Why economic growth dynamics matter inassessing climate change damages: illustrationon 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 their probability distributions. 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. In the model, dynamic processes multiply the extreme event direct costs by a factor 20. Half of this increase comes from short-term processes, that long-term growth models cannot capture. The model exhibits also a bifurcation in GDP losses: for a given distribution of extremes, there is a value of the ability to fund reconstruction below which GDP losses increases dramatically. This bifurcation may partly explain why some poor countries that experience repeated natural disasters cannot develop. It also shows that changes in the distribution of extremes may entail significant GDP losses and that climate change may force a specific adaptation of the economic organization. These results show that averaging short-term processes like extreme events over the yearly time step of a long-term growth model can lead to inaccurately low assessments of the climate change damages.

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

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1 Introduction

Modellers who assess economic impacts of climate change face a dilemma that has been very frankly presented by William Nordhaus: "*Along the economically efficient emission path, the long-run global average temperature rises sharply. After 500 years, it is projected to increase by 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.*" (Nordhaus, 1997, p. 332). It is thus not only outsiders of mainstream economics (*e.g.*, Azar and Schneider, 2003) who question the legitimacy of the very few per cent 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 the overall climate change damages. Also, most studies evaluating optimal abatement trajectories envisage only certainty cases. 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 to be analysed, 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 same 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.

This paper aims at showing out 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 a first section we present a model, NEDyM (Non-Equilibrium Dynamic Model), whose asymptotic behaviour reproduces the Solow's model, but which allows for disequilibria during the transient processes. The second section explains how available information about *large weather extreme events* (including uncertainty about their occurrence) is translated in economic terms. The third section applies NEDyM and conducts comparative exercises.

2 A Dynamic Model to capture unbalanced growth pathways

NEDyM pictures 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 akin to the Solow model. This makes it easy to reproduce the 'after shock' behaviour of a Solow model and to compare it with the behaviour 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:

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

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

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

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

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

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

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

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 but not-instantaneously: the equality of production and demand is verified only over the long term, and the delay in price adjustments break this equality over the short term.

(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

[2] The good 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 allows to account also for services, which are a large part of the current economy and which cannot be stocked.

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 increases (resp. decreases) if labor demand is higher (resp. lower) than the equilibrium level L_{full}, restoring progressively the equilibrium level of the employment rate:

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

(3) *Household behavior*: such as in Solow (1956), NEDyM uses a constant saving ratio but it sophisticates the arbitrage between consumption and saving ($S = \Gamma_{inv} Y$, Eq. (5)) 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 equating automatically investments and savings ($I = S$, Eq. (6)) NEDyM describes an investment behavior "*à la* Kalecki (1937)" and introduces a stock of liquid assets hold 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:

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

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

This ratio ensures that the redistributed dividends satisfy an exogenous required return on equity ρ demanded by the shareholders. This describes

[3] In this stylized model the share dividends represents all gains of investors: redistributed dividends, revenues from bonds, but also 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). Every value is in thousands of billions of euros.

a specific growth regime under which producers invest the amount of funds available when the required amount of dividends have been paid [4].

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

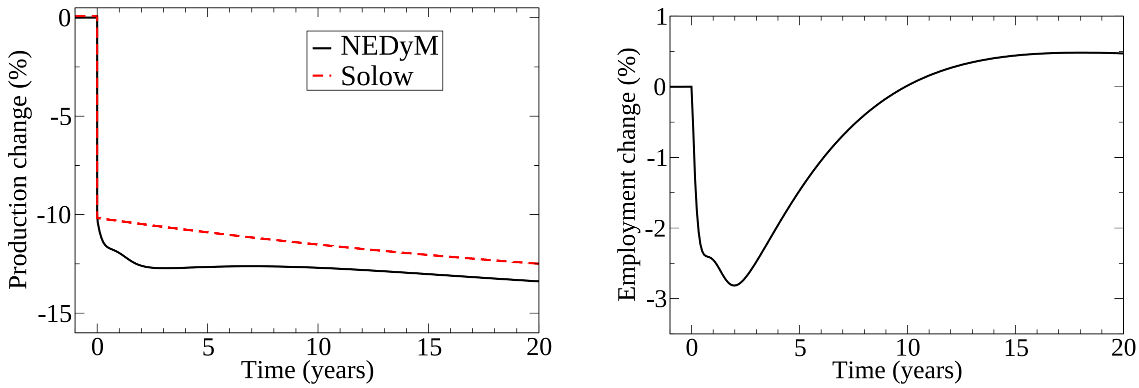
2.1 Calibration and Dynamic properties of NEDyM

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 on a steady state. Table 1 allows for comparing the value of this steady state and 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 $\Gamma^*_{save} = 22\%$.

