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3rd International Workshop on

INTEGRATED CLIMATE MODELS:
AN INTERDISCIPLINARY ASSESSMENT OF
CLIMATE IMPACTS AND POLICIES

12-13 January 2006
ICTP, Trieste, Italy

WHY ECONOMIC DYNAMICS MATTER IN ASSESSING CLIMATE CHANGE DAMAGES: ILLUSTRATION ON EXTREME EVENTS

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Why economic dynamics matter in assessing climate change damages: illustration on extreme events

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Abstract

Extreme events are one of the main channels through which climate and socio-economic systems interact, and it is likely that climate change will modify the probability distribution of the losses they generate. The long-term growth models used in climate change assessments, however, cannot capture the effects of such short-term shocks. To investigate this issue, a non-equilibrium dynamic model (NEDyM) is used to assess the macroeconomic consequences of extreme events. This exercise allowed us to define the *economic amplification ratio*, as the ratio of the overall production loss due to an event to its direct costs. This ratio could be used to improve the cost-benefit analysis of prevention measures. We found also that, unlike a Solow-like model, NEDyM exhibits a bifurcation in GDP losses: for each value of the capacity to fund reconstruction, GDP losses remain moderate if the intensity and frequency of extremes remain under a threshold value, beyond which GDP losses increase sharply. This bifurcation may partly explain why some poor countries that experience repeated natural disasters cannot develop. Applied to the specific issue of climate change, this model suggests that changes in the distribution of extremes may entail significant GDP losses in absence of specific adaptation. It suggests, therefore, that to avoid inaccurately low assessments of damages, researchers must take into account the distribution of extremes instead of their average cost and make explicit assumptions on the organization of future economies.

Key words: Economic Dynamics, Extreme events, Economic impacts, Climate Change

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1 Introduction

Modelers who assess economic impacts of climate change face a dilemma that has been very frankly presented by William Nordhaus (1997): *"After 500 years, [global average temperature] is projected to increase 6.2 °C over the 1900 global climate. While we have only the foggiest idea of what this would imply in terms of ecological, economic, and social outcomes, it would make most thoughtful people – even economists – nervous to induce such a large environmental change. Given the potential for unintended and potentially disastrous consequences, it would be sensible to consider alternative approaches to global warming policies."* It is thus not only outsiders of mainstream economics (*e.g.*, Azar and Schneider, 2003) who question the legitimacy of the very low percent of GDP losses estimated by the published assessments of climate change damages (*e.g.*, Peck and Teisberg, 1992; Nordhaus, 1998; Mendelsohn et al., 2000; Tol, 2002a,b), and the consequently unambitious optimal abatement trajectories prescribed by these studies.

Part of the problem comes from the fact that the quantification of impacts is still in its infancy. The third assessment report of the IPCC (IPCC, 2001a) highlights that many important sectors are not considered by published studies. Taking into account these neglected sectors may modify significantly the assessment of overall climate change damages. Also, most studies evaluating optimal abatement trajectories envisage only certainty cases, in which we know exactly the future climate. Ambrosi et al. (2003) showed, however, that inserting uncertainty about climate sensitivity in stochastic optimal control models suffices to justify significant departures from reference emissions trends, even if the most-likely damage level remains moderate.

But another part of the problem may lie in the description of the law of motion of the economic growth. Since resorting to long-term growth model was made necessary by the time horizon of the climate change issue, the professional reflex of economists was unsurprisingly to rely on extensions of the Solow model (*e.g.*, Nordhaus, 1994). These models, however, describe economies moving along balanced pathways and readjusting easily to exogenous shocks. They consequently neglect the fact that welfare losses resulting from a given amount of climate change impact may be drastically different, would it fall on healthy economies or on economies weakened by various disequilibria or experiencing inertia in their readjustment process.

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This paper aims at framing the orders of magnitude at stake. It compares economic consequences of a given climate impact falling on economies similar in all respects, except that one follows an equilibrated growth pathway while the other experiences transient disequilibria. We take extreme events in Europe as an example, because they are one of the most documented channels through which climate and economy interact, and because the order of magnitude of this interaction is significant enough to support an aggregate analysis.

In the first section we present a model, NEDyM (Non-Equilibrium Dynamic Model), which reproduces the behavior of the Solow model over the long term, but which allows for disequilibria during the transient process. The second section explains how available information about *large-scale extreme weather events* (including uncertainty about their occurrence) can be translated in economic terms. The third section describes the calibration and validation of NEDyM and the three following sections apply NEDyM and present comparative exercises.

2 A Dynamic Model to capture unbalanced growth pathways

NEDyM models a closed economy, with one representative consumer, one producer, and one good, used both for consumption and investment [1] . This very aggregate representation presents the drawbacks of the absence of sector-based or geographical differentiation; but it has the advantage of being very similar to the Solow model. This makes it easy to reproduce the 'after shock' behavior of a Solow model and to compare it with the behavior of an economy with transition difficulties towards the same 'after shock' equilibrium. We thus ignore possible hysteresis effects in order to focus on the 'pure' transition mechanisms.

We explain below the main changes applied to the basic Solow model, starting with its core set of equations where Y is production; K is productive capital; L is labor; A is total productivity; C is consumption; S is consumer savings; I is investment;Γ_{inv} is the investment (or, equivalently, saving) ratio; τ_{dep} is the depreciation time; and L_{full} is the labor at full-employment:

$$\frac{dK}{dt} = I - \frac{K}{\tau_{dep}} , \tag{1}$$

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[1] A comprehensive description of NEDyM is available online. URL: www.centre-cired.fr/forum/rubrique.php3?id_rubrique=71

$$Y = f(K, L) = AL^{\lambda}K^{\mu} \ , \tag{2}$$

$$C + I = Y \ , \tag{3}$$

$$L = L_{full} \ , \tag{4}$$

$$S = \Gamma_{inv} Y \ , \tag{5}$$

$$I = S \ . \tag{6}$$

NEDyM introduces the following changes to this generic structure:

(1) *Goods markets*: a goods inventory G is introduced, opening the possibility of temporary imbalances between production and demand instead of a market clearing at each point in time ($Y = C + I$, Eq. (3)):

$$\frac{dG}{dt} = Y - (C + I) \ . \tag{7}$$

This inventory[2] encompasses all sources of delay in the adjustment between supply and demand (including technical lags in producing, transporting and distributing goods). The goods inventory situation affects price movements:

$$\frac{dp}{dt} = -p \cdot \left(\alpha^1_{price} \cdot \frac{Y - (C + I)}{Y} + \alpha^2_{price} \cdot \frac{G}{Y} \right) \ . \tag{8}$$

Note that price adjustments operate non-instantaneously: the equality of production and demand is verified only over the long term, and the delay in price adjustments breaks this equality over the short term.

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[2] The goods inventory can be either positive or negative. It should be interpreted as the difference with an equilibrium value or, when divided by production, as the opposite of a *delivery lag*. A positive value indicates temporary overproduction and can be interpreted as the time necessary to sell the production. A negative value indicates underproduction and can be interpreted as the time necessary for a consumer to get the goods he or she ordered. Such formalism also allows the model to account for services, which are a large part of the current economy and which cannot be stocked.

