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Accounting for Extreme Events in the Economic Assessment of Climate Change

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Summary

Extreme events are one of the main channels through which climate and socio-economic systems interact. It is likely that climate change will modify their probability distributions and their consequences. The long-term growth models used in climate change assessments, however, cannot capture the effects of short-term shocks; they thus model extreme events in a very crude manner. To assess the importance of this limitation, a non-equilibrium dynamic model (NEDyM) is used to model the macroeconomic consequences of extreme events. Its conclusions are the following: (i) Dynamic processes multiply the extreme event direct costs by a factor 20; half of this increase comes from short-term processes; (ii) A possible modication of the extreme event distribution due to climate change can be responsible for significant GDP losses; (iii) The production losses caused by extreme events depend, with strong non-linearity, both on the changes in the extreme distribution and on the ability to fund the rehabilitation after each disaster. These conclusions illustrate that the economic assessment of climate change does not only depend on beliefs on climate change but also on beliefs on the economy. Moreover, they suggest that averaging short-term processes like extreme events over the five- or ten-year time step of a classical long-term growth model can lead to inaccurately low assessments of the climate change damages.

Keywords: Climate change, Extreme events, Economic impacts

JEL Classification: E10, E22, O16, O40

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1 Introduction

Because of the very long characteristic times involved, the assessments of the economic damages due to climate change are carried out with long-term economic growth models, designed to capture the long-term features of the economy (Nordhaus (1994), Tol (1997), Peck and Teisberg (1992), Ambrosi et al. (2003) or Hallegatte (2004)). In these models, however, climate change impacts on the economy are represented only through continuous and regular changes in the mean productivity, linked to the increase in temperature. As a consequence, climate change only results in a slight reduction of the long-term economic growth, which is more than largely compensated by the productivity rise linked to technical change. This has fueled a lasting controversy on the long-term costs of climate change (*e.g.* Gerlagh and Papyrakis (2003) and Azar and Schneider (2003)).

Extreme events are one of the main channels through which climate and economy interact. According to the reinsurance companies (Munich-Re (2004), Swiss-Re (2004)), they impact the life of millions of human beings every year, are responsible for a large number of deaths (35,000 in 2003), for significant annual costs (about 65 billions US$ in 2003) and they are suspected of being strong obstacles to the development of poor countries (IFRCRCS (2002), Benson and Clay (2004)). This year, the tropical cyclone landfall in Haïtia (more than 2000 fatalities), the four ones in Florida (about 50 billions U.S.$ of economic losses) and the very active cyclonic season in Asia remind the importance of the weather extreme events for many regions in the world.

Moreover, it is possible that the frequency and the intensity of the extreme events will be modified by climate change in the future (*e.g.* Déqué (2004b), Beniston (2004), Schär et al. (2004), Christensen and Christensen (2003), Choi and Fisher (2003), West et al. (2001),...), leading to protection maladjustments and increased damages. As a consequence, it is essential to take into account extreme events in the assessment of economic damages due to climate change. But, as stated by Goodess et al. (2003), extreme events are currently poorly represented in integrated assessment models. The main difficulty is linked to the fact that the extreme event consequences involve essentially short-term processes: capital destruction, production break-out, rupture of essential services (drinking water, health and hospitals, electricity,...). It is not possible to include such processes in classical long-term growth models with five- or ten-year time steps.

To assess how important these neglected effects are, we use a modified Solow growth model. This model, NEDyM (Non-Equilibrium Dynamic Model), calibrated over Europe, is found to be able to capture short-term processes, while equivalent to the Solow model over the long term. NEDyM is used to assess the macroeconomic consequences of current extreme events and of possible changes in the extreme event distribution due to climate change [1]. The first section of this article defines the *large weather extreme events* that are considered, and proposes a modeling of their probability distribution function. The second section reviews the expected changes in extreme events triggered by climate change and proposes a modeling approach of these changes. The third section describes the NEDyM macroeconomic model and its disaster module. The fourth section apply NEDyM to the assessment of the current and future consequences of the extreme events on the economy.

2 Large Weather Extreme Events

2.1 Definition

In the following, we consider LWEEs as one-month periods during which significant capital destructions occur in Europe. We choose to model only LWEEs, with significant macro-economic consequences and to which it is very difficult to adapt. Thus, we model only the weather events against which we cannot protect ourselves by dams or other protection (or at unbearable costs) [2]. The "frequent" WEEs that occur several times a year in Europe will be neglected as they do not constitute strong shocks, thanks to the insurance smoothing effect, and because it is often possible to adapt to them to downsize their damages. We will focus on exceptionally strong shocks that have direct macro-economic impacts.

In the following, we will focus on four types of LWEE: floods, winter storms (and the corresponding storm surge), droughts and heat waves. Other LWEEs are not considered.

2.2 Data

Munich-Re (2003) provides a list of major weather catastrophes of the last 20 years in Europe. Moreover, still according to Munich Re, the number of weather catastrophes per decade increased by a factor 4.4 between the 1960's and the 1990's and the corresponding economic losses increased by a factor 7.9. Assuming that the LWEE natural variability did not change during this period

[1] In this paper, the other non-extreme consequences of climate change are disregarded.
[2] Examples of such events are the 2002 floods in Germany or the 1910 floods in Paris.

(which is an acceptable assumption since no conclusive results are available on the change in the distribution of extremes during the XXth century (IPCC (2001), chp. 2)), it means that the mean economic losses per event increased by a factor 1.8, because of an increase of our vulnerability. This corresponds to an increase of the economic losses of a representative event of 2% per year. It allows us to define *normalized economic losses*, as a rough assessment of the economic losses that a LWEE would have been responsible for, if it occurred today.

Following classical extreme event modeling (Katz et al. (2002)), the complete modeling of the LWEEs is done through (i) the choice of a loss threshold; (ii) the occurrence probability of a LWEE exceeding this threshold, over one month; (iii) when a LWEE occurs, the probability density function of its intensity or of its associated losses.

Since small and frequent WEEs are neglected, the minimum threshold of our LWEEs is fixed at 0.01% of the GDP of the European Union. For the EU, it corresponds to damages amounting for approximatively $s_{EE} = 800$ millions euros. Since we assume that the last 20 years are representative for the statistical distribution, that the distribution was stationary during this period and that LWEEs are independent, the total probability of occurrence of a weather event responsible for more than 800 millions euros of losses will be $p_{EE} = 0.06$ [3].

Figure **??** shows an histogram of the distribution of LWEE costs in 4 ranges. It represents, if a LWEE occurs, the probability that it is responsible for losses that are in the considered box. In spite of the shortness of the series, that prevents from any rigorous statistical study, we will use this distribution as the representative one. Our aim being to provide a rough assessment of the macroeconomic costs of the LWEEs and to validate our modeling framework, a crude calibration of the extreme distribution is, however, sufficient.

