “smooth” part of climate damage it cannot decrease the probability of the catastrophic occurrence. This is governed by temperature increase and thus by emissions that can be controlled only by mitigation.

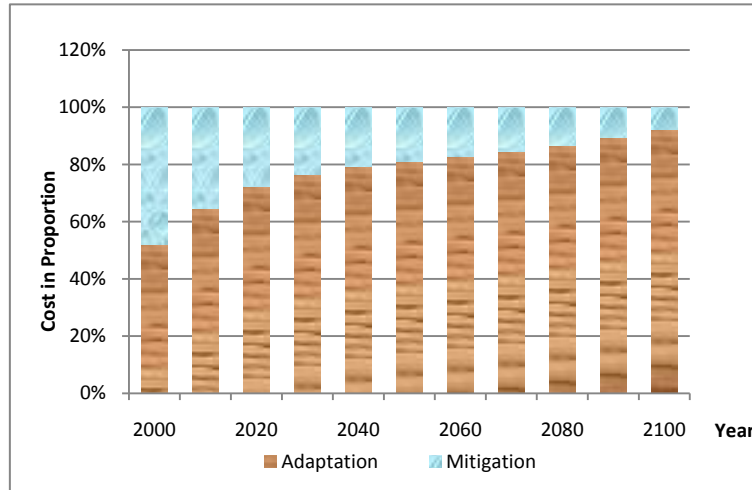


Figure 6 Optimal Expenditure Allocation across Mitigation and Adaptation: Certainty Case

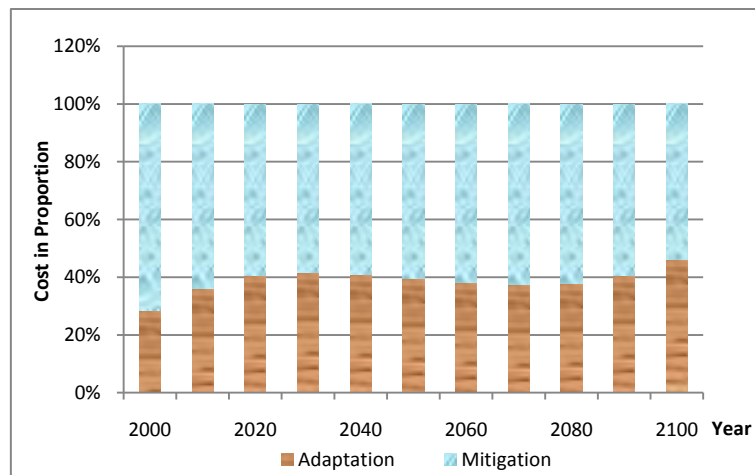


Figure 7 Optimal Expenditure Allocation across Mitigation and Adaptation: Uncertainty Case

