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"Mitigation, Adaptation, Suffering" : In search of the right mix in the face of climate change

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"Mitigation, Adaptation, Suffering" :
In search of the right mix in the face of climate change[1]

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ABSTRACT

The usually assumed two categories of costs involved in climate change policy analysis, namely abatement and damage costs, hide the presence of a third category, namely adaptation costs. This dodges the determination of an appropriate level for them. Including adaptation costs explicitly in the total environmental cost function allows one to characterize the optimal (cost minimizing) balance between the three categories, in statics as well as in dynamics. Implications are derived for cost benefit analysis of adaptation expenditures.

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1 A classical model

The simplest and most standard form of modeling that serves as a basis for the economic theoretic analysis of international environmental agreements on climate change is the following[3] :

$$J_i = c_i(e_i) + d_i(\Delta T) \quad \text{where} \quad \Delta T = F(e_1,...,e_i,...,e_n) \quad i = 1,...,n. \tag{1}$$

In this model (called hereafter the "c+d model"),

- the index i denotes all countries of the world,

- the variables $e_i \geq 0$ are the countries' flows of emissions of CO_2 "greenhouse gas",

- and ΔT is the resulting world temperature change fro some initial date, say 1800;

- the transfer function[4] $F(\, . \,)$ (assumed increasing) describes the highly complex process whereby greenhouse gas emissions induce temperature increases all around the globe,

- $c_i(e_i)$ is a function (assumed decreasing and convex) describing the cost to country i of its abatement decisions, that is, of *reducing* its emissions , also called "mitigation",

- $d_i(\Delta T)$ is a function (increasing and strictly[5] convex) that denotes the cost of the damages incurred by country i as a result of temperature change ,

- and finally J_i is the *overall environmental cost* borne by country i, adding up abatement and damage costs. All costs are measured in € per unit of time and all functions assumed to be differentiable.

When working with this standard model of *multilateral externality[6]* due to the phenomenon described by the function $F(.)$, the literature[7] considers two alternative patterns of behavior of the countries: in the first one, each country behaves so as to minimize its overall environmental cost J_i just defined by choosing in isolation emissions $\overline{e}_i$, and taking

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[3] It was formulated first by MÄLER 1988, in a slightly different form because the application was to the acid rains problem.

[4] While the simplified expression above prevents one to understand the details of that transformation, the stated function is sufficient to evoke the fact of the by now universally recognized influence of anthropogenic CO_2 emissions (and accumulation – more on this below) on temperature change.

[5] By assuming linear damage cost curves with intercept at zero, STERN 2007 (p459) precludes the analysis developed in this paper.

[6] Also to be characterized as a "global public good" due to the diffuse (as opposed to directional) nature of the way it occurs

[7] A non technical presentation of which is offered in EYCKMANS and TULKENS 2005.

as given the emissions $\overline{e}_j$ of the other countries: **a Nash type of behavior**. According to the second pattern, the countries choose jointly emissions e_i^* so as to minimize $\sum_{i=1}^{n} J_i$, that is, the sum of the countries' overall costs, and thus internalizing at the world level the multilateral externality occurring : **a Paretian behavior**.

In either case, a balance is struck between the costs of mitigation $c_i(e_i)$ and the costs of damages $d_i(\Delta T)$, which is easily obtained from the first order conditions of the maximization problems involved in the two alternative patterns of behavior. In the class-room simplifying case of a linear additive form $\Delta T = \sum_{i=1}^{n} e_i$ of the transfer function $F(.)$, these conditions look as follows:

— the Nash equilibrium is a vector $(\overline{e}_1,...,\overline{e}_n,\Delta\overline{T})$ such that

$$c_i'(\overline{e}_i) = d_i'(\Delta\overline{T}) , \ i=1,\ldots,n,$$

 or, in words, such that in each country abatement be pushed and damages be incurred up to the point where marginal abatement cost equals the domestic marginal damage cost, while

— Pareto efficiency is a vector $(e_1^*,...,e_n^*,\Delta T^*)$ such that

$$c_i'(e_i^*) = \sum_{j=1}^{n} d_j'(\Delta T^*) , \ i=1,\ldots,n,$$

 or, in words, such that abatement be pushed and damages be incurred up to the point where in each country marginal abatement cost equals the sum over all countries of their domestic marginal damage costs.