There is some evidence that LWEE natural intensity probability exhibits a power tail (Katz et al. (2002)). However, the link between LWEE natural intensity and the corresponding economic losses is a very open question. In the following, we will assume that the probability density function (pdf) tail of the LWEE economic losses follows a Weibull distribution and is given by (for $s > s_{EE}$):

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

[3] We assume that there is at most one LWEE in one month, even if we have examples to the contrary.

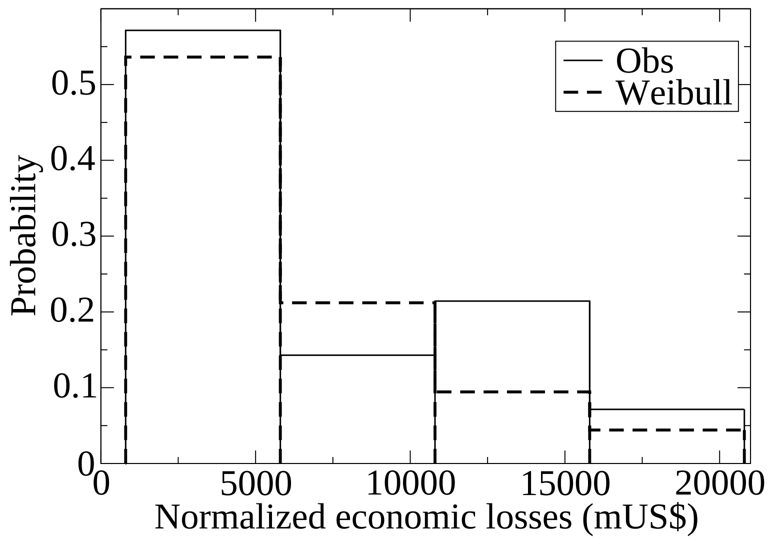


Fig. 1. Histogram of weather event probability with respect to its economic losses, in 4 ranges, for the observations (*Obs*) and the fitted Weibull distribution f_ζ (*Weibull*).

The fit gives $\lambda = 0.897933333$ and $\beta = 0.000178672$, and the corresponding Weibull distribution is reproduced in Fig. 1. This function fits reasonably well to strong events and allows to carry out a first analysis of the LWEE consequences[4].

3 Extreme events and Climate change

3.1 Change in extreme events due to climate change

Climate change is likely to modify the economic losses due to LWEEs. For instance, it is possible that the mean storm trajectory changes, impacting regions that are not currently adapted to strong storms. In this case, the storm frequency does not need to change to lead to stronger damages on non-adapted regions. But climate change may also modify the LWEE frequency, as meteorological conditions that are considered today as extreme may become more and more frequent. For example, the heat wave in Europe during summer 2003 is exceptional in current climate, but corresponds to an usual summer in 2080 as simulated by most of the climate models: see in Fig. 2 the observed summer mean temperature over France from 1960 to 2003 and the corresponding pre-

[4] To assess the sensitivity of our results to changes in the distribution function, a linear fit is also calibrated and used.

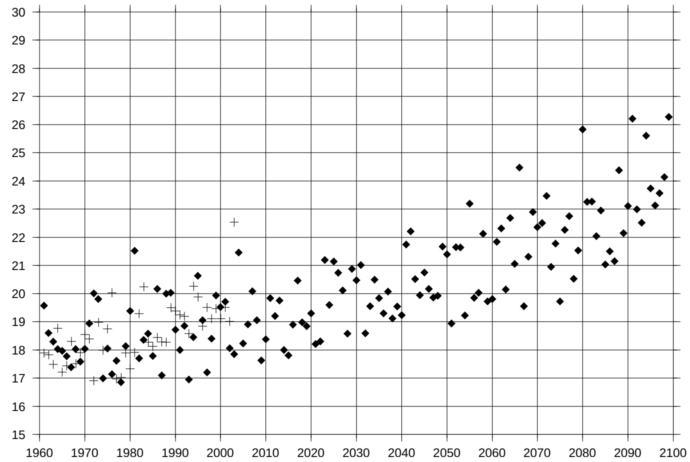


Fig. 2. Observed summer mean temperature (in °C) over France from 1960 to 2003 (crosses), and the corresponding prediction from ARPEGE-Climat up to 2100 (diamonds). Figure by Michel Déqué, from Déqué (2004a).

diction from ARPEGE-Climat (Gibelin and Déqué (2003)) up to 2100 with the SRES/A2 scenario (IPCC (2000)). According also to Beniston (2004), the 2003 heat wave is a good proxy of the possible future summers in the latter part of the 21^{th} century.

In addition to the changes in mean temperatures, Schär et al. (2004) found an increased temperature variability (by up to 100%) in regional climate models over Europe. They also highlight the fact that a 50% increase in the standard deviation of summer temperature series (without change in the mean) would raise the probability of a 2003-like event by a factor 150. Another illustration of the threshold effects in extreme events is given by Déqué (2004b): the probability of exceeding 35°C in summer is predicted to jump from 1% today to 11% in 2070 in Paris and from 1% to 27% in Marseille. More precisely, the number of days during which the maximum daily temperature exceeds 30°C for at least 10 consecutive days is multiplied by more than 20 in 2071-2100 when compared with 1961-1990. There are also strong concerns about the occurrence of severe flooding, as shown by Christensen and Christensen (2003) about summertime flooding over Europe.

Nevertheless, the increase in LWEE costs will be limited because: (i) LWEE natural intensities are limited by natural ceilings that cannot be exceeded even in case of climate change; (ii) economic losses due to LWEEs are closely related to the economic value and the vulnerability of the impacted area and there exist loss potentials that cannot be exceeded even if the LWEE natural intensity increases [5]; (iii) adaptation measures will be undertaken to reduce the LWEE costs. Thus, the link between these LWEE distribution changes

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

and the corresponding losses need further investigations. So far, only a few studies are available, which all suggest that climate change may multiply the cost of extreme events: according to Choi and Fisher (2003), a 1% increase in annual precipitation would enlarge U.S. catastrophe loss by 2.8%, leading to an increase in flooding losses between 100% and 250% and an increase in hurrican losses between 150% and 300% at the doubling CO_2 concentration. Dorland et al. (1999) assessed the relationship between wind intensity and storm damages in Netherlands. They found that a 6% increase in the wind intensity could lead to a 500% increase in average annual damages. West et al. (2001) found that sea level rise alone could increase the storm damages at least by 5%.

3.2 Modeling of the extreme events changes

In the following, climate change will be modeled as a $1\ \% \cdot yr^{-1}$ increase of CO_2 concentration. No relationship between economic activity and emissions or temperature is considered[6]. Mean temperature, which is used as a *climate state indicator*, is calculated by:

$$\frac{\partial T}{\partial t} = \frac{1}{\tau_c} \left(T_{2X} \frac{ln\left(\frac{[CO_2]}{[CO_2]_{ini}}\right)}{ln(2)} - T \right) \tag{2}$$

τ_c is fixed at 10 years; T_{2X}, which is the equilibrium temperature increase at doubled CO_2 concentration is fixed at $T_{2X} = 3.5$ (which is the current mean value of the climate sensitivity among IPCC models).