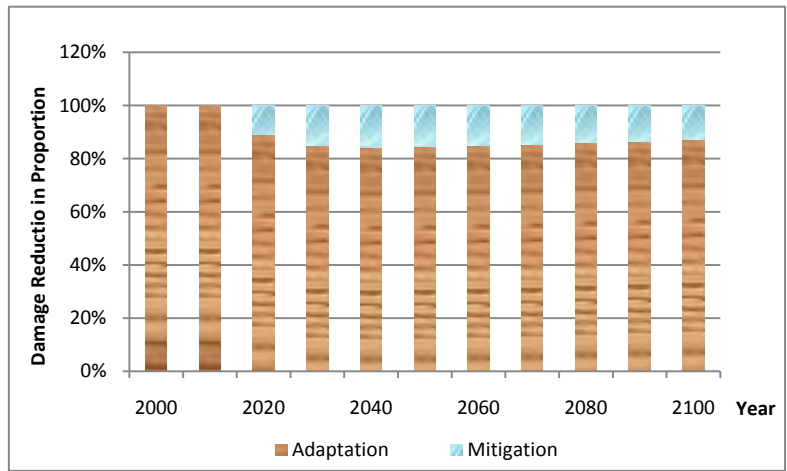


Figure 8 Proportion of Damage Reduction: Certainty Case

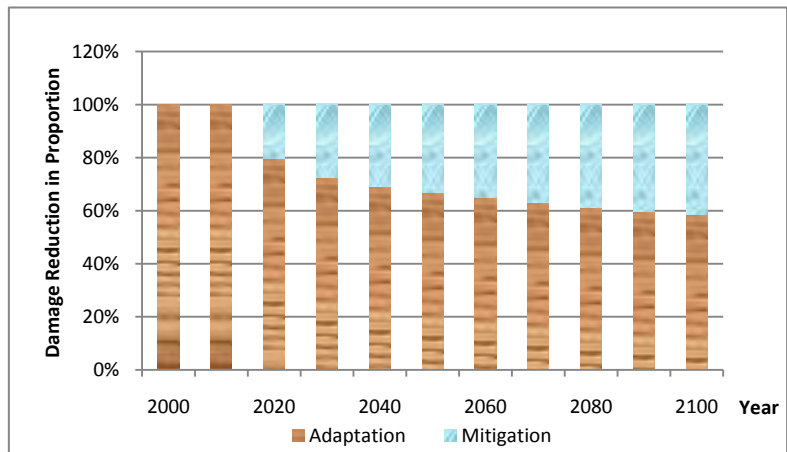


Figure 9 Proportion of Damage Reduction: Uncertainty Case

This translates into a drastically increased amount of resources devoted to mitigation than to adaptation (comparison of Fig. 6 and Fig.7) and to an evident, but more moderate increase of the percent of damage reduction due to mitigation with respect to adaptation (comparison of Fig. 8 and Fig. 9).

All these said it could be noted that adaptation remains the strategy relatively more effective in damage reduction. This however refers to the non catastrophic damage component. Indeed even though uncertainty roughly increases mitigation by 50% this then typically deploys its stronger effects with a delay, especially after the end of the century. Along the century adaptation still is the main damage reducer.

As an exercise it can be interesting to compare these results with the mitigation targets currently debated in the international context. In the framework of its climate change strategy the EU proposed a safety threshold for temperature increase of 2 °C with respect to pre-industrial levels within the century (*CEC 2007*). This target has been recently iterated in the 2009 Copenhagen Accord. Copenhagen, also proposed a set of non binding commitments by many countries ranging from explicit carbon reduction policies to carbon and energy efficiency targets. It has been estimated (*Carraro and Massetti 2010*) that if all these commitments were fulfilled and all the resources potentially mobilized were devoted to

mitigation the temperature increase could be kept below 2.5 °C (reasonably close to the goal of 2 °C). Our model would replicate such an outcome if, keeping the catastrophic probability at its calibrated level (7%) the related damage would be increased to roughly the 75% of world GDP, or conversely if, with a damage kept at its calibrated level (25%), the catastrophic probability would be increased to 30%, for a doubling of CO₂ concentration. These simple estimates constitute some “back of the envelope” calculations revealing the implicit risk perception of the policy decision maker that interestingly enough are close to the scientific perception.

To sum up, we find that compared with the certainty case, the event uncertainty pulls up the optimal level of mitigation; whereas the level of adaptation investment remains unchanged or even decreases. Accordingly, as far as the relationship of the two policies is concerned, the event uncertainty decreases the substitutability of adaptation with mitigation and increases the appeal of mitigation. This suggests an important policy implication. In a world characterized by smooth climatic damages mitigation is a marginal option, viable and welfare improving if coupled with adaptation, but anyway secondary if compared with what adaptation can cost efficiently achieve. In a world with catastrophic event uncertainty mitigation becomes the only strategy able to reduce the probability of the catastrophic outcomes and becomes the key policy variable. As a consequence mitigation should be decided at the outset on the basis of precautionary considerations (and not on “standard” cost-benefit approach based on perfect information) and adaptation has to be deployed to tackle the residual damage not accommodated by mitigation.

4.2 Mitigation and Adaptation under Spatial Uncertainty

In the presence of spatial uncertainty, the policy decision maker does not know exactly with which intensity climate change damage can hit a given region. The implication is an expected damage at the regional and at the world level which differ from those under certainty (Fig. 9 and Fig. 10). Differences however are more pronounced in the first than in the second case. Indeed, when the world is considered, higher expected damages in one region tend to be partially compensated by lower expected damages in another. Accordingly, expected damage at the world level differs from that under certainty by the 18% at maximum in 2100, while regional damages differ from the certainty case in a range between the -36% and 52% in 2100.