(2) *Labor market*: the producer sets the optimal labor demand L_e that maximizes profits as a function of real wage and marginal labor productivity:

$$\frac{w}{p} = \frac{df}{dL}(L_e, K) \; . \tag{9}$$

But full-employment is not guaranteed at each point in time such as in Eq. (4) ($L = L_{full}$), (i) because institutional and technical constraints create a delay between a change in the optimal labor demand and the corresponding change in the number of actually employed workers:

$$\frac{dL}{dt} = \frac{1}{\tau_{empl}}(L_e - L) \; ; \tag{10}$$

and (ii) because wages are rigid over the short-term. Indeed, wages increase (resp. decrease) if labor demand is higher (resp. lower) than the equilibrium level L_{full}, progressively restoring the equilibrium employment rate:

$$\frac{dw}{dt} = \frac{w}{\tau_{wage}} \frac{(L - L_{full})}{L_{full}} \; . \tag{11}$$

(3) *Household behavior*: as in Solow (1956), NEDyM uses a constant saving ratio but it makes the tradeoff between consumption and saving ($S = \Gamma_{inv} Y$, Eq. (5)) more sophisticated by considering that households (i) consume C, (ii) make their savings available for investment through the savings S, and (iii) hoard up a stock of money M.

(4) *Producer behavior*: instead of automatically equating investments and savings ($I = S$, Eq. (6)), NEDyM describes an investment behavior "*à la* Kalecki (1937)" and introduces a stock of liquid assets held by banks and companies. This stock is filled by the difference between sales $p(C + I)$ and wages (wL) and by the savings received from consumers (S). These liquid assets are used to redistribute share dividends[3] (Div) and to invest (pI). This formulation creates a wedge between investment and savings.

$$\frac{dF}{dt} = p(C + I) - wL + S - Div - pI \; . \tag{12}$$

The dynamics of the system is governed by an investment ratio which allocates these liquid assets between productive investments and share dividends:

$$I = \Gamma_{inv} \cdot \frac{1}{p} \cdot \alpha_F F \; . \tag{13}$$

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[3] In this stylized model, the share dividends represents all gains of investors: redistributed dividends, revenues from bonds, sales of assets, capital gains, spin-offs to shareholders, repurchase of shares, payments in liquidation, payoffs resulting from merger or acquisition, and awards in shareholders' lawsuits.

Symbol	Description	Steady state	2001 EU-15 observed values
Y	production (=demand)	9	8.8
L	number of employed workers	93%	92.6 %
wL	total annual wages	6	5.6
C	consumption	7	6.8
S	available savings	2	1.8
Div	share dividends (*i.e.* all investor's gains)	3	3.2
I	physical investment	2	1.8

Table 1
NEDyM steady state (net flows) and EU-15 economic variables in 2001 according to Eurostat (2002). Values are in thousands of billions of euros.

$$Div = (1 - \Gamma_{inv}) \cdot \alpha_F F \; . \tag{14}$$

This ratio ensures that the redistributed dividends satisfy an exogenous required return on equity ρ demanded by the shareholders. This describes a specific growth regime under which producers invest the amount of funds available when the required amount of dividends have been paid [4].

$$\frac{d\Gamma_{inv}}{dt} = \begin{cases} \alpha_{inv}(\gamma_{max} - \Gamma_{inv}) \cdot \left(\frac{Div}{p \cdot K} - \rho\right) & \text{if } \frac{Div}{p \cdot K} - \rho > 0 \\ \alpha_{inv}(\Gamma_{inv} - \gamma_{min}) \cdot \left(\frac{Div}{p \cdot K} - \rho\right) & \text{if } \frac{Div}{p \cdot K} - \rho \leq 0 \end{cases} . \tag{15}$$

2.1 Calibration and Dynamic properties of NEDyM

The model is calibrated so that the benchmark equilibrium is the economic balance of the European Union in 2001(EU 15), assuming that the economy was then in a steady state. Table 1 compares the value of this steady state with the observed values from Eurostat (2002). Note that this steady state is consistent with a Solow-like growth model with a constant savings ratio set at $\Gamma^*_{save} = 22\%$.

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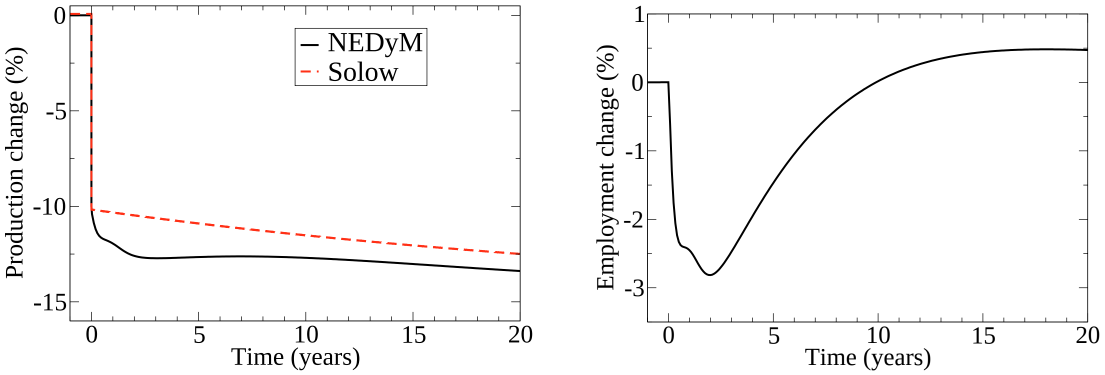
[4] Of course, other economic regimes are possible, for example a regime in which the priority is given to investments: in such a "managerial economy", producers redistribute to shareholders the amount of funds available when all profitable investments have been funded.



(a) Production

(b) Employment rate

Fig. 1. Model response to a 10% decrease in productivity, for NEDyM and the Solow model. Over the long term, both models have the same final state.

2.1.1 Balanced growth and transient pathways

With a regular growth rate of productivity A of 2% per year, the model follows a conventional pathway: production increases by 3% a year; and real wages and real capital incomes grow regularly under full employment.

To understand better the model response to shocks, let us consider NEDyM and its 'Solowian' equivalent, both without productivity growth, and let us compare how they react to a 10% instantaneous decrease of the productivity coefficient A, starting from an identical equilibrium and, in the absence of hysterisis, ending in the same steady state.

Figure 1, which displays the responses of both models, show that the transient frictions are responsible for a stronger shock in NEDyM than in the Solow model.

The underlying mechanism in NEDyM is as follows. Production decreases instantaneously after the shock on productivity, and this decrease is amplified by the fact that, because of price and wage rigidities, a lower labor productivity leads to a lower employment rate. In parallel, the decrease of profits reduces the re-invested share of savings. The resulting reduction in consumption and investment lead to a Keynesian amplification of the initial shock. At the apex of the crisis peak two years after the productivity shock, unemployment is 3% higher than its equilibrium level. Employment returns to equilibrium 10 years after the shock as a result of the labor market adjustment, and is followed by a slight overshoot due to inertia. In the Solow model instead, the wage adjustment is assumed instantaneous, which explains the large difference between the short-term responses of the two models.