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.

[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 7% decrease in productivity, for NEDyM and the Solow model. Over the long term, both models have the same final state.

To understand better of 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, the unemployment is 3% higher than its equilibrium level. This unemployment disappears 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, unlike in the Solow model: in the present experiment, the investment ratio decreases by 22%, and the overall physical investment by 30%.

If the productivity is decreased by the same 10%, but now progressively instead of instantaneously, the NEDyM behavior gets closer from the Solow behavior as the productivity decrease becomes 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 the 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 increases only 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 totally equivalent to the Solow model.

3 Modeling economic impacts of Large Weather Extreme Events (LWEE)

There is no strict scientific definition of Large Weather Extreme Events (LWEE); 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).

Lower media-impressive gradual changes (*e.g.* a progressive ill-adaptation of infrastructure and housing Hallegatte (2005)) may ultimately be as important channels of economic costs of global warming as extreme events. We concentrated however on the latter because they attract attention on the linkages between short-run responses to shocks (capital destruction, break-out 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.

[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 register records of damages caused by major weather catastrophes. According to Munich-Re (2003), their frequency increased by a factor 4.4 between the 1960's and the 1990's and the corresponding economic losses by a factor 7.9. This statistics reflects primarily a better reporting of disasters and the location of more assets in vulnerable places (*e.g.* costal 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 LWEE. This figure is close to the economic growth rate over the period, suggesting that, even though their frequency increases, the severity of each event is constant and that its cost increases as the income level.

Obviously climate change is likely to modify significantly economic costs of LWEEs. Even with no change of frequency and intensity of strong storms, changes in their mean trajectory would suffice in causing higher damages by impacting regions not currently adapted to them. There is also good reasons why the meteorological conditions that are considered today as extremes will be more frequent. Beniston (2004) show that the exceptional heat wave in Europe in 2003 is a good proxy of 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 to be multiplied by about 20 in 2071-2100. This is in part caused 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).

This body of reasons explain why Choi and Fisher (2003) suggests that the annual precipitation increase at the doubling 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 in our numerical exercise because such studies are still incomplete and because of the difficulties to correlate changes in the characteristics of LWEE weather and their consequences. Since our objective is not an in 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

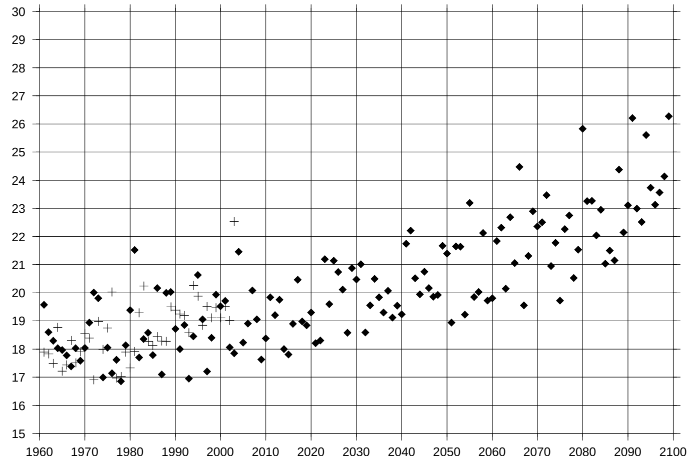


Fig. 2. Observed summer mean temperature (in °C) over France from 1960 to 2003 (crosses), and the corresponding prediction from ARPEGE-Climat up to 2100 (diamonds). According to this model, the extreme heatwave over France in 2003 becomes usual from 2070. Figure by Michel Déqué, from Déqué (2004a).

of magnitude meaningful enough for the objectives of this paper.

3.2 Definition of LWEE in numerical experiments

We focus here below on four types of LWEE: 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 LWEE exceeding this threshold over a period of one month; (iii) the probability density function of the losses due to one LWEE.