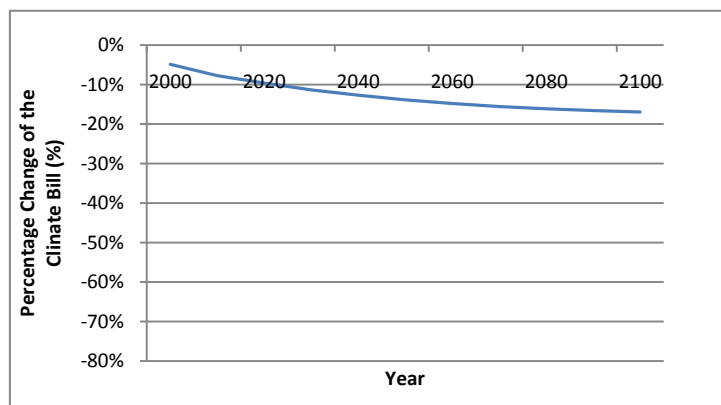


Figure 10 Percentage change of the expected global climatic damage w.r.t. certainty case

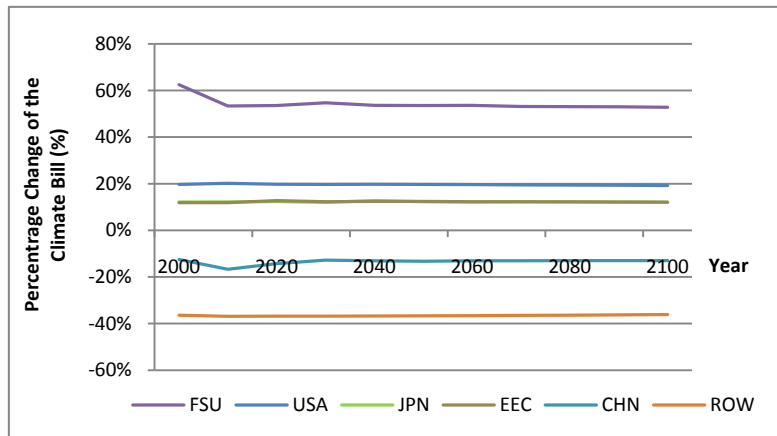


Figure 11 Percentage change of the expected regional climatic damage w.r.t. certainty case

Spatial uncertainty influences both mitigation and adaptation decisions, but the impact on mitigation differs from that on adaptation.

Mitigation is a global public good accordingly total abatement effort is driven by total climate change damage. This effort is then distributed across regions in order to equalize marginal abatement costs, but these are not affected by spatial uncertainty. The consequence is that the (moderately) reduced total damage at the world level induces a roughly uniform moderate reduction of abatement effort in each region of the model (roughly -2% see Fig. 12). Interestingly all regions reduce their abatement effort irrespectively of the fact that expected damages in some of these regions can increase.

Adaptation, on the contrary, is a private good. It tackles local damages and benefits the region that is adapting. Thus adaptation responds much more than mitigation to changes in regional damages. It increases when the expected damage increases and vice versa (see Fig. 13). More specifically, expected damages are higher in FSU, USA, JPN, EEC and lower in CHN and ROW and this is then mirrored by adaptive responses. Note also that changes in adaptation expenditure are larger than those in damages. This is the consequence of the interaction between mitigation and adaptation: under spatial uncertainty total mitigation effort is reduced and this pushes up adaptation.