As stated in the previous section, modeling the changes in the LWEE cost distribution requires to account both for changes in the frequency, intensity and localization of the extreme events and for the effects of adaptation measures. To do so, the modeling from Hallegatte (2004) is used: an adaptation process is implemented, through an "adaptive temperature" (T_{ada}). This temperature is equal to the actual surface temperature at the equilibrium, but it diverges from it whenever climate changes faster than the adaptation characteristic time of the socio-economic system (τ_{ada}):

[6] It would be possible to include a schematic relationship between production and emissions. However, it has been considered that it is worth focusing on the understanding of climate change damages before to accounting for the whole climate-economy feedback (about the climate-economy feedback characterization, see Hallegatte (2004)). The scope of this study is thus deliberately reduced to go deeper into the modeling of the consequences of climate change.

$$\frac{\partial T_{ada}}{\partial t} = \frac{1}{\tau_{ada}}(T_s - T_{ada}) \tag{3}$$

τ_{ada} is fixed at 50 years (which is around the mean lifetime of the high inertia economic sectors (energy and infrastructures)).

Climate change impacts are then linked to a race between climate change and adaptation processes. When T_{ada} and T_s differ, the socio-economic system is not adapted and it faces increasing LWEE costs: the LWEE probabilities and costs are modeled through:

$$p_{EE}(T_s, T_{ada}) = p^0_{EE} \cdot (1 + \alpha_p \cdot |T_s - T_{ada}|) \tag{4}$$

$$f_{\beta,\lambda,\sigma}(s) = \beta \cdot \lambda^\beta \cdot \left(\frac{s - s_{EE}}{\sigma}\right)^{\beta-1} \cdot exp\left(-\left(\lambda\left(\frac{s - s_{EE}}{\sigma}\right)^\beta\right)\right) \tag{5}$$

$$\sigma(T_s, T_{ada}) = 1 + \alpha_z \cdot |T_s - T_{ada}| \tag{6}$$

It means that the probability of occurrence is multiplied by $(1 + \alpha_p)$ and the mean cost is multiplied by $(1 + \alpha_z)$ for a 1°C maladjustment.

These hypotheses are very optimistic since they assume that we are currently perfectly adapted to LWEE - their costs cannot be reduced further by adaptation measures - and that society is able to adapt to any climate as well as to the current one: no climate is better than another. Thus, we focus only on the transition period in which the socio-economic system is not adapted to a new LWEE distribution. The advantages of this formulation are as follows: (i) climate change intensity and rate are both taken into account; (ii) present climate is not used as an absolute reference; (iii) a characteristic time for adaptation is introduced; (iv) any temperature change has negative impacts.

4 The NEDyM model and its disaster module

To take into account extreme events in the assessment of climate change, the NEDyM model and a specific disaster module are used. They are presented in this section.

NEDyM models a stylized economy, closed and homogeneous [7]. Its dynamic core is akin to the classical Solow growth model, picturing an economy with one representative producer, one representative consumer and one good, used both for consumption and investment. The Solow model is composed of a static core describing the market equilibrium, and a dynamic relationship describing the productive capital evolution. In NEDyM, the translation of the static core into dynamic relationships is done by introducing stocks and delays in the pathways toward equilibrium with fixed characteristic times.

A comprehensive description of NEDyM is available online [8]. The main changes applied to the Solow growth model are the following:

- Goods market

  In the Solow model, the price is determined by the equality of production and demand. In NEDyM, a goods inventory is introduced, filled by the production and emptied by the demand. At any time t, the production can differ from the demand: temporary overproduction or underproduction is possible. Price increases or decreases as a function of the goods inventory and of the difference between production and demand, tending to return to the equilibrium with a null goods inventory. As a consequence, the equality of production and demand is verified on average in the long term, but delays in price adjustment can break this equality in the short term and lead to imbalances.
- The labor market

  In the Solow model, the wages is such that the economy is always at full-employment. NEDyM models instead the producer as setting an effective labor demand that would maximize his profits, as a function of price and wages (which are flexible over the long-term and rigid over the short-term). The number of employed workers is driven by this effective labor demand with a delay. If labor demand is higher (resp. lower) than the equilibrium level, wages increases (resp. decreases), to drive the employment level back to its equilibrium value.
- Consumer behavior

  In the Solow model, total income is always equal to consumption plus savings. In NEDyM, the consumer has an income and can consume, or save, either by stocking or by making this savings available for investment.
- Producer behavior

  In the Solow model, sales equal wages plus profits. In NEDyM, an invest-

[7] At this stage, the spatial and sectoral shock propagations will be disregarded in spite of their potential major consequences.

[8] URL: www.centre-cired.fr/forum/rubrique.php3?id_rubrique=71

ment module inspired by the ideas of Kalecki (1937) is implemented. The stock of liquid assets of banks and companies is introduced. An investment ratio, which depends on the mean profitability of the productive capital, is used to distribute these liquid assets between physical investment and redistributed capital incomes.

4.2 NEDyM steady state and dynamics

4.2.1 Calibration and Steady state

If the productivity is constant, NEDyM has a stable equilibrium. Some parameters of the model are calibrated such that this equilibrium is the 2001 economic state of the European Union (15 countries). The other parameters are not calibrated but their values are chosen in an *ad hoc* manner. The steady state is reproduced in Tab. 4, together with observed values from Eurostat (2002) [9].

The steady state represented in Tab. 4 is that of a Solow model calibrated with a particular savings ratio γ_{save}. With its current parameter set, the NEDyM steady state is that of a Solow model with an equivalent saving ratio $\gamma^*_{save} = 22\%$. This steady state is also that of a Ramsey model with a rate of pure preference for the present equal to 2.54 %. However, their responses to shocks are different, as will be demonstrated in the following sections.

4.2.2 Balanced growth pathway

With technical change, modeled through a regular increase in the productivity A, the model reaches a balanced growth pathway, in which the employment, wages and capital incomes are at their equilibrium values, and in which the price is decreasing regularly (this is due to the fact that money creation is not allowed in the model, contrary to the reality). For a productivity increase of 2% per year, production increases by 3% a year. This behavior is equivalent to the Solow growth model behavior.

[9] It is noteworthy that the model does not consider *net flows* over one year (as the national accounting system does) but *gross flows* summed up over one year. To compare the NEDyM steady state to the national accounting system, it is necessary to calculate the corresponding net flows, that are indicated between brackets in Tab.4.