3.2.1 Level of the threshold

According to Munich-Re (2004) or Swiss-Re (2004), floods in Germany caused in 2002 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 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 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

[6] All these figures represent only direct losses.

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

A power tail of the losses pdf is, however, consistent with what appears in Figure 3, that shows the probability density of single-LWEE 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 LWEE 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].

[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 also tested a linear fit (see below).

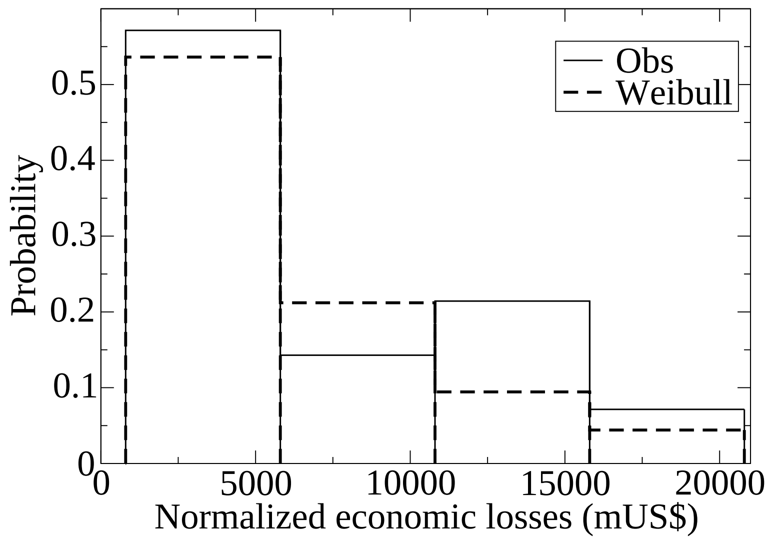


Fig. 3. Histogram of weather event probability with respect to its economic losses, in 4 ranges, for the observations (*Obs*) and the fitted Weibull distribution f_ζ (*Weibull*).

3.3 Modelling costs of capital losses

Disasters mainly destroy the stock of productive capital and a natural modelling 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 treat an after-disaster economy as equivalent to an economy in which past investments would have been lower. Such a modelling, hereafter referred to as *H1*, would however introduce three biases for impact assessment: (1) it amounts to consider 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 modelling solution 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 would have been lower amounts to consider that capital destruction would affect only the less efficient capital. Indeed, in a Cobb-Douglas function ($Y = f(K, L) = AL^\lambda K^\mu$) the "after LWEE" production would be $Y_1 = f(L, K_0 - \Delta K)$, and a $x\%$ loss of equipments would reduce the production by less than $x\%$ (see Fig. 4).

To account for the fact that LWEEs may affect whatever capital stock, we modified the Cobb-Douglas production function, by introducing a term ξ_K, which is the proportion of non-destroyed capital. The variable

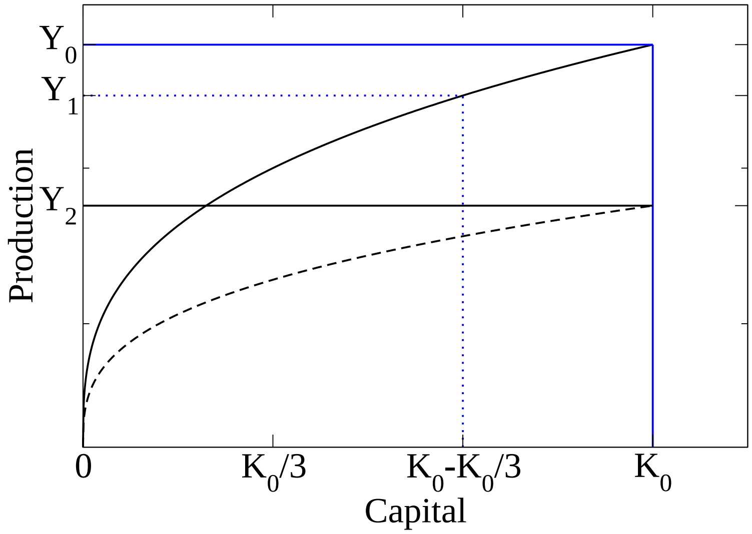


Fig. 4. Production with respect to production capital for different hypotheses.