In summary, these conditions identify alternative levels for the mitigation activities, based on the damages they allow to avoid.

2 Introducing adaptation

There is an important difference in nature between the two categories of costs involved: while abatement costs are "out of pocket" expenditures resulting from voluntary decisions to abate, damage costs are rather incurred in terms of lost values, most often undergone involuntarily, and not resulting from expenditure decisions.

In this interpretation, the option of adaptation is not explicitly brought up, and some authors assert that it need not be because adaptation can be considered as implicit in the damage functions d_i (.). These should be seen, they argue, as net of adaptation expenditures. Yet, this eschews the issue of what is an appropriate level of adaptation, an important issue because adaptation activities are not free. Indeed, they entail out of pocket costs of their own, which vary with their size. On the other hand, what is the economic justification for adaptation expenditures? It essentially lies in their contribution to reducing the damages incurred or their cost, either by avoiding the physical damages or by circumventing their effects thanks to protection from their impacts.

Now, these adaptation costs can possibly be higher or lower than the damage cost reductions they are meant to achieve. They would obviously be justified only in the latter case, but to what extent? In this note, we provide an answer to that question, taking account of its effect on the countries' *overall* environmental costs stated above.

Adaptation is made explicit in the c+d model by:

(i)   Specifying in terms of an aggregate magnitude that we denote by $\alpha_i \geq 0$ the physical activities whereby a country i seeks to protect itself against the effects of global warming and by having them appear as the argument of an additional cost function $a_i(\alpha_i)$, increasing, that accounts for the adaptation expenditures made in country i.

(ii) Introducing α_i as an additional argument in the function d_i to make it read $d_i(\Delta T, \alpha_i)$, with the assumed properties that for every ΔT, $\partial d_i / \partial \alpha_i < 0$ and $\dfrac{\partial^2 d_i}{\partial \Delta T \, \partial \alpha_i} < 0$ while keeping $\partial d_i / \partial \Delta T > 0, \partial^2 d_i / \partial \Delta T^2 > 0$. The costs accounted for with this function do *not* include adaptation costs anymore, since these have just been stated separately with $a_i(\alpha_i)$. They are only costs incurred from damages undergone involuntarily as suggested above, for short "suffered damage costs" - see below). The two derivatives with respect to α_i imply respectively that more adaptation reduces not only the total

suffered costs incurred (graphically in the $\text{\euro}$-ΔT space, a shift downward of the whole curve) but also the marginal such costs (*i.e.* a reduction in the slope of the curve)[8].

We then have three sources of costs, and these lead us to modify the usual expression (1) for the *overall environmental cost* of each country into the following function with three terms:

$$J_i = c_i(e_i) + a_i(\alpha_i) + d_i(\Delta T,\ \alpha_i) \quad \text{where} \quad \Delta T = F(e_1,...,e_i,...,e_n). \tag{2}$$

These three sources of costs are precisely those that come to the mind of an economist when reading, as in our title: "*Civilization has only three options: mitigation (…), adaptation (…) and suffering (…)*". With this trilogy John Holdren (2008, p. 430) compactly and beautifully summarizes what *can* be done in the face of climate change.

He pursues with what I read as a direct challenge to economists that we hardly can leave unanswered: *"We are already doing some of each and will do more of all but what the mix will be depends on choices that society will make going forward"*. Within the above framework and with the help of some economic theory we feel we can enlighten these choices in the direction of what *should* be done or, in other terms, what would be the "right" mix. One way to do that in the c+d framework is to abandon the ambiguous "damage cost" terminology used for $d_i(\Delta T)$ in the function (1), split the function instead into the two components of "adaptation cost" $a_i(\alpha_i)$ and "suffered damage cost"[9] $d_i(\Delta T,\alpha_i)$ and approach in those terms the right mix question.