Symbol	Description	Steady state (and net flows)	2001 EU-15 observed values
Y	production (=demand)	9	8.8
L	number of employed workers	93%	92.6 %
$L \times w$	total annual wages	6	5.6
			(including taxes)
C	consumption	7	6.8
S	available savings	3 (2)	1.8
R	annual capital incomes	4 (3)	3.2
I	physical investment	2	1.8

Table 1
NEDyM steady state (when necessary the corresponding net flows defined similarly with the national accounting system are in brackets) and EU-15 economic variables in 2001 according to Eurostat (2002). Every value is in thousands of billions of euros.

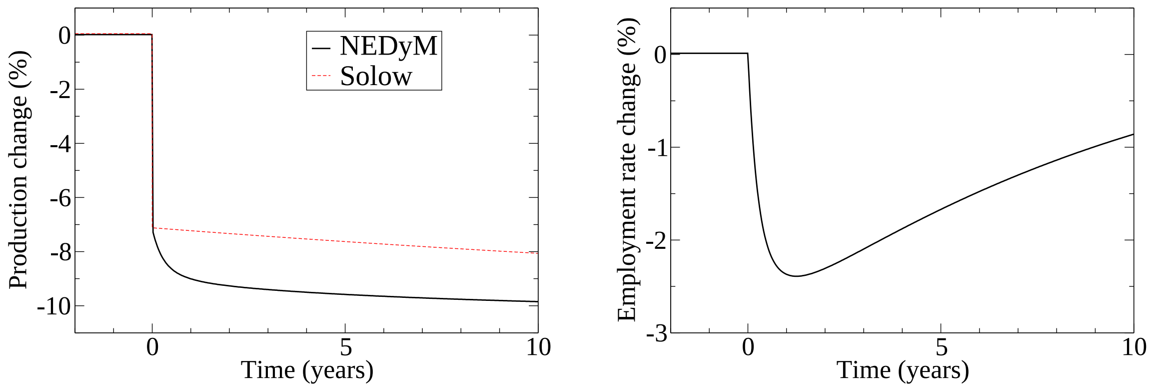
4.2.3 Transition between two balanced pathways

From the previous balanced growth pathway, if the productivity growth rate is instantaneously reduced from 2% to 0%, the production keeps growing during 80 years (because of the productive capital adjustment time lag). From the time when productivity growth is reduced, unemployment increases by 2% in 10 years, and returns to the initial value about 30 years later. During this period, the real wage is reduced by 7% and the investment ratio by 25%.

4.2.4 Response to a shock in productivity

To get a better understanding of the model response to shocks, we consider now the model without productivity growth. In this case, the model has a stable equilibrium. From this equilibrium, the productivity A is instantaneously decreased by 7%. The production and employment response of the model to such a shock is reproduced in Fig. 3, together with the response of a Solow model, calibrated to have the same steady state than NEDyM.

Following the decrease in productivity, production decreases instantaneously. This decrease is amplified by a decrease in labor demand: given the price and the wage, a lower labor productivity leads to a lower employment rate. This is due to the inertia in wages and prices. This shock leads also to a decrease of the profits that reduces the investment ratio. The consequence is a decrease of the physical investment that amplifies the shock.



(a) Production (b) Employment rate

Fig. 3. Model response to a 7% decrease in productivity.

Finally, the transient unemployment and the investment decrease are responsible for a much stronger shock than in the Solow model, even if the final equilibrium is the same. At the crisis peak, the unemployment is 2.5% higher than its equilibrium level. At the new steady state, reached about 50 years after the shock, the real wage is reduced by 10%, the price has been increased by 15% and the production is 10% lower than before the shock.

4.2.5 Conclusions about NEDyM

If NEDyM cannot be considered as a realistic model because of its simplicity and the lack of some major processes, it is able to reproduce the Solow model behavior when the parameters are changing slowly. When shocks occur, breaking the equilibrium, the model response exhibits short-term Keynesian characteristics. This fulfills the Solow requirement for an economic dynamics Keynesian over the short-term and neoclassical over the long-term.

4.3 The disaster module

The specific issue of climate change necessitates to take into account disasters like extreme events. However, such disasters do not impact strongly mean productivity. They mainly destroy production capital, infrastructure and housing. These two hypotheses are equivalent only if the damages are averaged over a long period (at least several years). As an example, Munich-Re (2003) provides an assessment of the damages due to the 2002 floods in Germany: these floods lead to a one billion euros production loss during the month they last. But they made (in Germany only) damages amounting for 10 billions euros, spread out between infrastructures (4 billions euros), trade & industry (2 billions euros), household (2 billions euros) and others (2 billions euros). According to the same source, the Mississippi floods in 1993 in the US are responsible for losses amounting for 18 billions US$. Swiss Re, in Swiss-Re (1998), provides an assessment of the loss potentials for several countries. Among them, Netherlands exhibits a 30 to 60 billions US$ flood damage potential and a 100 billions US$ damage potential in case of storm surge. In the same way, the winter'99 windstorms over Europe have lead, according to Munich-Re (2002), to 20 billions euros of losses, even if direct production losses were small (production stopped for days in most cases, for weeks in the worst ones mainly because of energy distribution network damages).

To model climate change impacts, it is thus necessary to represent explicitly the economic response to productive capital losses. The next sections propose a model able to do so.

4.3.1 Modeling of productive capital losses: a modified Cobb-Douglas production function

The productive capital destruction due to a disaster can be taken into account through an instantaneous decrease in the amount of productive capital K. However, this way of modeling can be discussed. The model is based on the decreasing returns assumption: as productive capital increases, it becomes less and less efficient. If a disaster occurs, and that the productive capital decreases brutally ($K \longrightarrow K - \Delta K$), it means that the situation is equivalent to a situation in which investments have been lower. But in reality, the situation is very different between a situation in which investment have been lower and a situation in which a share of the productive capital in use has been destroyed by a disaster.

To explore this problem, consider that initially $K = K_0$ and the production is equal to Y_0. If one third of the available capital disappears, K is changed from K_0 to $K_0 - K_0/3$.

In the classical Solow modeling (hereafter referred to as *H1*), the Cobb-Douglas production function ($Y = f(K, L) = AL^\lambda K^\mu$) is used to calculate the new production as a function of the productive capital K and of the labor L. It gives a new production $Y_1 = f(L, K_0 - K_0/3)$ (see Fig. 4). But using this production function means assuming that the situation after the disaster is equivalent to a situation in which past investments have been weaker, which is unrealistic.

We thus propose a modified Cobb-Douglas production function, by introducing a term ξ_K, which is the proportion of non-destroyed capital. ξ_K is such that the real effective productive capital K (after the capital destructions) is given by $K = \xi_K \cdot K_0$ but with the new production function:

$$Y_2 = \xi_K \cdot f(L, K_0) \tag{7}$$

Here $(1 - \xi_K)$ is the proportion of capital destroyed. In this case, where one third of the productive capital has been destroyed, $\xi_K = 2/3$. In Fig. 4, this is represented by a new production function reproduced in dashed-line, which leads to a new production Y_2, significantly lower than Y_1 [10].