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 LWEE, 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 now necessary to modify the investment modelling, which leads us to the second bias we mentioned.

(2) In our first modelling, there was no distinction between the investments devoted to increase capital stocks and the reconstruction investments, in

[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:

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

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:

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

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 all first devoted to replace the destroyed capital because they have higher returns 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 LWEEs compared with annual investments, this modelling 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 first source of friction is that insurance and re-insurance companies or public organizations need some time to direct high amount of money at repairing works. This constraint is crucial 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 winter-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

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

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 $f_{max} = 10$ % means that the economy can mobilize about 2% of the GDP per year for the reconstruction *i.e.* about 180 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 Irak. Two per cent of GDP for a specific reconstruction activity thus represents a significant effort.

3.3.1 Calibration and sensitivity analysis

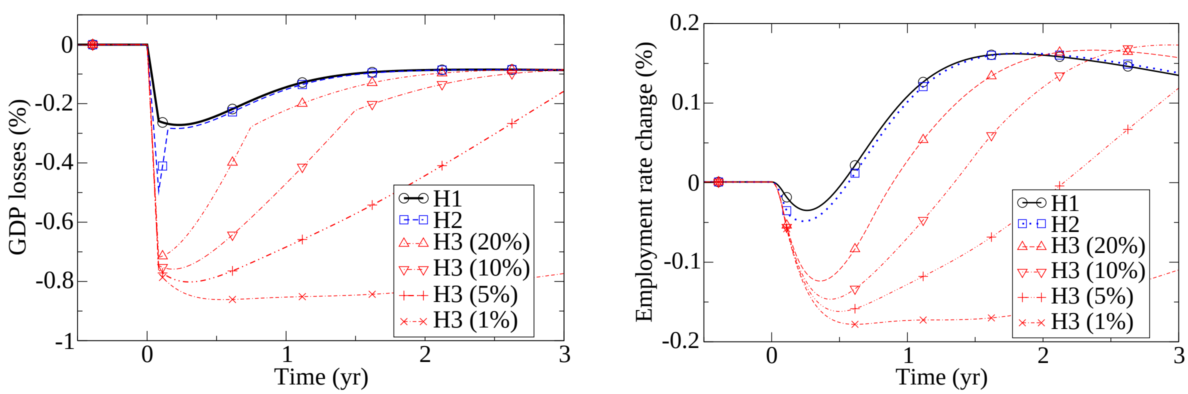
To validate these modelling options, a disaster is applied on the economy at steady state in NEDyM with the different hypotheses summarized in Tab.2. This disaster destroys the stock of productive capital for an amount equivalent to 3% of GDP, or 0.75% of the productive capital stock. This amount is 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 (1999) or OECD (2003). According to these sources, this earthquake destroyed productive capital amounting for between 1.5 and 3.3% of GDP.

Figure 5 shows the economic responses to a disaster under the modelling frameworks *H1*, *H2* and *H3* with different values of f_{max}: 20%, 10%, 5%, 1%. It shows first that the maximum intensity of the shock is multiplied by 2 in *H2* compared with *H1*, and by 2 again in all *H3* cases compared with *H2*. Second, the duration of the production losses and unemployment period spans from a few month in *H1* to several years in *H3* with $f_{max} = 1\%$. Third, there is a significant increase in the employment rate during the rebuilding phase in all hypotheses even though a small production loss remains.

As to the annual growth rate (Fig. 6), it is reduced by 0.2% the year of the disaster in *H1* and *H2*, and by between 0.45 and 0.8% in *H3*. The next year, it is still reduced only in *H3* with a constraints as tight as $f_{max} = 1\%$ but it is higher than the baseline in all the other simulations because of the catching-up effect and the boosting through reconstruction works. These effects then vanish progressively the following years.

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 modelling.



(a) Production (b) Employment rate

Fig. 5. Production and employment rate pathways, in response to a disaster destroying capital amounting for 3% 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).