The new steady state is reached about 50 years after the shock in NEDyM, mainly because of the slow adjustment in the productive capital. This 50-year characteristic time of the economy in NEDyM has to be compared with the 100-year characteristic time of the Solow model. This difference is due to the investment ratio adjustment in response to price signals, which is possible in NEDyM, but not in the Solow model: in the present experiment, the investment ratio decreases by 22%, and the overall physical investment by 30%.

If productivity is reduced by the same 10%, but progressively instead of instantaneously, the NEDyM behavior aligns more closely with the Solow behavior, as the productivity decrease is slower. While an instantaneous decrease in productivity yields, at the crisis peak, an underemployment increase of 3% and an investment ratio decrease of 22%, a 20-year progressive decrease of productivity yields only an underemployment maximum increase of 0.5% and an investment ratio decrease of 5%. If the productivity is decreased over 40 years, underemployment only increases by less than 0.2% and the investment ratio by 3%. At the infinite limit, if the time scale of the productivity decrease is much longer than the model time scales, there is no additional underemployment nor changes in the investment ratio. In that latter case, NEDyM is equivalent to the Solow model.

3 Modeling economic impacts of Large-scale Extreme Weather Events (LEWE)

There is no strict scientific definition of Large-scale Extreme Weather Events (LEWE); they are rather characterized by their media impact and their capacity to generate sudden and large social concerns [5] . We will however define them as rare climate events causing important capital destructions over time periods ranging from one day (cyclones) to several weeks (floods).

Less media-impressive gradual changes (*e.g.* a progressive ill-adaptation of infrastructure and housing (Hallegatte et al., 2005)) may ultimately be responsible for larger damages than extreme events. We concentrated however on the latter because they attract attention to the linkages between short-run responses to shocks (capital destruction, break-down of essential services like electricity or drinking water) and long-term dynamics. Another reason is that they are both poorly represented in current integrated assessment models (Goodess et al., 2003) and far more documented than other types of climate impacts.

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[5] Examples of such events are the 2002 floods in Germany or the recent landfall of Katrina in New Orleans.

Insurance and re-insurance companies keep records of damages caused by major weather catastrophes. According to Munich-Re (2003), their frequency increased by a factor 4.4 between the 1960s and the 1990s and the corresponding economic losses by a factor 7.9. These statistics reflect, primarily, a better reporting of disasters and the existence of more assets in vulnerable places (*e.g.* coastal areas). Assuming that the distribution of extremes did not change significantly since the sixties (IPCC, 2001b, chp. 2) leads to a multiplication by 1.8 of the mean economic losses per event, corresponding to an increase of 2% per year of the cost of the representative LEWE. This figure is close to the economic growth rate over the period, suggesting that, even though frequencies increased, natural intensities are constant and costs increases as the income level.

Obviously, climate change is likely to significantly modify economic costs of LEWEs. Even without changes in the frequency and intensity of strong storms, changes in their mean trajectory would suffice to cause higher damages by impacting regions not currently adapted to them. There are also good reasons why meteorological conditions that are considered as extremes today will become more frequent. Beniston (2004) suggests that the exceptional heat wave in Europe in 2003 could be a good proxy for the average summers in the latter part of the 21^{th} century. This prediction is also supported by Fig. 2, from Déqué (2004a). Along the same line, Déqué (2004b) predicts the number of days during which the maximum daily temperature exceeds 30°C for at least 10 consecutive days will increase by a factor 20 in 2071-2100. This is caused in part by the higher mean temperature, but also by an increase of the temperature variability (up to 100% in 2100) predicted by regional climate models (Schär et al., 2004). The same type of concerns exist about the occurrence of severe summertime flooding in Europe (Christensen and Christensen, 2003), or about the destructiveness of tropical cyclones (Emanuel, 2005; Webster et al., 2005).

This body of research explains why Choi and Fisher (2003) suggests that the annual precipitation increase with a doubling of atmospheric CO_2 concentration would increase U.S. losses due to flooding by about 100% to 250% and losses due to hurricanes by 150% to 300%. Dorland et al. (1999) found that a 6% increase in the wind intensity could lead to a 500% increase in average annual damages in Netherlands.

Without denying the interest of such insights we will not incorporate them directly in our numerical exercise because such studies are still incomplete and because of the difficulties in correlating changes in the characteristics of LEWE weather and their consequences. Since our objective is not an in-

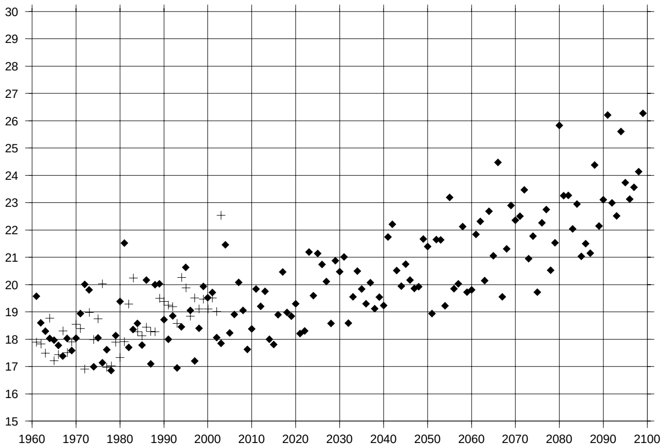

Fig. 2. Observed summer mean temperature (in °C) over France from 1960 to 2003 (crosses), and the corresponding prediction from ARPEGE-Climat up to 2100 (diamonds). According to this model, the extreme heatwave over France in 2003 becomes usual from 2070. Figure by Michel Déqué, from Déqué (2004a).

depth discussion of how changes in frequency, intensity and unitary damages of natural phenomena will affect their direct costs, we will assume that existing data provide orders of magnitude meaningful enough for the objectives of this paper.

3.2 Definition of LEWE in numerical experiments

We focus here on four types of LEWE: floods, winter storms (and the corresponding storm surges), droughts and heat waves. Following Katz et al. (2002), we characterize them through three criteria: (i) a minimum threshold for the magnitude of economic losses, (ii) the occurrence probability of a LEWE exceeding this threshold over a period of one month; (iii) the probability density function of the losses due to one LEWE.

3.2.1 Level of the threshold

According to Munich-Re (2004) or Swiss-Re (2004), floods in Germany in 2002 caused direct damages [6] amounting to 10 G$, spread out between infrastructures(4 G$), trade & industry (2 G$), household (2 G$) and others (2 G$). According to the same source, the Mississippi floods in 1993 in the US caused 18 G$ losses and the winter'99 windstorms over Europe around 20 G$ losses (Munich-Re, 2002). Swiss-Re (1998) shows that the Netherlands exhibits a 30 to 60 billions US$ flood damage potential and a 100 billions US$ damage potential in case of storm surge. The flash-floods in the south of France are

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[6] All these figures represent only direct losses.

at the other end of the spectrum of events that are considered as catastrophic with a typical cost around 1 G$ per event(*e.g.* Nimes, 1999). Given these orders of magnitude we set the minimum threshold for an LEWEs at 0.01% of the GDP of the EU 15, which corresponds to damages amounting to 0.80 G$.