With this modeling (hereafter referred to as *H2*), K_0 is now a potential productive capital, that is the amount of productive capital when no capital is destroyed. This potential productive capital is hereafter denoted as K_p and the effective capital K is equal to $K = K_p \cdot \xi_K$.

As a consequence, the Cobb-Douglas production function is replaced by:

$$Y = f_{CC}(L, \xi_K, K_p) = \xi_K \cdot A \cdot L^\lambda \cdot K_p^\mu \tag{11}$$

It becomes necessary to distinguish in the investment after a disaster between I_n, the investment in new capital (*i.e.* an increase in K_p), and I_r, the rehabilitation investments, used to repair the damages due to the disaster (*i.e.* an

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[10] To illustrate this point, we can rewrite the Cobb-Douglas production function as:

$$Y = f(L, K_0) = \int_0^{K_0} \partial_2 f(L, k) \cdot dk\,, \tag{8}$$

where $\partial_2 f$ is the derivative of f with respect to its second argument (the productive capital). This means that we assume that the productive capital is not homogenous but is a sum of a continuum of ever less efficient capitals. Our way of modeling capital destruction is to assume that the capital is equally removed, independently of its productivity. It is done through the factor ξ_K in the production function:

$$Y = \int_0^{K_0} \partial_2 f(L, k) \cdot \xi_K \cdot dk \tag{9}$$

This is equivalent to:

$$Y = \xi_K \int_0^{K_0} \partial_2 f(L, k) \cdot dk = \xi_K f(L, K_0) = \xi_K \cdot A \cdot L^\lambda \cdot K_0^\mu \tag{10}$$

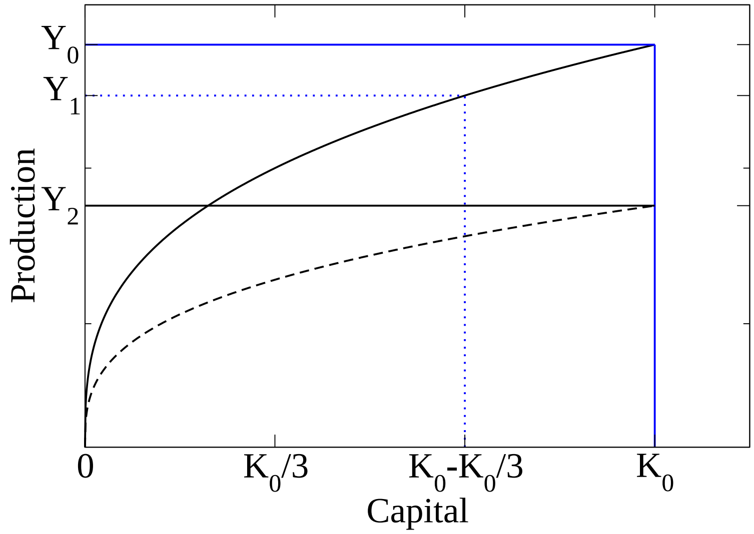


Fig. 4. Production with respect to production capital for different hypotheses.

increase in ξ_K):

$$\underbrace{\dot{K}}_{I-1/\tau_{dep}\cdot K} = \underbrace{\dot{\xi_K} \cdot K_p}_{I_r} + \underbrace{\xi_K \cdot \dot{K_p}}_{I_n-1/\tau_{dep}\cdot K} \tag{12}$$

The classical equation for capital dynamics ($dK/dt = -K/\tau_{dep} + I$) is replaced by:

$$\frac{\partial K_p}{\partial t} = \frac{-1}{\tau_{dep}} K_p + \frac{I_n}{\xi_K} \tag{13}$$

"Repairing" is modeled through:

$$\frac{\partial \xi_K}{\partial t} = \frac{I_r}{K_p} \tag{14}$$

We will first assume that, as soon as $\xi_K < 1$ (*i.e.* as soon as there are capital losses), all the investment is used to replace the lost capital (since its productivity is higher) in order to draw back ξ_K to 1. I_r and I_n are given by:

$$\begin{cases} I_n = I - I_r \\ \\ I_r = \begin{cases} Min(I, (1-\xi_K) \cdot K_0) & \text{if } \xi_K < 1 \\ 0 & \text{if } \xi_K = 1 \end{cases} \end{cases} \tag{15}$$

4.3.2 Limitation of the repairing expenditures

Weather extreme events are examples of productive capital destructions. In these cases, the amount of destroyed capital is very small compared with the annual amount of investments. As a consequence, the capital destructions (ξ_K) are always repaired in less than one year in the model with the *H2* hypothesis. But according to Munich Re, the 2002 floods in Germany necessitate repairing expenditures (amounting for 10 billions euros) spread over 3 years. This shows that it is not possible to use all the investment for repairing expenditures. In reality, these repairing expenditures are mainly paid by insurance and re-insurance companies, by public organizations and by consumers, which cannot mobilize such a high amount of money in a short delay. Of course, this problem is even more crucial in developing economies, as stated by Benson and Clay (2004). Moreover, repairing is often linked to specific activities that cannot face a huge increase in demand (this problem has been met dramatically after the French winter storms in 1999, when roofers were unable to repair the damages in less than one year). Thus there is not only a problem with the amount of available money for investment but also technical and practical limitations.

Thanks to our description, it is possible to assess the consequences of hypotheses regarding the distribution between repairing expenditures and new investments. For example, assuming that repairing expenditures cannot exceed a fraction f_{max} of the total investment (repairing plus new investment) leads to the new equations:

$$\begin{cases} I_n = I - I_r \\ \\ I_r = \begin{cases} Min(f_{max} \cdot I, (1-\xi_K) \cdot K_0) & \text{if } \xi_K < 1 \\ 0 & \text{if } \xi_K = 1 \end{cases} \end{cases} \tag{16}$$

The hypothesis will be referred to as *H3*. This value is a measure of the ability of the economy to fund, over the short-term, the rehabilitation of the damages due to extreme events. This value is closely related to the economic organization (particularly concerning the reinsurance industry and public funding of repairing) and evolves as a function of the considered region and of the considered period.