The model response which is the most consistent with observation is produced using the *H3* hypothesis and $f_{max} = 10\%$. 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 0.65% GDP

[11] These figures are confirmed by estimates from the OECD or by the Turkish

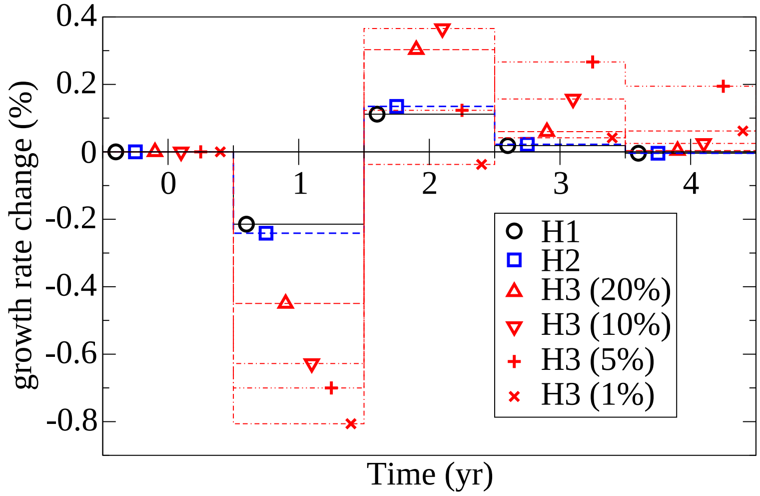


Fig. 6. Changes in economic growth due to the disaster, year per year, for the different hypotheses.

reduction found by the model in the *H3-10%* hypothesis.

The 0.3% production increase found by the model during the next year seems underestimated. Three reasons can be proposed. First, it has been suggested (*e.g*, OECD, 2003) that the replacement of the old destroyed capital by more recent capital would increase the productivity after the disaster. Considering the situation in the immediate aftermath of the earthquake, it seems however very unlikely that the Turkish industries could afford at that time to conduct a technical improvement of their production techniques. 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 and the 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 to apply the shock on an unbalanced economy. These issues will be investigated in following papers.

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) are generally much smaller than the underlying economic variability (*e.g.* Albala-Bertrand (1993)).

Industrialists and Businessmen Association (TUSIAD) (see OECD (2003)).

Cost assessment model	Mean GDP losses due to LWEEs
Averaged direct cost	180 millions euros 0.002 % of GDP
Solow-like growth model assessment	2 billions euros 0.02 % of GDP
NEDyM assessment	4.5 billions euros 0.05 % of GDP

Table 3
Mean costs of LWEEs : averaged direct costs; GDP losses with a Solow-like model; GDP losses with a NEDyM assessment

4 The macroeconomic costs of LWEEs

We conduct in this section numerical experiments to a better understand how the assessment of climate change impacts could be sensitive to assumptions upon the very functioning of the growth engine of the impacted economy. We do so under assumptions of stable LWEE distribution in a first step and under changing distributions in a second step. This forces to encompass a 200 years time period because we need a representative set of very rare LWEEs. 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 LWEE distribution and to compare its magnitude with observations.

4.1 Macroeconomic costs due to the current LWEE distribution

The LWEE distribution calibrated in section 3.2.3 is used to generate a set of LWEEs. NEDyM finds an annual mean direct cost of about 0.002% of GDP (*i.e.* 180 millions euros per year at present GDP). This negligible direct cost causes a far more significant GDP loss of 0.02% in a Solow-like model and a 0.05

Moreover, NEDyM can capture the magnitude of this adjustment process: the largest shocks reaches 0.15% of production decrease over a few years. Therefore, taking into account short-term adjustments modifies damage assessments in two ways: first, the mean GDP loss is larger; second, significant short-term shocks overlie this mean GDP losses.

Beyond the cost-multiplying effect of transitions, costs may be found higher by considering spatial aggregation issues. If we assume indeed that there is