3.2.2 Probability of occurence

Taking the last 20 years as representative of the statistical distribution of climate events and assuming that their distribution was stationary during this period and that they are independent, the probability of occurrence over one month of a weather event causing more than 0.800 G$ of losses is $p_{EE} = 0.06$ according to the Munich Re data. For simplicity sake, we assume that there is at most one LEWE in one month, even though examples exists of the contrary (*e.g.* the two winter-storms in Europe in December 1999).

3.2.3 Probability density function

There is evidence that LEWE natural intensity probability exhibits a power tail (Katz et al., 2002). The link between LEWE natural intensity and the corresponding economic losses, however, is still a very open question. No direct relationship can be established for two reasons: (i) losses do not increase regularly with natural intensity, but involve thresholds, one being the maximum economic loss potential of each impacted area, that cannot be exceeded even though LEWE natural intensity increases[7]; (ii) progressive adaptation measures will reduce LEWE costs as their frequency or intensity is augmented.

A power tail of the losses pdf is, however, consistent with what appears in Figure 3, that shows the probability density of single-LEWE economic losses, ranked in four categories based on Munich-Re's assessments.

Therefore, to work with a tractable function, we will assume in the following that the probability density function (pdf) tail of the LEWE economic losses follows a Weibull distribution and is given by (for $s > s_{EE}$).

$$f_{\beta,\chi}(s) = \beta \cdot \chi^{\beta} \cdot (s - s_{EE})^{\beta-1} \cdot exp\left(-\left(\chi(s - s_{EE})^{\beta}\right)\right) \tag{16}$$

The fit gives $\chi = 0.897933333$ and $\beta = 0.000178672$, and the corresponding Weibull distribution is reproduced in Fig. 3. This function fits to existing statistics reasonably enough for our exercise[8].

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[7] An evaluation of such potential of losses for some extreme events and some regions is proposed by Swiss-Re (1998)

[8] To assess the sensitivity of our results to changes in the distribution function, we

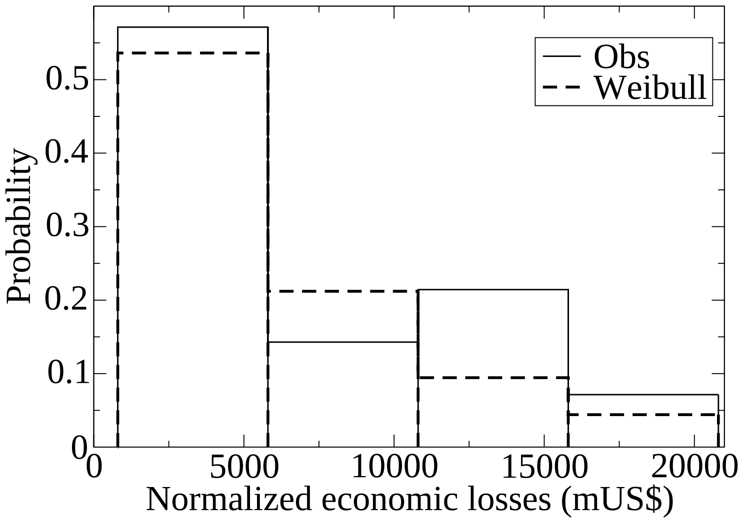

Fig. 3. Histogram of weather event probability with respect to its economic losses, in 4 ranges, for the observations (*Obs*) and the fitted Weibull distribution f_ζ (*Weibull*).

3.3 Modeling costs of capital losses

Disasters mainly destroy the stock of productive capital and a natural modeling option to represent their consequences is to consider that they reduce instantaneously the total productive capital ($K \longrightarrow K - \Delta K$). This option amounts to treating an after-disaster economy as equivalent to an economy in which past investments were lower. Such an hypothesis, hereafter referred to as *H1*, would however introduce three biases for impact assessment: (1) it amounts to assuming that only the less efficient capital is destroyed by a disaster; (2) it does not distinguish between productive investments and reconstruction investments; and (3) it does not take into account the constraints that slow down the reconstruction process. We will now discuss these biases and propose modeling solutions to avoid them.

(1) Since most production functions exhibit decreasing returns, considering an after-disaster economy as equivalent to an economy in which past investments were lower amounts to assuming that capital destruction would affect only the less efficient capital. Indeed, in a Cobb-Douglas function ($Y = AL^\lambda K^\mu$) the "after LEWE" production would be $Y_1 = AL^\lambda (K_0 - \Delta K)^\mu$, and a $x\%$ loss of equipment would reduce the production by less than $x\%$ (see Fig. 4).

To account for the fact that LEWEs may affect a range of capital stock,

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also tested a linear fit (see below).

we modified the Cobb-Douglas production function by introducing a term ξ_K, which is the proportion of non-destroyed capital. The variable ξ_K is such that the *effective capital* is $K = \xi_K \cdot K_0$, where K_0 is the *potential productive capital* in absence of LEWE, and the new production function is[9]:

$$Y_2 = \xi_K \cdot f(L, K_0) = \xi_K \cdot A \cdot L^\lambda \cdot K_0^\mu \tag{19}$$

This new production function is such that a $x\%$ destruction of the productive capital reduces production by $x\%$ (see dashed-line in Fig. 4). The replacement of the productive capital K by the two new variables K_0 and ξ_K makes it necessary to modify the modeling of investment, which leads us to the second bias we mentioned.

(2) In our first representation, there was no distinction between the investments devoted to increase capital stocks and reconstruction investments, in spite of their difference in nature[10]. Denoting now I_n the investments that increase the potential capital K_0, and I_r the reconstruction investments that increase ξ_K, we can write:

$$\frac{dK}{dt} = \frac{d\xi_K}{dt} \cdot K_0 + \xi_K \cdot \frac{dK_0}{dt} = I_r + \left(I_n - \frac{1}{\tau_{dep}} \cdot K \right) , \tag{20}$$

which leads to:

$$\frac{\partial K_0}{\partial t} = \frac{-1}{\tau_{dep}} K_0 + \frac{I_n}{\xi_K} \tag{21}$$

$$\frac{\partial \xi_K}{\partial t} = \frac{I_r}{K_0} \tag{22}$$

Assuming that, when $\xi_K < 1$, investments are first devoted to replace the destroyed capital — because these investments have higher returns

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[9] We rewrite the Cobb-Douglas production function as:

$$Y = f(L, K_0) = \int_0^{K_0} \partial_2 f(L, k) \cdot dk \,, \tag{17}$$

where $\partial_2 f$ is the derivative of f with respect to the productive capital. To describe a situation where equipments are equally affected independently of their productivity, we adopted the following specification:

$$Y = \int_0^{K_0} \partial_2 f(L, k) \cdot \xi_K \cdot dk = \xi_K f(L, K_0) = \xi_K \cdot A \cdot L^\lambda \cdot K_0^\mu \tag{18}$$

[10] This distinction has been introduced by Albala-Bertrand (1993).