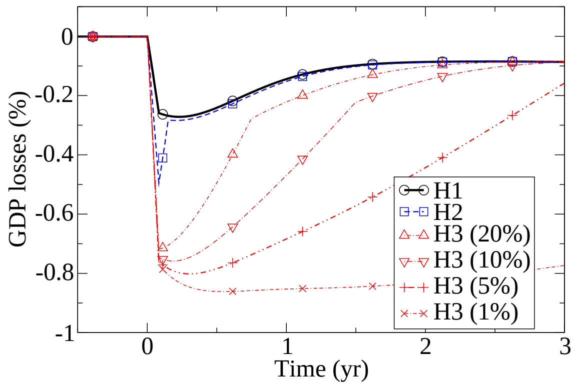
4.3.3 Case study and sensitivity analysis

To validate these modeling hypotheses, a disaster is applied on the economy at steady state. The disaster destroys productive capital for an amount equivalent to 3% of the GDP. This large amount is chosen such that the disaster has clear macroeconomic consequences that can be compared with real shocks, not over EU that has not experienced such a huge shock these last decades, but over other regions. For example, the 1999 Marmara earthquake, in Turkey, destroyed productive capital amounting for between 1.5 and 3.3% of GDP (World Bank (1999)), which is comparable with our experiment, even if the macroeconomic situation is Turkey is different from the EU's one.

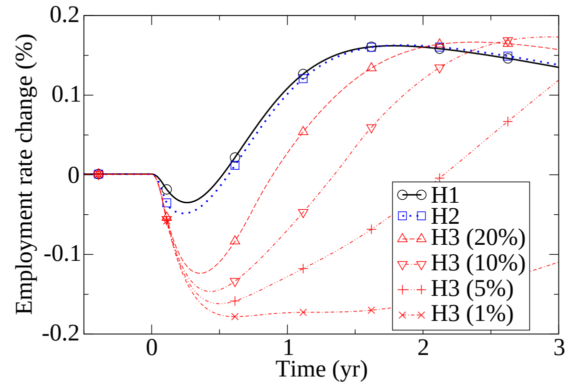
Figure 5 shows the employment and production responses for the hypotheses *H1*, *H2* and for *H3* with different values of f_{max}: 20%, 10%, 5%, 1%. It shows that the shock is very different depending on the modeling framework. First, the maximum intensity of the shock is multiplied by 2 in *H2* compared with *H1*, and multiplied by 2 again in all *H3* cases compared with *H2*. Moreover, the duration of the production losses and unemployment period depends strongly on the hypothesis: from a few month in *H1* to several years in *H3* with $f_{max} = 1\%$. Note that in all hypotheses, there is a significant increase in the employment rate during the rebuilding phase.

Figure 6 exhibits the change in growth rate due to the disaster for all hypotheses. During the year of the disaster, the growth rate is reduced by 0.2% in *H1* and *H2*, and by between 0.45 and 0.8% in *H3*, depending of the value of f_{max}. The next year, the growth rate is still reduced only in *H3* with $f_{max} = 1\%$. In all the other cases, the growth rate is enhanced by the disaster, even if the production is still lower than before its occurrence. The growth is increased by about 0.1% in *H1* and *H2*, and by between 0.1 and 0.45% in *H3* with f_{max} between 5% and 20%. The following years, the impact of the disaster on growth is negligible in most cases, except in *H3* with $f_{max} = 5\%$ or 1%.

The shock characteristics with *H3* and $f_{max} = 10\%$, in particular the fact that replacing the destroyed capital takes 2 years, are more consistent with observations than results with other hypotheses. 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."* This is roughly consistent with the 0.65% GDP reduction found by the model in the *H3-10%* hypothesis. The 0.3% production



(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* (repairing expenditures are limited).

increase found by the model during the next year is underestimated, even if it is difficult to confirm *a posteriori* the World Bank prediction of an additional 1% growth.

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}, even if further calibration and validation should be carried out on a larger set of events and regions.

5 The macroeconomic costs of LWEEs

NEDyM is very simple. However, this kind of simple models has the advantage to be general enough to be robust to the technical and institutional changes to be experienced in the next century. As a consequence, such a simple model can be considered as a good tool to get a better understanding of the consequences of extreme events over the long-term and in the climate change context. This is the aim of this section.

5.1 Macroeconomic costs due to the current LWEE distribution

This section assesses the production changes due to LWEEs over 200 years in the NEDyM model, starting from its stable equilibrium (no population change

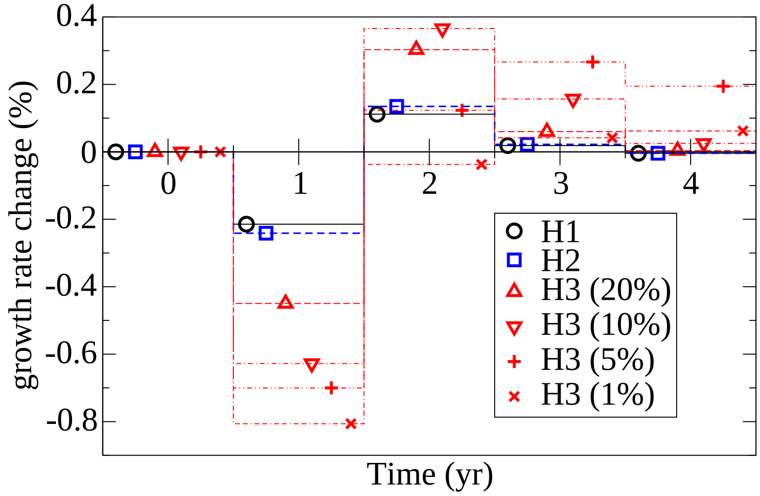


Fig. 6. Changes in economic growth due to the disaster, year per year, for the different hypotheses.

nor technical change is included). Obviously, the aim of is not to simulate 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. In order to have a representative set of very rare LWEEs, the simulation has to be very long, justifying the 200-year time horizon.

In this case, the annual mean cost of the LWEEs is about 0.002% of GDP (*i.e.* 180 millions euros per year). Figure 7 shows the macro-economic consequences on production: because of LWEEs, the mean production decreases by about 0.05% over the long term, showing that the dynamic processes multiply by a factor 20 the extreme event costs. To assess the robustness of these figures, the same simulation is carried out with a linear pdf tail instead of the Weibull pdf tail. This additional simulation leads to production losses of the same order of magnitude (-0.04%), showing the meaningfullness of the results in spite of the LWEE series shortness.

To assess the importance of the short-term processes, that cannot be taken into account in a classical long-term growth model, the annual mean loss of the LWEEs is applied to the model instead of the year-per-year losses. In this case, the production is only reduced by 0.02%, showing that taking into account the short-term processes multiply by two the mean macroeconomic costs of the LWEEs. Thus, the short-term processes are responsible for 50% of the long-term costs, and are neglected in a Solow-like growth model. The mean GDP losses with the different hypotheses are summarized in Tab. 2.

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

Table 2
Mean GDP losses due to LWEEs with three different models: the averaged direct costs (mean of the LWEEs costs); the long-term growth model (Solow-like) dynamic costs, taking into account long-term dynamics; the NEDyM assessment, taking into account short-term processes.