3 Optimal adaptation

Notice first the two opposing roles played by the adaptation variable α_i in the second and third terms of the new overall cost function (2): increasing and decreasing, respectively. This suggests that when we introduce adaptation in the minimization, a balance is also struck between these two aspects of it. More precisely, the first order condition for a minimum of J_i with respect to α_i is that it satisfies

$$da_i / d\alpha_i\ +\ \partial d_i(\Delta T,\alpha_i) / \partial\alpha_i\ =\ 0. \tag{3}$$

In words:

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[8] The justification of this second property will appear below as a condition for α to be positive at an optimum.
[9] We prefer this expression to the one of "residual" damage cost, proposed by STERN 2007 and used in DE BRUIN, DELLINCK and TOL 2007.

Proposition 1 : *Adaptation is achieved optimally in a country if it is pushed up to a level where the cost to the country of more adaptation becomes equal to the value of the suffered costs thereby avoided.*

Beyond its apparent banality, notice the following properties of the rule so established:

(i) Condition (3) holds for both Nash and Paretian behaviors, since they both result from some form of global cost minimization.

(ii) The rule applies to each country separately: the optimality condition is a purely domestic one. There is neither an international externality nor a global public good involved [10].

(iii) The condition holds true for any level of ΔT.

(iv) The condition is independent of the abatement policy e_i of country i, but it varies with the state ΔT of the environment.

Of course, properties *(i), (iii)* and *(iii)* do not imply that the total amount of optimal adaptation expenditure is the same in the various occurrences where the marginal occurrences hold.

A further interest lies in what the rule allows one to say conceptually, and to do in practice, when it is *not* satisfied in one or several countries. Let us consider first the conceptual developments.

4 An « optimally adapted » damage cost function

Let $\alpha_i{}^*$ be the amount of adaptation activities that satisfies the minimization condition (3) for some country i. Unless $d_i(\Delta T, \alpha_i)$ is separable, this magnitude is likely to vary as a function of ΔT. It should therefore rather be written as $\alpha_i{}^*(\Delta T)$. As a result, the second and third terms of (2) may be seen as a function of ΔT only and read together as

$$h_i{}^*(\Delta T) = a_i(\alpha_i{}^*(\Delta T)) + d_i(\Delta T, \alpha_i{}^*(\Delta T)) \tag{4}$$

with the asterisk reminding one that adaptation is optimal at any point along the function. We shall call $h_i{}^*(\Delta T)$ country i's "optimally adapted" damage cost function.

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[10] Unless, of course, an adaptation activity carried out in one country has spillover effects in one of several neighboring ones. This can be accommodated in condition (3) in a fairly straightforward way, but entails amendments in the reasoning that follow.