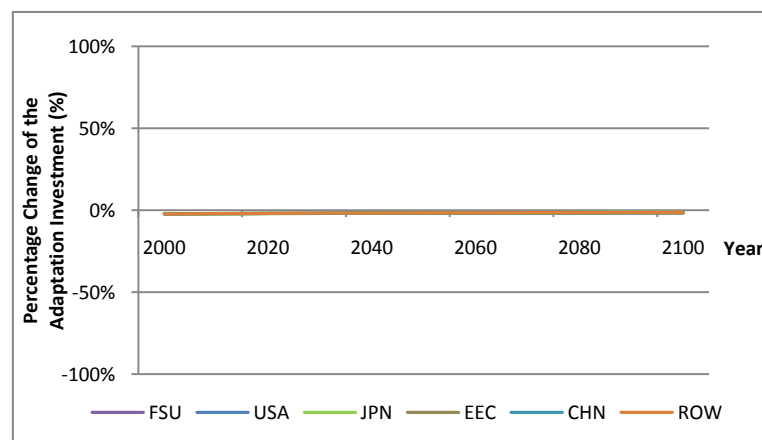


Figure 12 Percentage change of the optimal adaptation investment

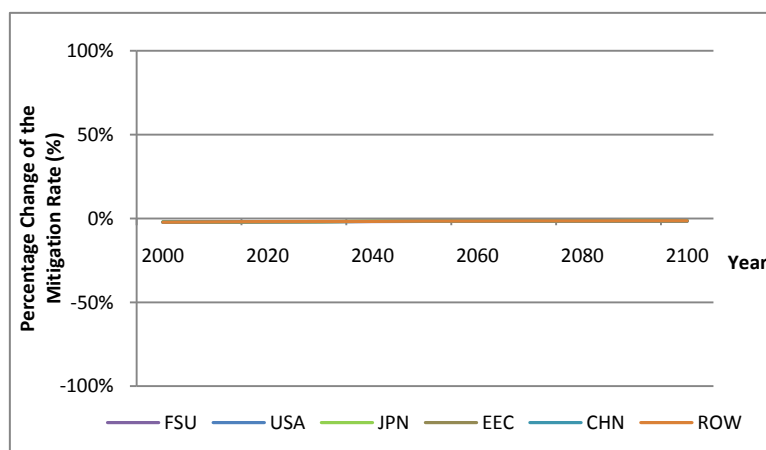


Figure 13 Percentage change of the optimal mitigation rates

To sum up, spatial uncertainty changes the damage distribution among the regions, hence changes the distribution of adaptation investments, which is implemented to reduce regional damages. By contrary, the expected damage at the global scale does not change as significantly as the regional damage, and the variation of the optimal mitigation rate is not as significant as that of adaptation investment.

This has also important policy implication. We cannot claim as suggested by *Lecoq and Shalizi (2007)* that spatial uncertainty increases the cost-effectiveness of mitigation respect to that of adaptation, and the need for mitigation should be strengthened. In fact spatial uncertainty can well increase considerably adaptation investment with respect to the certainty case, when there is a good probability to experience higher damages. Nevertheless we show clearly that optimal mitigation, designed to respond to global damages, is much less sensitive to spatial uncertainty than adaptation. Under this perspective, mitigation offers a “safer” or more robust strategy to a policy decision maker than adaptation. In other words in a spatial uncertainty context, a given mitigation policy can be expected to perform on average better, or to be revised less, than a given adaptation policy. This is an additional factor that should be considered, especially during international negotiation processes, in deciding mitigation efforts that can play in favor of mitigation compared to adaptation.

5. Conclusion

Mitigation and adaptation are two wings that support the policy maker in the struggle against climate change. While there is a broad consensus about the importance of both of them, there is still a significant knowledge gap in defining the effective optimal mix between mitigation and adaptation, their trade off and complementarities. Although a growing, albeit still thin literature addressed this issue using economic-climate-environmental integrated assessment models, none of them included explicitly uncertainty in the picture. The present work fills this gap by introducing two sources of uncertainty into the analysis: event uncertainty or the uncertain occurrence of a climate catastrophe triggered by temperature increase, and spatial uncertainty i.e. an imperfect knowledge on the geographic distribution of the climatic damage. We show that in both cases uncertainty works in the direction to make mitigation a more

advantageous strategy over adaptation, but because of different causes.

When event uncertainty is concerned mitigation becomes relatively more important than adaptation as, by curbing emissions, it helps to reduce temperature increase and hence the probability of the occurrence of the event. Adaptation has no impact on this. Therefore, the optimal mitigation rate is pulled up under the event uncertainty, while the adaptation investment is insensitive to it. In fact, the higher mitigation effort moderately decreases adaptation investment. Indeed mitigation and adaptation remain economic substitutes under event uncertainty: more adaptation decreases the need to mitigate and more mitigation that to adapt. However this crowding-out effect is much weaker if compared to that in the certainty case.

It is also shown that optimal mitigation responses are much less sensitive than adaptation responses to spatial uncertainty. Mitigation responds to global damages, while adaptation to local damages. The first, being aggregated, change less than the second in the presence of spatial uncertainty as higher expected losses in some regions are compensated by lower expected losses in other. Accordingly, mitigation changes less than adaptation. Thus if it cannot be really claimed that spatial uncertainty increases the weight of mitigation respect to that of adaptation, however its presence makes mitigation a “safer” or more robust strategy to a policy decision maker than adaptation.

This has important policy implications: in a world with climate-related catastrophic event uncertainty mitigation becomes the key policy variable as it is the only strategy able to reduce the probability of the catastrophic outcomes. As a consequence mitigation should be decided, possibly without delay, following precautionary considerations in the presence of discontinuity and irreversibility and not, or not only at least, following standard cost benefit analyses performed in a smooth/continuous damage context. Then adaptation can be deployed to tackle the residual damage not accommodated by mitigation. Investing on mitigation has another advantage: considering the difficulty to assess ex-ante the economic dimension of region-specific damages, it endows the policy decision maker with a tool which is more robust to uncertainty than adaptation. Therefore the policy decision maker can be confident that by mitigating the probability of a planning mistake is somewhat smaller. All what said obviously applies in the context of a global policy which aims to internalize climate externalities. In a non-cooperative world adaptation will remain the preferred strategy.