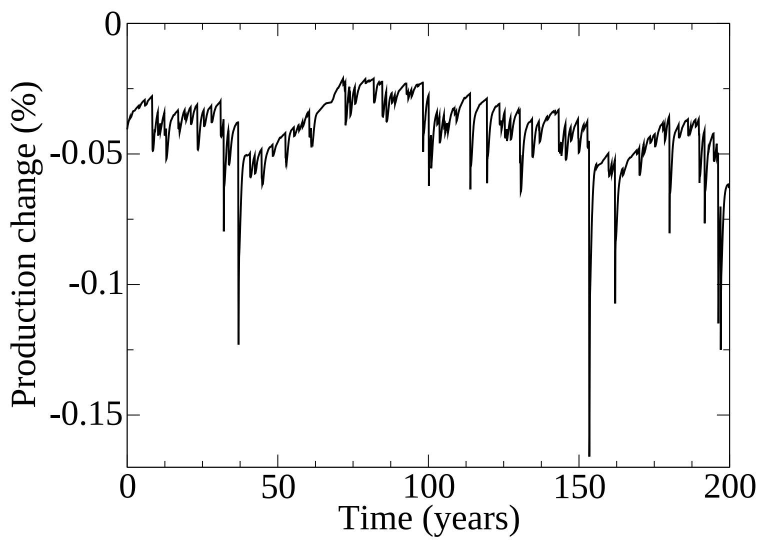


Fig. 7. Production change due to the current LWEE distribution for the EU.

Moreover, in NEDyM, short-term consequences are added to this higher mean GDP loss: the largest shocks reach 0.15% of production decrease over a few years, which is really significant. The consequences on unemployment are small, about 0.02%, negative just after the shocks and positive during the rebuilding phases (not shown).

Still, the consequences on social groups or regions may be more significant. To illustrate this, LWEEs are assumed not to impact European Union as a whole (with perfect sharing of the damages over Europe), but only a smaller country. The surface of this country and its economy are supposed to be 10% of the European ones. In this case, the annual mean cost of the LWEEs is unchanged, about 0.002% of the GDP, since LWEEs are more intense but less frequent. The consequences, however, are very different: LWEEs occur only every 40 years in average and their consequences are large. Just after the shock, production is reduced by more than 0.5%, and the shock can last up to one decade. Additional unemployment can reach 0.2% during the shock.

This suggests that risk sharing helps to cope with LWEEs: most of the adverse effects on welfare come from the shock, during the few years following a LWEE. Risk sharing increases the frequency but decrease the intensity of the shocks, leading to approximately the same mean production losses, but smoothing the shocks and their effects on welfare: risk sharing on a scale as large as possible is beneficial in NEDyM.

5.2 Economic Consequences of a change in the LWEE distribution due to climate change

The aim of this section is to assess whether changes in the LWEEs distribution due to climate change could have significant impacts on macroeconomic aggregates.

5.2.1 Scenario

The modeling of LWEE distribution changes described in section 3.2 is used. In a first step, *scenario* simulations are carried out with *ad hoc* hypotheses: $\alpha_p = 1$ (*i.e.* the extreme event probability is multiplied by 2 for a maladjustment of 1°C) and $\alpha_z = 1$ (*i.e.* the mean cost of an extreme event is multiplied by 2 for a maladjustment of 1°C). Several simulations are carried out in order not to depend on one realization of the random process.

In the simulations, the maladjustment increases from 0°C to 2°C in 2100 and is stabilized at 2.5°C in 2250. The annual mean LWEE costs rise from about 0.002% of GDP in 2000 to about 0.06% of GDP in 2100. Results in terms of production are reproduced in Fig. 8. It shows that additional extreme events due to climate change lead to a mean production loss of about 0.5% in 2100 and about 0.7% in 2200.

The increase of the production losses due to LWEE (from 0.05% of GDP in the current climate to 0.5% in 2100 because of climate change) shows that the economy is vulnerable to extreme events and that climate change can raise significantly the macro-economic costs of the LWEEs.

As illustrated by the sensitivity analysis in section 4.3.3, the production losses due to extreme events depend strongly on the ability of the economy to fund

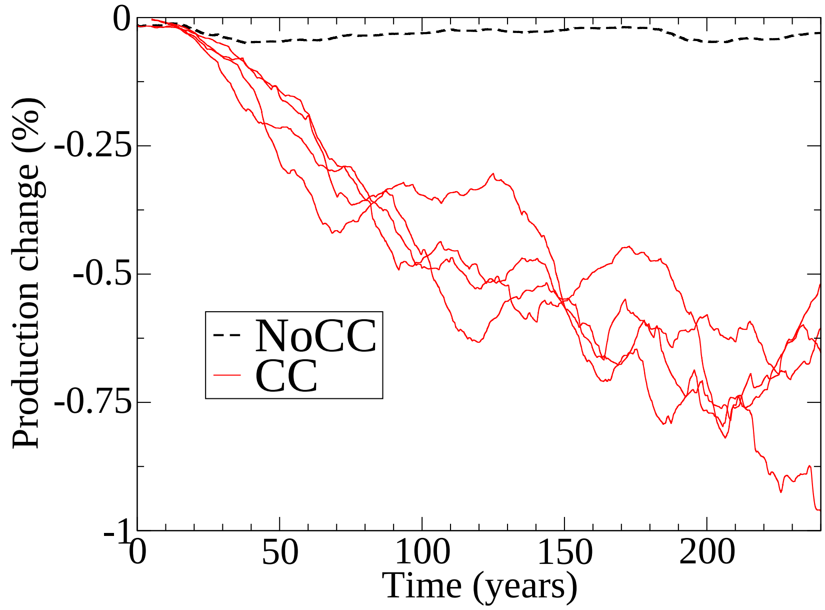


Fig. 8. 10-year running average of the production changes due to LWEEs without climate change (referred to as *No CC*) and with climate change (*CC*, 4 realizations), for $f_{max} = 10\%$.

a quick rehabilitation of the damages. This is modeled through f_{max}, which represents the maximum amount of repairing expenditures, with respect to the total amount of investments. Here, the value of f_{max} is high (10%) and requires some discussion. First, in case of climate change, many investments could be required to adapt the productive capital and the infrastructures to the new climate (*e.g.* changes in housing, in harbor infrastructures, in nuclear plant cooling systems, in agriculture practice...) and to respond to an increasing number of "small" WEEs, that are neglected in this simulation. These investments may reduce the amount of money the economy can afford for LWEE damage repairing. Second, this simulation focus on Europe, that is a rich region able to mobilize large financial means. The case of poor countries is very different: they currently have strong difficulty to fund the rehabilitation after each natural disaster (Benson and Clay, 2004) and it is likely that the value of f_{max} in developing countries is much lower than 10%.

These problems, and the uncertainty on climate change, justify to carry out a sensitivity study on f_{max}, α_z and α_p.