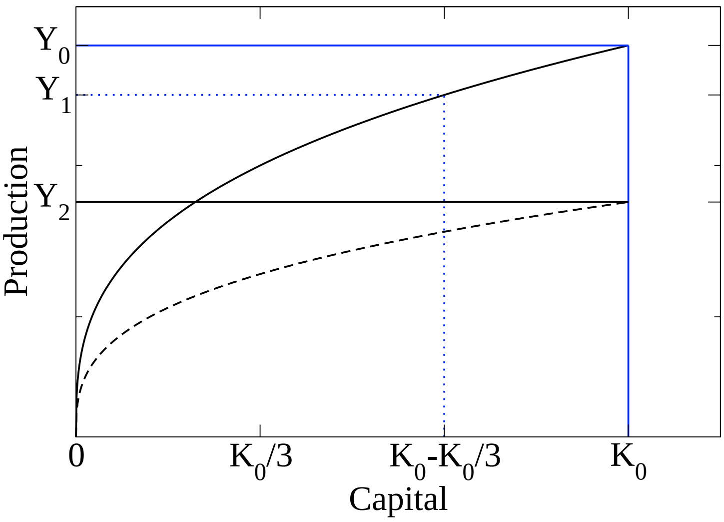

Fig. 4. Production with respect to productive capital for different hypotheses. The solid line shows the production given by a Cobb-Douglas production function. In hypothesis *H1*, when one-third of productive capital is destroyed by a disaster, K is decreased and the production function is unchanged: production is thus reduced from Y_0 to Y_1. In *H2* or *H3*, such a disaster change the production function from the solid line to the dashed line, without changing the *potential productive capital* K_0. Production is, therefore, reduced from Y_0 to Y_2, which is much lower than Y_1.

— leads to:

$$I_r = \begin{cases} Min(I, (1-\xi_K) \cdot K_0) & \text{if } \xi_K < 1 \\ 0 & \text{if } \xi_K = 1 \end{cases} \tag{23}$$

We can then easily derive I_n from :

$$I_n = I - I_r \tag{24}$$

This hypothesis will be hereafter referred to as *H2*.

(3) Considering the small amount of capital destroyed by past LEWEs compared with annual investments, such modeling of the post-disaster reconstruction would lead to a very rapid recovery from any event. But past experience suggests that some constraints reduce the reconstruction pace. For example, the 10 G$ of reconstruction expenditures after the 2002 floods in Germany have been spread over more than 3 years, even if 10G$ is small compared with the total annual investment in Germany. One source of friction is that consumers, insurance and re-insurance companies, other companies and public organizations need some time to direct high amounts of money to reconstruction activities. This constraint is cru-

cial in developing economies (Benson and Clay, 2004). Another source of friction is that the sectors involved in reconstruction activities have skills and organizational capacities adapted to the normal state of affairs and cannot face huge increases in demand (after the French storms in 1999 or after the AZF explosion in Toulouse, roofers were not numerous enough and the reconstruction took several years).

To capture how these constraints may impact significantly the transition pathways back to the equilibrium, we bounded by f_{max} the fraction of total investment that reconstruction investments can mobilize. This last specification will be referred to as *H3*.

$$\begin{cases} I_n = I - I_r \\ \\ I_r = \begin{cases} Min(f_{max} \cdot I, (1 - \xi_K) \cdot K_0) & \text{if } \xi_K < 1 \\ 0 & \text{if } \xi_K = 1 \end{cases} \end{cases} \tag{25}$$

A value $f_{max} = 5$ % means that the economy can mobilize about 1% of GDP per year for the reconstruction *i.e.* about 90 G$ per year for EU-15. This order of magnitude can be compared with other efforts diverting investments from productive activities such as the 1.2% of US GDP spent yearly for the Vietnam war and the 0.5% for the 1990-1991 war in Iraq. One per cent of GDP for a specific reconstruction activity thus represents a significant effort.

It is worth noting that reconstruction capacity should be strongly dependent on the level of cost-sharing in the economy. Consider one region impacted by a disaster. If production resources of the entire country this region belongs to are used for the reconstruction, the amount of reconstruction investments can reach high values and f_{max} could be as high as 5 or 10%. On the other hand, if the region has to carry out the reconstruction by itself because the rest of the country is not mobilized, f_{max}, which represent the portion of *nationwide* investments that can be devoted to reconstruction, will be much lower.

4 Calibration and Validation

To validate these modeling options, a disaster is applied to the economy at steady state in the NEDyM model with the different hypotheses summarized in Tab.2. This disaster destroys the stock of productive capital by an amount equivalent to 2.5% of GDP. This amount is chosen because it is comparable (in relative terms) with the 1999 Marmara earthquake, the consequences of which are large and have been well described, see for example World Bank

Hypothesis	Description
H1	Cobb-Douglas production function No distinction between productive investments and reconstruction investments
H2	Modified Cobb-Douglas production function Distinction between productive investments and reconstruction investments No limitation of the reconstruction investments
H3	Modified Cobb-Douglas production function Distinction between productive investments and reconstruction investments Limitation of the reconstruction investments at f_{max} % of the total investments

Table 2
Summary of the different hypotheses on disaster modeling.

(1999) or OECD (2003). According to these sources, this earthquake destroyed productive capital amounting to between 1.5 and 3.3% of GDP.

Figure 5 shows the economic responses to a disaster under the modeling frameworks *H1*, *H2*, and *H3* with different values of f_{max}: 10%, 5%, 3%, 1%. It shows first that the maximum intensity of the shock is multiplied by 2 in *H2* compared with *H1*. The production gap between these two hypotheses, however, lasts a very short period of time, because all investments are first devoted to reconstruction, making the situations in both hypotheses equivalent a few months after the disaster. For this reason, there is no significant differences over the medium-term between *H1* and *H2*.

The difference between *H2* and *H3* is more significant. Indeed, the duration of the production losses spans from a few months in *H1* and *H2* to several years in *H3* with $f_{max} = 1\%$. The resulting differences over the medium-term can be measured by the change in the annual growth rates, that are reproduced in Fig. 6. The growth rate is reduced by 0.2% the year of the disaster in *H1* and *H2*, and by between 0.5 and 0.7% in *H3*. Unlike in the *H1* and *H2* hypotheses, the disaster also leads in all *H3* hypotheses to an additional unemployment of about 0.15%.

On the other hand, two years after the disaster, the growth rate is still reduced only in *H3* with a constraint as tight as $f_{max} = 1\%$; it is higher than baseline in all the other simulations, because of both the catching-up effect and the economic boost from reconstruction activities. This increased growth rate, that vanishes progressively in subsequent years, yields a significant increase in the employment rate in all hypotheses.

The model response that is the most consistent with observations of the Marama earthquake is produced using the *H3* hypothesis and $f_{max} = 5\%$.