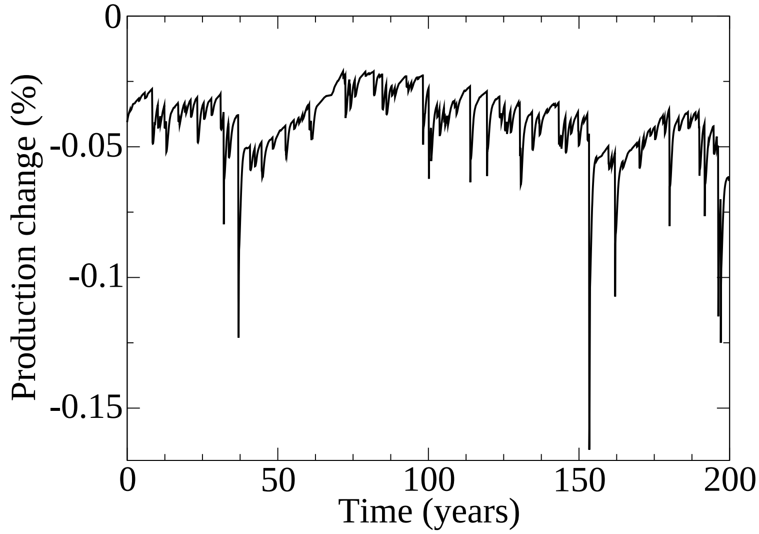


Fig. 7. Production change due to the current LWEE distribution for the EU.

no perfect damage cost-sharing over Europe, and if we consider a country representing 10% of the European area, this country will suffer less frequent LWEEs. But, for an unchanged natural intensity of the events, damages due to one event will represent a larger part of the country GDP. In this case, the consequences of one event can be significantly larger: just after the shock, production can be reduced by more than 0.5%, and the shock can last up to one decade.

This suggests that risk sharing helps to cope with LWEEs, as most of the adverse effects on welfare occur during the few years following each LWEE. Risk sharing increases the frequency but decreases the relative intensity of the events, leading to approximately the same mean production losses, but smoothing the shocks and their effects on welfare.

4.2 Economic vulnerability to changes in the LWEE distribution

Let us now examine the hypothesis under which climate change might raise significantly the costs of the LWEEs either because their frequency or intensity increases or because of changes in the localization of physical assets and populations.

To do so we carry out a sensitivity analysis modifying:

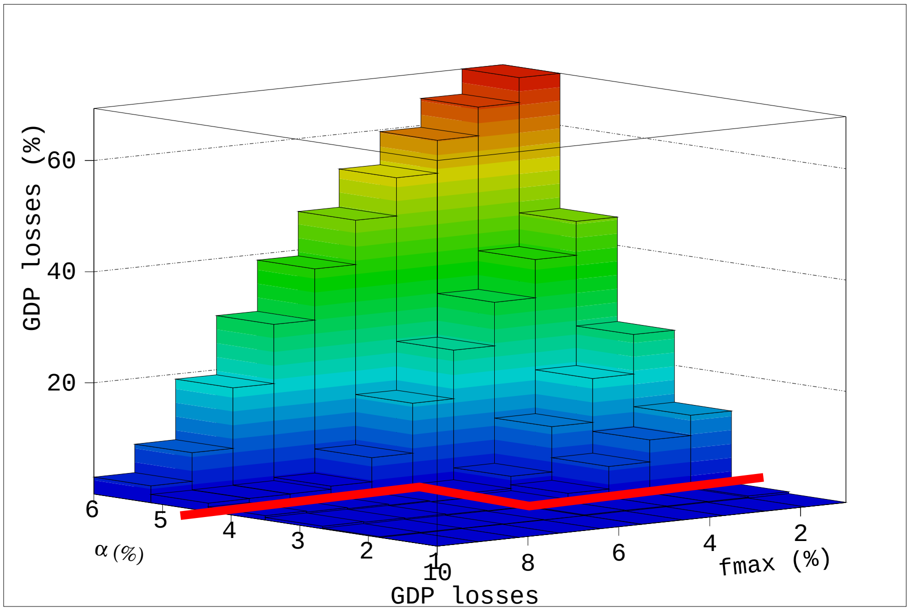


Fig. 8. Mean GDP losses due to LWEEs after 100 years, in percent of GDP, with respect to the value of f_{max} (in %) and to the value of the LWEE parameters ($\alpha_p = \alpha_z$, in %). The red line separates the parameters for which the GDP losses are below 1% of GDP.

- The extreme event probability which is multiplied by α_p

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

- 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 simplicity sake the frequency and the mean cost of the LWEEs are both multiplied by the same amount ($\alpha_p = \alpha_z$) for the six values {1, 2, 3, 4, 5, 6}.

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

Figure 8 represents the averaged annual production loss due to LWEEs after 100 years with respect to the value of f_{max} and to the value of α_p and α_z.