Graphically (Figure 1), the function $h_i^*(\Delta T)$ appears as an envelope of a family of suffered damage cost functions $d_i(\Delta T, \alpha_i)$ as defined earlier. In the space $(\text{\euro}, \Delta T)$, the graphs of these functions differ from one another according to the amount of adaptation expenditure and level of these activities $a_i(\alpha_i)$ chosen by the country. Formally, the difference between these functions results from a difference in costs that are fixed with respect to ΔT. This is similar to differences between alternative short run cost functions enveloped by the long run one in standard microeconomics. This analogy is pursued further by noticing that with every (fixed) adaptation expenditure $a_i(\alpha_i)$ there is logically associated a specific suffered cost function $d_i(\Delta T, \alpha_i)$, variable with ΔT and where α_I is a parameter. Hence, for any given ΔT the optimal adaptation expenditure is the one whose associated suffering cost function is tangent, at the point ΔT, to the envelope of all possible suffering cost functions.
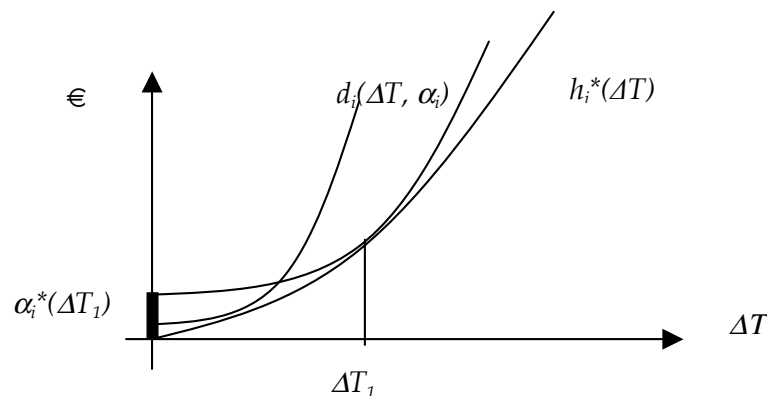

Figure 1 Two suffered damage cost functions "enveloped" by an optimally adapted damage cost function

From the tangency points in this diagram there emerges an interesting property: for any given level of temperature change, say ΔT_1, the optimal adaptation expenditure $a_i(\alpha_i^*(\Delta T_1))$ is the one for which:

$$\left. \frac{dh_i^*(\Delta T)}{d\Delta T} \right|_{\Delta T = \Delta T_1} = \left. \frac{\partial d_i(\Delta T, \alpha_i^*(\Delta T))}{\partial \Delta T} \right|_{\Delta T = \Delta T_1} . \tag{5}$$

In words,

Proposition 2 : *The marginal adapted damage cost entailed by temperature change is equal to the marginal suffering costs* **only** *and does not include costs of adaptation.*

This results from taking into account the optimality condition (3) on α in the specification of the marginal *adapted* damage cost which is derived from (4). Indeed, and more explicitly, from this condition one has (dropping momentarily the arguments of the functions, to alleviate, as well as the subscript *i* which is immaterial here) :

$$
\begin{aligned}
\frac{dh^*}{d\Delta T} &= \frac{da}{d\alpha}\frac{d\alpha}{d\Delta T}\bigg|_{\alpha=\alpha^*} + \frac{\partial d}{\partial \Delta T} + \frac{\partial d}{\partial \alpha}\frac{d\alpha}{d\Delta T}\bigg|_{\alpha=\alpha^*} \\
&= \frac{d\alpha}{d\Delta T}\bigg|_{\alpha=\alpha^*}\left(\frac{da}{d\alpha} + \frac{\partial d}{\partial \alpha}\right) + \frac{\partial d}{\partial \Delta T} \\
&= \frac{\partial d}{\partial \Delta T} \; .
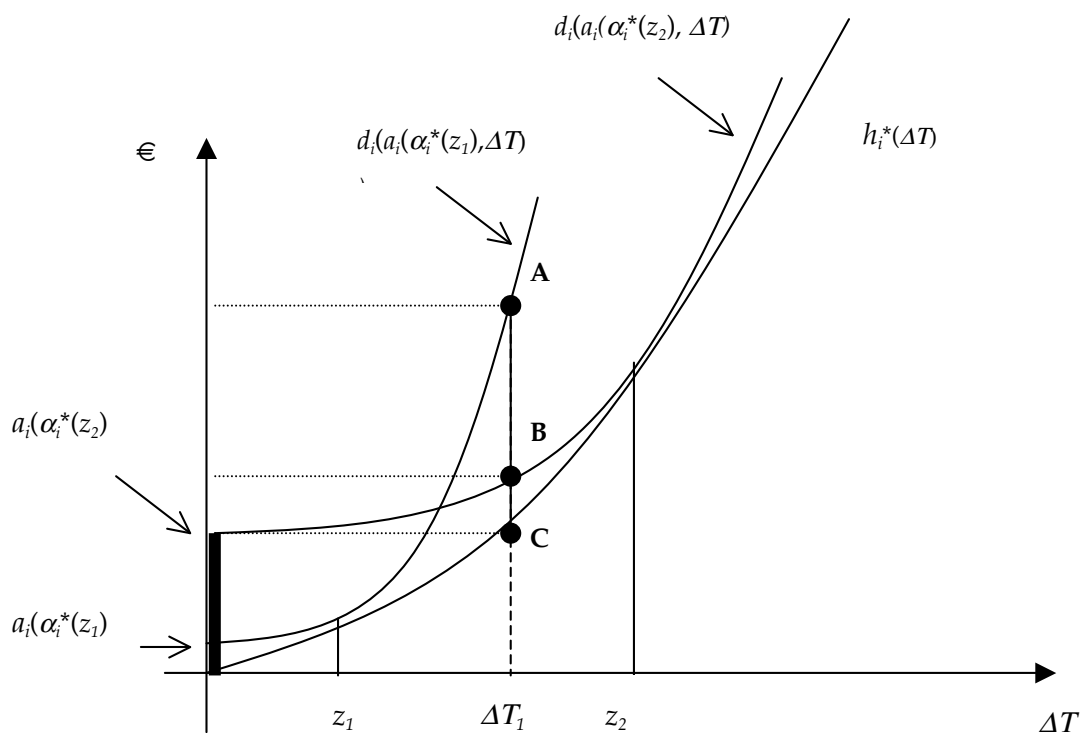\end{aligned}
$$