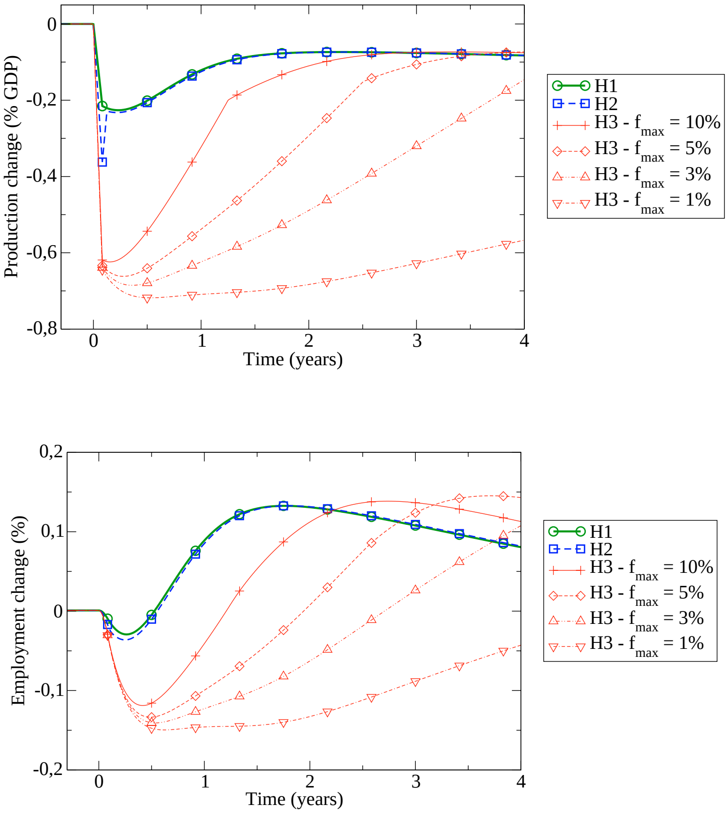

Fig. 5. Production and employment changes in response to a disaster destroying capital amounting for 2.5% of GDP, in the classical hypothesis *H1* (only the less efficient capital disappears), *H2* (capital disappear equally with respect to its efficiency) and *H3* (reconstruction investments are limited).

In particular, the model reproduces the two-year reconstruction duration and the growth rate reduction the year of the disaster. Indeed, according to the World Bank: *"In terms of indirect costs, the Bank team estimates that the earthquake will reduce GNP in 1999 by 0.6 percent-1.0 percent. [...] In the year 2000, GNP growth is expected to exceed baseline forecasts by some 1 percent of GNP due primarily to reconstruction activity."* [11] . These estimates are roughly consistent with the 0.6% GDP reduction found by the model in the *H3-5%* hypothesis.

The 0.2% production growth (over baseline) found by the model during the following year seems underestimated. Three reasons can be proposed. First, it has been suggested (*e.g*, OECD, 2003) that the replacement of the old

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[11] These figures are confirmed by estimates from the OECD and from the Turkish Industrialists and Businessmen Association (TUSIAD) (see OECD (2003)).

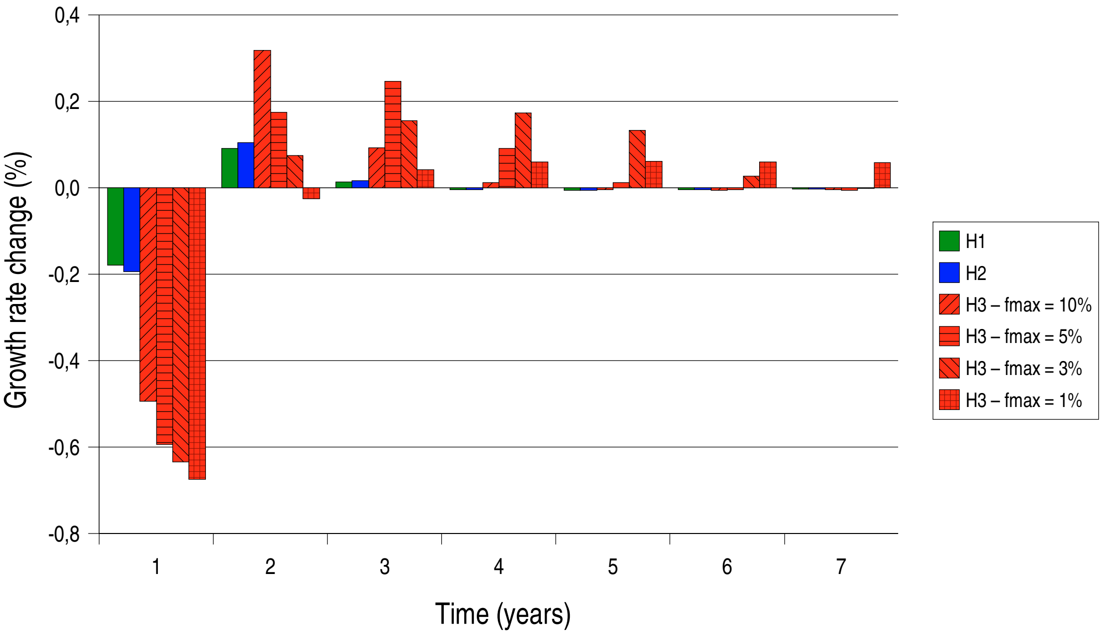

Fig. 6. Changes in economic growth due to the disaster, year per year, for the different hypotheses.

destroyed capital by more recent capital would increase the productivity after the disaster. Considering the situation in the immediate aftermath of the earthquake, however, it seems very unlikely that the Turkish industries could afford to conduct a technical improvement of their production techniques at that time. Second, the government and international trade, which are so far not modeled in NEDyM, can help to increase the investment ratio. Third, it is difficult to disentangle the effect of the shock from underlying economic evolution. For example, the Turkish GDP decreased by 7% the year preceding the Marmara earthquake. Taking into account the underlying economic situation would require applying the shock on an unbalanced economy. These issues will be investigated in future work.

These results show that NEDyM is able to qualitatively reproduce the macroeconomic consequences of a large disaster, for a carefully selected value of f_{max}. It is, however, difficult to validate it more rigorously, because the impact of a disaster on the national account aggregates (like annual GDP) is generally much smaller than the underlying economic variability (*e.g.* Albala-Bertrand, 1993).

Direct costs (% GDP)	Modeling Hypothesis					
	H1	H2	H3			
			$f_{max} = 10\%$	$f_{max} = 5\%$	$f_{max} = 3\%$	$f_{max} = 1\%$
0.25	0.21 (0.85)	0.21 (0.86)	0.22 (0.86)	0.22 (0.88)	0.23 (0.91)	0.26 (1.03)
1.25	1.04 (0.83)	1.04 (0.83)	1.14 (0.91)	1.26 (1.01)	1.41 (1.13)	2.18 (1.75)
2.5	2.07 (0.82)	2.08 (0.83)	2.51 (1.00)	2.98 (1.19)	3.60 (1.44)	6.64 (2.66)
5.0	4.12 (0.83)	4.27 (0.85)	5.98 (1.20)	7.86 (1.57)	10.32 (2.06)	22.06 (4.41)

Table 3
Total production losses in % of GDP, due to a disaster responsible for direct costs amounting to 0.25%, 0.5%, 2.5% and 5% of GDP, as a function of the modeling hypothesis. The numbers in parentheses are the Economic Amplification Ratios.

5 The Economic Amplification Ratio

In the previous simulation with $f_{max} = 5\%$, the disaster, which yields direct losses amounting to 2.5% of GDP, leads to a total production loss of 3% of initial GDP, spread over more than 10 years. This relationship allows us to define the *Economic Amplification Ratio*, as the ratio of the overall production losses due to the disaster to its direct losses. In this case, the economic amplification ratio is $3/2.5 = 1.2$.