The interesting finding is the existence of a threshold line: for each value of f_{max}, LWEE damages remain limited if α_p and α_z are lower than a certain value, beyond which production losses increase rapidly. 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.

These results show that the fact that the macroeconomic consequences of one event are in most cases small (Albala-Bertrand, 1993) does not mean that a distribution of events cannot have long-term consequences, especially on poor countries. The fact that extreme events and constraints on reconstruction capabilities can be strong obstacles to economic development has already been stressed by Gilbert and Kreimer (1999) or Benson and Clay (2004). According to our results, this effect may even contribute to their bifurcation towards poverty traps: because they face regular extreme events and because they do not have the financial capacity to rebuild quickly enough their infrastructures after each shock, they cannot accumulate productive capital. As an example, Guatemala adds to its social unrest an impressive series of weather catastrophes [12] 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)).

But more generally, our results highlight that economic vulnerability is due to the interplay of a given intensity of impacts and of an economic and technological mobilisation capacity. As a consequence, one cannot assess the potential damages due to climate change without specific hypotheses on the economic organization of the future societies. For instance, a rise in extreme event costs because of climate change, could lead to high damages, unless a specific adaptation of the economic organization is implemented, allowing for a quicker reconstruction after each extreme event. This specific adaptation could be for instance changes in the reinsurance regulation (*e.g.* the *Solvency* package of the EU that aims at increasing the solvency margins of the insurance sector) or the creation of specific funds (*e.g.* the Florida Hurricane Catastrophe Fund or the French *Cat-Nat* system), and can be modeled in NEDyM through an increase in f_{max}.

5 Conclusions

1.confirm the intuition : equilibrium models are unable to assess climate costs.

2.we have developed an analytical tool

3.substantive conclusions are bifurcation

[12] The hurricane *Mitch* in 1998, 3 years of drought from 1999 to 2001, and the hurricane *Michele* in 2001

1.poverty traps 2.climate change et outils assurantiels

This article presents the non-equilibrium dynamic model NEDyM. NEDyM is demonstrated to be equivalent to the neoclassical Solow growth model over the long-term, when parameters are evolving slowly with respect to the adjustment delays.

To be able to capture the consequences of disasters like extreme events, a capital destruction modeling is proposed. This modeling takes into account a realistic limitation of the short-term maximal amount spent in reconstruction activities, due to financial and technical constraints. This modeling allows for a better representation of the macro-economic consequences of disasters, as shown by a validation against the 1999 Marmara earthquake in Turkey.

An assessment of the costs of extreme events is then carried out. It shows that dynamic processes multiply the extreme event instantaneous costs by a factor 20. The short-term processes alone are responsible for 50% of this cost amplification. This highlights how important it is to capture short-term processes to assess the long-term damages due to extreme events.

The GDP losses due to extreme events depend, with strong non-linearity, both on the distribution of extremes and on the ability to fund the reconstruction after each disaster. For a given distribution of extremes, there is a bifurcation value of the ability to fund reconstruction: beyond this value, GDP losses are low; below this bifurcation value, GDP losses increase dramatically. This illustrates the deep difference between considering one single event or a distribution of events: a series of almost negligible extreme events can have significant consequences at the macroeconomic level. This result may partly explain the lack of development of poor countries that experience repeated natural catastrophes without large funding capacity.

The model also shows that future changes in the distribution of extremes may entail significant GDP losses and that climate change may force a specific adaptation of the economic organization. These results illustrate that the economic assessment of climate change does not depend only on beliefs on climate change, but also strongly on beliefs on the current and future economic organization.

Finally, these results suggest that climate change damages might be more related to the intensity of shocks (like extreme events) than to the evolution of the mean productivity. After the first enumerative studies of climate change impacts (*e.g.* Nordhaus (1991), Cline (1992), Mendelsohn and Neumann (1999)), it has been argued that it was necessary to account for long-term economic dynamics (by Tol (1996) or Fankhauser and Tol (2005)). This article suggests that it is also absolutely necessary to account for short-term dynamics and for the consequences of shocks like extreme events: further work on short-term/long-term interactions in economics, and particularly the accounting for business cycles, is needed in order to produce confident assessments of climate change impacts.

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