Figure 2   Two suffered damage cost functions $d_i(a_i, \Delta T)$ with non optimal adaptation for target ΔT_1 and damage cost function optimally adapted for all ΔT

In the presentation of Figure 2, non optimal adaptation is illustrated in the following way. Taking ΔT_1 as a target or alternatively as the prevailing situation, that is, as the temperature change to be achieved or actually occurring, if adaptation expenditure a_i is equal to $a_i(\alpha_i^*(z_1))$, then country i adapts too little, the excess cost (of suffering) being AC at the target. A hint of this is given by the fact that at C, whose abscissa is the target, the marginal suffering cost is higher than what it would be if adaptation were larger. Therefore, adapting more costs less than the suffering cost it saves. Alternatively, if a_i is equal to $a_i(\alpha_i^*(z_2))$, country i adapts too much, the excess cost at the target being BC at the target. Here, a sign of excess adaptation is that at the target the additional suffering cost from adapting less is of lower value than the savings made from reducing adaptation activities.

5   The right mix — Static case

Going back now to our initial query of identifying the "right" amounts of mitigation, adaptation and suffering, let us reconsider it in the light of what we have developed so far. Everything is now driven by the newly defined overall environmental cost function (2). With optimal adaptation α_i^* it reads:

$$J_i^* = c_i(e_i) + a_i(\alpha_i^*(\Delta T)) + d_i(\Delta T,\ \alpha_i^*(\Delta T))$$

$$= c_i(e_i)\ +\ h_i^*(\Delta T)$$

and may be called the *optimally adapted overall environmental cost function.* Its further minimization with respect to mitigation (e_i), and temperature change (ΔT) yields the right mix in the following terms:

— In the case of the Nash equilibrium, a vector $(\bar{\bar{e}}_1,...,\bar{\bar{e}}_n,\bar{\bar{\alpha}}_1,...,\bar{\bar{\alpha}}_n,\Delta\bar{\bar{T}})$ such that for every i,

$$\left.\frac{dc_i(e_i)}{de_i}\right|_{e_i=\bar{\bar{e}}_i} = \left.\frac{dh_i^*(\Delta T)}{d\Delta T}\right|_{\Delta T=\Delta\bar{\bar{T}}},\ i=1,...,n,$$

$$= \left.\frac{\partial d_i}{\partial\Delta T}\right|_{\Delta T=\Delta\bar{\bar{T}}}$$

and

$$\left.\frac{da_i}{d\alpha_i}\right|_{\alpha_i=\bar{\bar{\alpha}}_i} = \left.\frac{\partial d_i(\Delta T,\alpha_i(\Delta T))}{\partial\alpha_i}\right|_{\alpha_i=\bar{\bar{\alpha}}_i}$$

— In the case of Pareto efficient behaviors, a vector $(e_1^{**},...,e_n^{**},\alpha_1^{**},...,\alpha_n^{**},\Delta T^{**})$ such that for every i,

$$\left.\frac{dc_i(e_i)}{de_i}\right|_{e_i=e_i^{**}} = \sum_{i=1}^{n} \left.\frac{dh_i^*(\Delta T)}{d\Delta T}\right|_{\Delta T=\Delta T^{**}}, \quad i=1,...,n,$$

$$= \sum_{i=1}^{n} \left.\frac{\partial d_i}{\partial \Delta T}\right|_{\Delta T=\Delta T^{**}}$$

and

$$\left.\frac{da_i}{d\alpha_i}\right|_{\alpha_i=\alpha_i^{**}} = \left.\frac{\partial d_i(\Delta T,\alpha_i(\Delta T))}{\partial \alpha_i}\right|_{\alpha_i=\alpha_i^{**}}.$$

In words, we have

Proposition 3 : *The right mix of mitigation, adaptation and suffering is the one such that in all countries:*

— marginal emissions abatement cost be equal to marginal suffering cost entailed by temperature change (domestic or global, according to the behavior considered), and

— marginal adaptation cost be equal to marginal domestic suffering cost avoided thanks to such adaptation.

6. **Adaptation over time: investment and the optimal stock of adaptation equipment**

The preceding analysis is entirely formulated in static terms, which means that all variables represent flows per unit of time. However, most examples of adaptation activities that come to mind imply investments in infrastructural equipments such as, for instance, dikes to protect against sea level rise. It is therefore essential to show whether and how the analysis can be extended to a dynamic context involving investment in protective physical capital of all kinds.

To proceed in this way, let us think in discrete time, with unit periods denoted $t = 1,2,...$. The climatic change ΔT_t that takes place at time t entails at that moment suffered damages for country i whose value is d_{it}, expressed in €/time unit. The adaptation activities, which allow to attenuate these damages can take various forms. Some are "ephemeral" in the sense that they only reduce d_{it} at time t itself, whereas other ones are durable and exert their protective effects over several time periods. In the first case, the protective activities are

flows, and we denote them α_{it}, whereas in the second case, they consist in accumulating in country i [11] a stock of protective equipments — in fact, a capital — whose amount at time t we denote B_{it}. Its durability over time is expressed by specifying :

$$B_{it} = B_{it-1}(1-\delta_\beta) + \beta_{it} \tag{6}$$

where β_{it} is the addition made to the stock at time t and δ_β is the depreciation rate of the stock during period t. The value of this last parameter varies of course according to the nature of the equipments involved, as well as with their life time. Here, we limit ourselves to a reasoning in aggregate terms, without ignoring that a disaggregate formulation, in terms of projects, is necessary for making policy relevant proposals. Our last section will go in that direction.

Let us denote by $b_i(\beta_{it})$ the expenditure entailed in country i by the addition β_{it} of protective equipments at time t. As far as the suffered damages are concerned, the existing stock of protective equipment now enters the damage cost function d_i, next to the flow of ephemeral protective activities, as follows:

$$d_{it} = d_i(\Delta T_t, \alpha_{it}, B_{it}), \tag{7}$$

the function being decreasing in its last two arguments.