This ratio, however, is far from constant. Indeed, it depends on a disasters destructiveness and on the hypothesis used to model disasters and reconstruction. This dependency is illustrated by Tab. 3, that shows, for hypotheses *H1*, *H2* and *H3* with $f_{max} = 10\%$, 5%, 3% and 1%, the total production losses due to a disaster responsible for direct costs amounting to 0.25%, 0.5%, 2.5% and 5% of GDP.

Table 3 confirms that there is no significant difference between *H1* and *H2* and that reconstruction constraints are not significant when coping with relatively small events, justifying our choice to focus on the largest disasters. It shows, however, that taking into account reconstruction constraints changes in a drastic manner the estimation of total production losses due to large-scale events. In our best-guess hypothesis of $f_{max} = 5\%$, the total production losses due to a disaster with direct costs amounting to 5% of GDP reach 7.9% of GDP, *i.e.* an economic amplification ratio of 1.6, almost twice as high as the one calculated without taking into account reconstruction limitations (*H1* or *H2*).

After a more precise calibration of the model, a table of Economic Amplification Ratios could be a useful tool to relate the direct cost of a possible event — like a flood — and its overall cost in terms of production loss. In particular, it would allow policymakers (i) to assess the benefits of increasing the reconstruction capacity of an economy, for instance through new regulations for the insurance sector; (ii) to take into account in a simple manner the second-order costs in the cost-benefit analysis of prevention or mitigation actions.

6 The macroeconomic costs of LEWEs

In this section, we conduct numerical experiments to assess how the macroeconomic costs of LEWEs depend on the way they are represented and the way the "growth engine" of the economy is modeled. First, we do so under assumptions of stable LEWE distribution and second, under changing distributions. This requires the use of a 400 years time period, because we need a representative set of very rare LEWEs. Obviously, the aim of is not to reproduce a realistic economic trajectory over such a long period, but rather to provide an assessment of the macroeconomic costs of the current LEWE distribution.

6.1 Macroeconomic costs due to the current LEWE distribution

The LEWE distribution calibrated in section 3.2.3 is used to generate a set of LEWEs. This distribution exhibits a mean annual direct cost of about 0.05% of GDP (*i.e.* 4.6 billions euros per year at present GDP). These direct costs lead to GDP losses of a comparable amount — between 0.05% and 0.06% — both in a Solow-like model and in NEDyM [12]. This equivalence shows that (i) in NEDyM, the deepening of the short-term production losses due to Keynesian processes is roughly compensated by the booming effect of the subsequent reconstruction, although the total impact on welfare should be negative; and (ii) the current economic capacity to fund and carry out reconstruction (*i.e.* f_{max}) is large enough not to represent a binding constraint. This is not surprising, since developed economies should have adapted their reconstruction capacity to the currently observed distribution of events.

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[12] The same simulation, carried out with a linear pdf instead of the Weibull pdf leads to production losses of the same order of magnitude (0.05%).

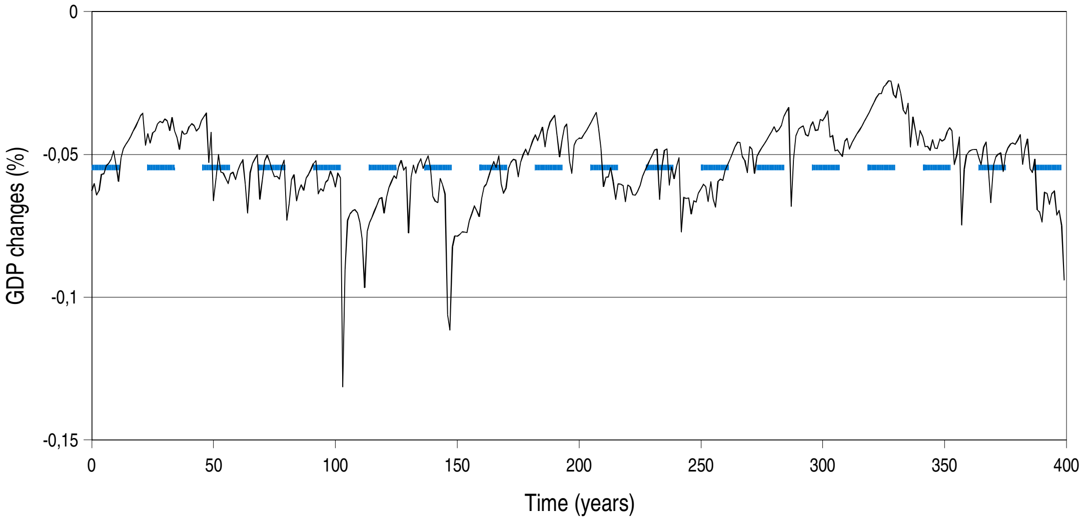

Fig. 7. Production change due to the current LEWE distribution in NEDyM.

While they predict the same averaged production losses, the difference between a Solow-like model and NEDyM is that the Solow model cannot be perturbed by shocks, as it is a long term model based on equilibrium assumptions. Therefore, in the Solow model, the productive capital is reduced at each point of time by the same amount[13], equal to the mean direct cost of the LEWEs. As a consequence, we cannot evaluate transition costs to return to equilibrium after each event. In NEDyM, since these transition costs are explicitly modeled, we can use event-per-event losses (Figure 7). This feature allows NEDyM to capture the magnitude of adjustment processes, that can last for several years, and the variability of GDP around its mean value.

6.2 *Economic vulnerability to changes in the LEWE distribution*

Let us now examine the hypothesis under which either climate change or changes in the localization of physical assets and populations raise the frequency and/or the direct losses due to LEWEs.

To do so, we carry out a sensitivity analysis, using both the Solow-like model and the NEDyM model, by modifying:

- The extreme event probability, which is multiplied by α_p

$$p_{EE} = \alpha_p \cdot p^0_{EE} \, , \tag{26}$$

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[13] Practically, we increased the depreciation rate of productive capital.

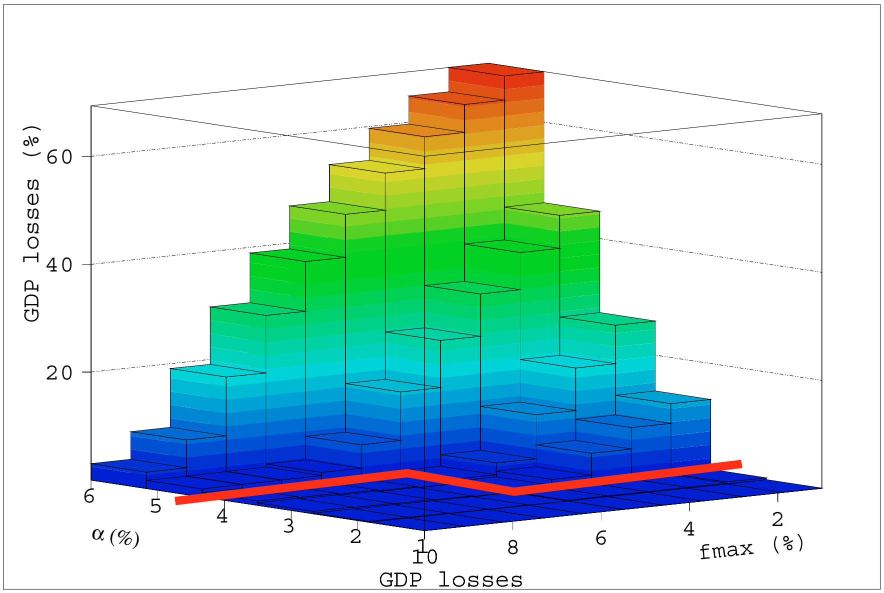

Fig. 8. Mean GDP losses due to LEWEs after 100 years, in percent of GDP, with respect to the value of f_{max} (in %) and to the value of the LEWE parameters ($\alpha_p = \alpha_z$, in %). The red line separates the parameters for which the GDP losses are below 1% of GDP.