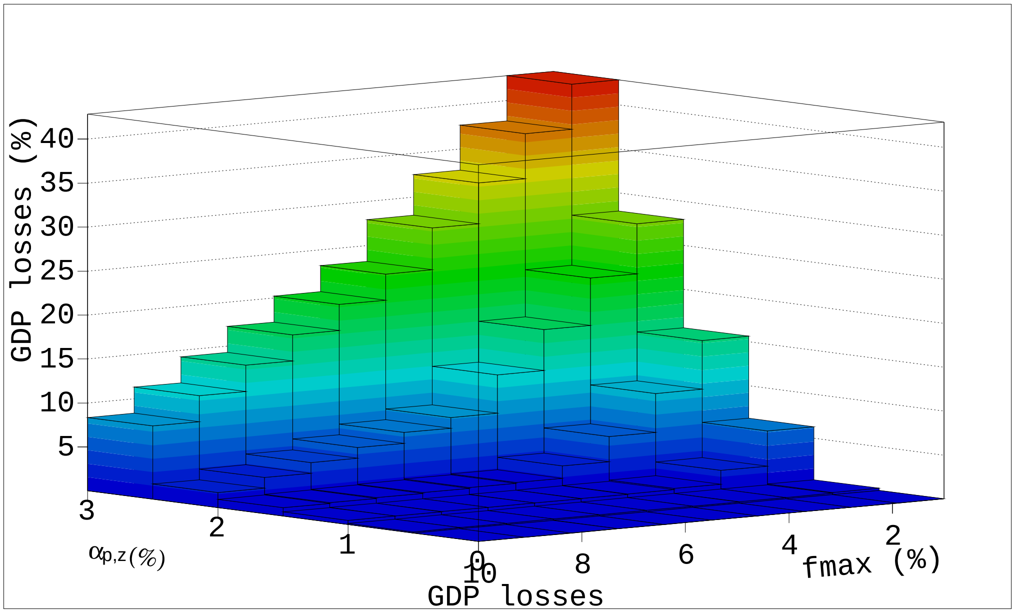


Fig. 9. Mean GDP losses due to LWEEs between 2100 and 2150, in percent of GDP, with respect to the value of f_{max} (in %) and to the value of the LWEE parameters ($\alpha_p = \alpha_z$).

5.2.2 *Sensitivity analysis*

The key parameters in the previous simulation are f_{max}, the ability to fund the rehabilitation and repair LWEE damages, and α_p and α_z, which describe how climate change will affect the LWEE distribution. Thus a sensitivity analysis is carried out, with 30 simulations with different parameter values: to simplify, it is assumed that $\alpha_p = \alpha_z$ and simulations are carried out with the values 1, 1.25, 1.5, 2 and 3. It means that the frequency and the mean cost of the LWEEs are multiplied by 2, 2.25, 2.5, 3 and 4. For each value of α_p, six simulations are carried out with six values of f_{max}: 10%, 5%, 4%, 3%, 2% and 1%.

Figure 9 represents the mean production loss due to LWEEs between 2100 and 2150, with respect to the value of f_{max} and to the value of α_p and α_z. For $f_{max} = 1\%$ and $\alpha_z = \alpha_p = 3$, the total production losses reach -60%. The interesting point is, however, the existence of a bifurcation: for each value of f_{max}, LWEE damages are limited while α_p and α_z are lower than a threshold, but, as soon as they exceed this threshold, the production losses increase rapidly until the economy collapse. This illustrates the economic vulnerability to LWEEs: as soon as extreme event costs exceed the economic funding capacity, the damages are multiplied very rapidly. It shows how important it is to have an economic organization able to cope efficiently with extreme events. If the extreme event costs rise because of climate change, it may require a specific adaptation of the economic organization, allowing for a quicker rehabilitation 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}.

This kind of bifurcation may also help to explain why no strong economic development is observed in some poor countries in spite of a large growth potential: because they face regular extreme events that destroy their infrastructures, and because they do not have the financial capacity that would allow them to repair quickly after each shock, they cannot accumulate productive capital and develop their economy. As an example, Guatemala adds to its social unrest an impressive series of weather catastrophes [11] that prevents from any development. In the same region, according to the Honduran prime minister, the hurricane *Michele* in 2001 *"put the country's economic development back 20 years"* (IFRCRCS (2002)). These model results give a quantitative assessment of the rehabilitation funding problem, considered as a strong obstacle to economic development by Gilbert and Kreimer (1999) or Benson and Clay (2004).

These results illustrate also that the economic assessment of climate change does not depend only on beliefs on climate change, but also strongly on beliefs on the current economic organization and resilience and on its adaptive capacity. The damages will be a function both of the climate change intensity and of the economic ability to respond to climate change.

More generally, this shows how a short-term feature (a maximum amount of expenditures allocated at any time to productive capital and infrastructure repairing) can change the behavior of a long-term growth model. Even if the model is very crude, interactions between short-term and long-term processes prevent from averaging the short-term perturbations over the time step of a long-term growth model.

6 Conclusions

This article presents the non-equilibrium dynamic model NEDyM. NEDyM is demonstrated to be equivalent to the neoclassical Solow growth model over the

[11] Guatemala faced the hurricane *Mitch* in 1998, 3 years of drought from 1999 to 2001, and the hurricane *Michele* in 2001, leading to catastrophic human and economic losses.

long-term, when parameters are evolving slowly with respect to the adjustment delays. Over the short-term, however, NEDyM exhibits Keynesian features and reproduces qualitatively realistic economic responses to shocks.

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 repairing disaster damages. This modeling allows for a better representation of the macroeconomic consequences of disasters, as shown by a validation against the 1999 Marmara earthquake in Turkey.

An assessment of the current and future costs of extreme events is then carried out, with the following conclusions: (i) Dynamic processes multiply the extreme event instantaneous costs by a factor 20; the short-term processes are responsible for 50% of this long-term cost amplification; (ii) Even though the current distribution of extreme events does not lead to significant macroeconomic damages, the climate-change-induced changes could be responsible for significant GDP losses. These results emphasize the need for large research efforts on the prediction of extreme events. (iii) Risk sharing of extreme event losses is likely to reduce the consequences of the shocks and to improve the economic resilience to extreme events. (iv) The future production losses due to extreme events depend, with strong non-linearity, both on the changes in the extreme distribution and on the economic ability to fund the rehabilitation after each extreme event. This last result shows that climate change may force a specific adaptation of the economic organization. It also illustrates how short-term economic constraints can dramatically change the long-term behavior of a model and may partly explain the lack of development of poor countries that experience repeated natural catastrophes without large funding capacity.

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 (2002)). 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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(lxvi) This paper has been presented at the 4th BioEcon Workshop on “Economic Analysis of Policies for Biodiversity Conservation” organised on behalf of the BIOECON Network by Fondazione Eni Enrico Mattei, Venice International University (VIU) and University College London (UCL) , Venice, August 28-29, 2003

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(lxxi) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications”, organised by Fondazione Eni Enrico Mattei and Consip and sponsored by the EU, Rome, September 23-25, 2004

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