The above leads us to redefine at each period t the overall environmental cost (2) of country i as

$$J_{it} = c_i(e_{it}) + a_i(\alpha_{it}) + b_i(\beta_{it}) + d_i(\Delta T_t, \alpha_{it}, B_{it}) \tag{8}$$

$$\text{where } B_{it} = B_{it-1}(1-\delta_\beta) + \beta_{it}$$

$$\text{and } \Delta T_t = G(T_{t-1}, e_{1t}, ..., e_{it}, ..., e_{nt}),$$

whose four components represent the four cost categories of mitigation, short term and long run adaptation and suffered damages, respectively[12].

The variable α_{it} — the ephemeral (short term) actions of adaptation — plays, within each period t, the same opposite two roles as in the preceding static analysis. One can thus similarly define at each t a specific optimally adapted overall environmental cost, that is, a cost including ephemeral adaptation expenditures α_{it}^* that verify :

$$da_i/d\alpha_{it} + \partial d_i/\partial\alpha_{it} = 0, \quad t = 1,2,... . \tag{9}$$

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[11] The qualification mentioned in footnote 7 above applies.
[12] The schematic temperature transfer function is modified here to account for the essentially dynamic nature of climate models which involve CO_2 accumulation.

A parallel role is played by the stock of equipments trough the variables involved in durable adaptation, namely the level of the stock B_{it} and the flow of periodic additions to it β_{it}. While the latter increase expenditures at time *t*, the former reduces the cost of suffered damages: there is thus a tradeoff, like before. However, the formulation of optimality conditions is more complex for two reasons. First, the reduction of damages resulting from each action β_{it} spreads over several future periods: to account completely for the benefit so obtained the analysis must become an intertemporal one, identifying for projects or equipments decided at time *t* the reduction in suffered damages occurring at each period $\tau =$ *t, t+1, t+2,…* of their life time. This brings about another dimension of the issue under consideration, namely that investments in adaptive protection do not necessarily take place once and for all, but instead can be realized, and in fact are, in terms of programs extending over several time periods. Therefore what is at stake at each *t* is not just one investment decision β_{it} but rather a sequence of them β_{it}, β_{it+1}, β_{it+2},…,β_{iT} — in other words an investment program where *T* is the horizon planning of the decision maker.

Optimality in durable adaptation equipments is then to be formulated at each time *t* in terms of an investment program, combined with ephemeral adaptation activities that solves:

$$\underset{\{\alpha_{i\tau},\,\beta_{i\tau}\}_{\tau=t}^{T}}{Min} \quad \sum_{\tau=t}^{T}\gamma^{\tau}[\ a_i(\alpha_{i\tau}) + b_i(\beta_{i\tau}) + d_i(\Delta T_t,\,\alpha_{i\tau},\,B_{i\tau})\ ] \tag{10}$$

$$\text{where } B_{i\tau} = B_{i\tau-1}(1-\delta_\beta) + \beta_{i\tau},$$

$$\Delta T_\tau = G(T_{\tau-1}, e_{1\tau},...,e_{i\tau},...,e_{n\tau}),$$

and γ>0 is a discount factor. Let $\alpha_{it}^*,\alpha_{it+1}^*,\alpha_{it+2}^*,...,\alpha_{iT}^*$, $\beta_{it}^*,\beta_{it+1}^*,\beta_{it+2}^*,...,\beta_{iT}^*$ be the solution to (10). The first order conditions that characterize this solution obviously satisfy (9) and also imply that at each *t* the adaptation investment β_{it}^* made at that time in country *i* satisfies

$$db_i/d\beta_{it}\ +\ \sum_{\tau=t}^{T}\gamma^{\tau-t}(1-\delta_\beta)^{\tau-t}\partial d_i/\partial B_{i\tau}\ =\ 0. \tag{11}$$

In words, *at any point in time t investment in adaptation is optimal only if at the margin its cost is equal to the value discounted at time t of the future suffered damages it will allow to avoid.*