- The pdf of the losses, such that mean loss is multiplied by α_z:

$$f(s) = \beta \cdot \chi^{\beta} \cdot \left(\frac{s - s_{EE}}{\alpha_z}\right)^{\beta - 1} \cdot exp\left(-\left(\chi\left(\frac{s - s_{EE}}{\alpha_z}\right)^{\beta}\right)\right) . \tag{27}$$

For simplicitys sake, the frequency and the mean cost of the LEWEs are both multiplied by the same amount ($\alpha_p = \alpha_z$), equal to one of six values {1, 2, 3, 4, 5, 6}.

Moreover, since GDP losses depend strongly on f_{max} in NEDyM, and given that this ratio may change in the future and that poor countries may have far lower reconstruction capabilities than those captured by our 5% best-guess assumption (Benson and Clay, 2004), we carried out simulations with ten values of f_{max}, ranging from 1% to 10%.

The simulations carried out with a Solow-like model (not shown), which are independent of f_{max}, yield a linearly growing amount of production losses as the intensity and frequency of LEWEs rise: from 0.05% when $\alpha_p = \alpha_z = 1$ to about 2% when $\alpha_p = \alpha_z = 6$.

Figure 8 represents the averaged annual production loss due to LEWEs after 100 years, as calculated by NEDyM, with respect to the value of f_{max} and to the value of α_p and α_z. The interesting finding in NEDyM is that, unlike in the Solow-like model, there exists a threshold line: for each value of f_{max}, LEWE damages remain limited if α_p and α_z are lower than a certain value, beyond which production losses increase sharply[14]. The red line in Fig. 8 shows, for each value of α_p and α_z, the minimum value of f_{max} that maintains the GDP losses below 1% of GDP. Such bifurcation in GDP losses arises when reconstruction investments cannot cope with the amount of damages because the financial or technical constraints represented by f_{max} become binding. In this case, the fraction of capital destroyed $(1-\xi_K)$ does not return to zero between events and the economy remains in perpetual reconstruction, preventing any significant increase in the potential capital K_0, *i.e.* any economic development.

These results highlight that, even though the macroeconomic consequences of weather extreme events are in most cases small (Albala-Bertrand, 1993), a distribution of such events can have long-term consequences, especially on poor countries. The fact that the joint effect of extreme events and constraints on reconstruction capabilities can be strong obstacles to economic development has already been stressed by Gilbert and Kreimer (1999) and Benson and Clay (2004). Our results suggest that extreme events may even contribute to bifurcations towards poverty traps: because they face regular extreme events and do not have the financial capacity to rebuild their infrastructures quickly enough after each shock, making it difficult to accumulate productive capital. As an example, Guatemala experienced an impressive series of weather catastrophes[15] that prevent any development. In the same region, the Honduran prime minister said, the single hurricane *Michele* in 2001 *"put the country's economic development back 20 years"* (IFRCRCS, 2002).

Additionally, our model suggests that modifications to the distribution of extremes — due to climate change or to changes in asset localization — can entail significant GDP losses. As a consequence, such modifications may force a specific adaptation of the economy to prevent damages from becoming unbearable.

More generally, our results suggest that climate change damages cannot be assessed without explicit hypotheses about the economic organization of future societies, including social structure, spatial scale of disaster cost-sharing, quality of infrastructure maintenance, insurance and reinsurance regulations (*e.g.* existence of the *Solvency* package of the EU that aims at increasing the solvency margins of the insurance sector), and existence of specific funds to cope with disasters (*e.g.* the Florida Hurricane Catastrophe Fund or the

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[14] Other simulations in which we vary independently α_p and α_z (not shown), show that the same type of bifurcation also occurs when only one of these parameters exceeds a threshold value, the other one being fixed.

[15] Hurricane *Mitch* in 1998, 3 years of drought from 1999 to 2001, and hurricane *Michele* in 2001

French *Cat-Nat* system).

7 Conclusions

The basic message of this paper is that the assessment of climate change damages depends strongly on assumptions about the functioning of the economy on which the impacts will fall. This demonstration is made through a modeling framework capable of representing (i) non-equilibrium dynamics in a way that makes the model equivalent to the neoclassical Solow growth model over the long-term; (ii) realistic constraints on the post-disaster reconstruction process. Although NEDyM provides a very stylized description of economic growth and is validated only against the 1999 Marmara earthquake in Turkey, it is generally of value for describing the mechanisms at play and their main determinants.

This exercise also allowed us to define the *Economic Amplification Ratio* as the ratio of the overall production loss due to an event to its direct costs. We showed that for large-scale events, this ratio can be significantly larger than one. As a consequence, this ratio should be used by policymakers to assess the benefits of mitigation or prevention measures, in order to take into account the second-order impacts of disasters in cost-benefit analyses.

Applied to extreme event distributions, this modeling showed that production losses due to extreme events depend, with strong non-linearity, both on the characteristics of the distribution and on the capacity to conduct reconstruction after each disaster. This capacity does not depend only on funding capacity; it depends also on the technical and organizational constraints limiting the capacity to spend money in a productive manner over the short term. In an economy with non-equilibrium phases, and for a given distribution of extremes, there is a bifurcation value for the capacity to reconstruct, under which mean GDP losses increase dramatically.

This paper highlights the importance of short-term processes and constraints in the assessment of long-term damages due to extreme events. It shows that in the case of high intensity shocks (like extreme events) with a certain frequency and probability distribution, the ultimate costs may be higher than suggested by sole consideration of the mean value of impacts. Applied on the specific issue of climate change, it suggests that assessing future damages requires both taking into account the distribution of extremes instead of their average cost, and making explicit assumptions about the organization of future economies.

These results are tentative, but they indicate, as a research priority, the incorporation of uncertainty about future economic organization in climate change damage assessments, in addition to climate uncertainty. Achieving a better understanding of the implications of this uncertainty will, however, require advances in the modeling of short-term/long-term interactions in economics.

8 Acknowledgments

The authors wish to thank Carlo Carraro, Patrice Dumas, Frédéric Ghersi, Jonathan Koehler, Tom Kram, Mike Mastrandrea and Richard Tol for their helpful comments and remarks. Conversations with Michael Ghil were also very fruitful and enriching. I would like to mention the stimulating role of the Trieste Workshop on Integrated Climate Models organized by Carlo Carraro and funded by the Ecological and Environmental Economics Program. This work was supported by the European Commission's NEST project "Extreme events: Causes and Consequences (E2-C2)."

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