Appendix: The Structure of the Model

Sets

n: 1-5, regions, with reference to USA (the United States), EEC (the European Union), JPN (Japan), CHN (China), FSU (Former Soviet Nations), ROW (Rest of the World);

t: 1-12, time scale, 10 years as a unit; from 1990 to 2010;

Parameters

ω : utility weight for every regions;

R: discount rate;

γ : elasticity of output with respect to the capital stocks;

b_1, b_2, b_3 : parameters of the mitigation cost function;

a_1, a_2 : parameters of the damage function;

δ_K : depreciation rate of capital stocks;

δ_{IA} : depreciation rate of adaptation capital stocks;

c_1, c_2, c_3, c_4 : parameters of climatic equation;

λ : feedback parameter in climatic equation

σ : CO₂ emission/GDP ratio

ΔM : the removal rate of CO₂ stocks in the atmosphere;

θ : the retention rate of CO₂ stocks in the atmosphere;

η : parameter #1 of the hazard rate function of the catastrophic occurrence

ϕ_0 : parameter #2 of the hazard rate function of the catastrophic occurrence

Exogenous Variables

A: the Total Factor Productivity;

L: the population level;

F_0 : the exogenous forces of the greenhouse gases other than CO₂;

Endogenous Variables

U: aggregated utility level

Y_G : gross output (trillion dollars);

Y_N : net output (trillion dollars);

Ω : damage parameter;

C: consumption (trillion dollars);

I: capital investment (trillion dollars);

K: capital stocks (trillion dollars);

IA: adaptation investment (trillion dollars);

SAD: adaptation investment stocks (trillion dollars);

μ : mitigation rate ($0 \leq \mu \leq 1$);

E: CO₂ emission to the atmosphere (hundred million tons);

M: CO₂ stocks in the atmosphere (hundred million tons);

T: atmospheric temperature (°C);

T_0 : oceanic temperature (°C);

F: radiative force of the greenhouse gases in the atmosphere;

D: residual damage suffered from the climate change.

Equations

Aggregated Utility Equation

$$U = P(t) * \sum_t \sum_n \left\{ (1 + R)^{10*(1-t)} * \omega(n) * L(n, t) * \log \left[0.75 * \frac{C(n,t)}{L(n,t)} \right] \right\} \\ + [1 - P(t)] * \sum_t \sum_n \left\{ (1 + R)^{10*(1-t)} * \omega(n) * L(n, t) * \log \left[\frac{C(n,t)}{L(n,t)} \right] \right\} \quad (A1)$$

Economic Equations

$$Y_G(n, t) = A(n, t) * K(n, t)^\gamma * L(n, t)^{(1-\gamma)} \quad (A2)$$

$$Y_N(n, t) = Y_G(n, t) * \Omega \quad (A3)$$

$$\Omega = a_1(n, t) * \frac{[1 - b_1(t) * b_2(n) * \mu(n,t)^{b_3(n)}]}{\{1 + 1/[1 + SAD(n,t)^{\frac{1}{2}}]\}} * \left[\frac{T(t)}{2.5} \right]^{a_2(n)} \quad (A4)$$

$$C(n, t) = Y_N(n, t) - I(n, t) - IA(n, t) \quad (A5)$$

$$K(n, t) = (1 - \delta_K) * K(n, t - 1) + I(n, t) \quad (A6)$$

$$SAD(n, t) = (1 - \delta_{IA}) * SAD(n, t - 1) + IA(n, t) \quad (A7)$$

Climatic Equations

$$T(t) = T(t - 1) + c_1 * \{F(t) - \lambda T(t) - c_2 * [T(t) - T_0(t)]\} \quad (A8)$$

$$F(t) = 4.1 * \left\{ \ln \left(\frac{M(t)}{590} \right) / \ln 2 + F_0(t) \right\} \quad (A9)$$

$$E(n, t) = [1 - \mu(n, t)] * \sigma(n, t) * Y_G(n, t) \quad (A10)$$

$$M(t + 1) = 590 + \theta * \sum_n E(n, t) + (1 - \Delta M) * [M(t) - 590] \quad (A11)$$

Uncertainty Equation

$$P(t) = 1 - \exp \left(\int_{T(0)}^{T(t)} \varphi_0 \eta [TE(t) - TE(0)]^{\eta-1} dTE \right) \quad (A12)$$

Expected Damage Equation

$$D(n, t) = P(t) * 0.25 * Y_N(n, t) + [1 - P(t)] * Y_G(n, t) * (1 - \Omega) \quad (A13)$$

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