After introducing these investment levels in the function (8) as well as the ephemeral activities α_{it}^* satisfying (9), the overall environmental cost of country *i* at time *t*, with both short run and long run optimal adaptation, reads:

$$J_{it}^* = c_i(e_{it}) + a_i(\alpha_{it}^*(\Delta T_t)) + b_i(\beta_{it}^*) + d_i(\Delta T_t, \alpha_{it}^*(\Delta T_t), B_{it}^*) \tag{12}$$

$$\text{where } B_{it}^*(\Delta T_t) = B_{it-1}(1-\delta_\beta) + \beta_{it}^*$$

and $\Delta T_t = G(T_{t-1}, e_{1t}, ..., e_{it}, ..., e_{nt})$.

Intuitively, and as it was the case with (2), an envelope property links in (12), at each *t*, the second and fourth terms of this function. In terms of Figures 1 and 2, the presence of B_{it}^* in the suffered damage function d_i(.) just shifts its graph upwards or downwards.

7 Conclusion: implications for integrated assessment modeling and cost-benefit analysis .

In most static as well as dynamic models, introducing adaptation in the damage cost functions leads to expressions such as J_i^* where adaptation is indeed implicit. I derive from this, and from the above explicitation of this practice, four implications for future policy modeling and decisions.

1°) In all IAMs (Integrated Assessment Models), the optimality condition on *emissions* is always, for each country, the equality of abatement marginal cost with damage marginal cost[13]. Is that just damage costs incurred, or does it include adaptation expenditures? Equality (5) teaches us that *if adaptation is optimal*, only undergone "suffering" costs are to be taken into account, without adding anything from adaptation expenditures. This does not mean that adaptation expenditure are to be ignored in general, but well, instead, that they mist be handled "separately", taking good care of whether their size indeed meets the conditions (3) or (9) — see 3° below.

2°) Therefore, it should always be examined in detail in all Integrated Assessment models whether or not they have included adaptation, as well as whether the amount of expenditure for it is an appropriate one.

3°) Most importantly, condition (3) and intertemporal conditions (9) and (11) for optimal adaptation may be considered as *a reference to guide the evaluation of investment projects in adaptation equipments,* as well as the selection among them when they are numerous.

The method to be followed is roughly the following: for every project under consideration at time *t*, the expenditure it requires may be assimilated to the first term of the equalities (9) or (11), depending upon the nature of the project – a fairly easy task. By contrast, the numerical evaluation of the right hand sides of these equations, for each individual project, is a major

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[13] Domestic in the case of "positive" Nash equilibrium, collective in the case of "normative" Pareto efficiency.

challenge, although an inescapable one if economic rationality is to prevail in the decision to adopt or discard projects. Bundling projects may of course be considered in the same spirit.

The conditions referred to are formulated in terms of "marginal" magnitudes (because they are determined by functions which are assumed to be differentiable). But of course, each project is a discrete unit. This does not put in question the relevance of applying the optimality conditions stated above, for the following two reasons:

— We are working here at a scale where each project is small with respect to the total investments involved;

— Solving the optimization problem that leads to (3), and (9) - (11) can be done in terms of an algorithm of gradual adjustment of the variables involved towards minimum cost, adjustment operating in discrete time. At each stage of this algorithm, each project, if adopted because the benefits it entails (the value of the damages it allows to avoid) is larger than its out of pocket cost, may be interpreted as a step towards this minimum.

4°) Resource transfers between countries are advocated in the literature for moving from Nash equilibria to Pareto efficiency. While most often designed as lump sum transfers, they could instead be earmarked and exclusively devoted to adaptation expenditures so as to have (3) and (9)-(11) achieved. See NORDHAUS and YANG 2006.

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In summary, these considerations are meant to be just a methodological introduction to cost-benefit analysis as applied to adaptation. Further work in this area should unquestionably take its inspiration from the second volume of IPCC 2007 which contains plenty of examples of application.

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