Endogenous Business Cycles and the Economic Response to Exogenous Shocks

Stéphane Hallegatte and Michael Ghil

NOTA DI LAVORO 20.2007

FEBRUARY 2007

ETA – Economic Theory and Applications

Stéphane Hallegatte, *Center for Environmental Sciences and Policy, Stanford University and Centre International de Recherche sur l'Environnement et le Développement, Ecole Nationale des Ponts-et-Chaussées, Nogent-sur-Marne, France*

Michael Ghil, *Département Terre-Atmosphère-Océan and Environmental Research and Teaching Institute, Ecole Normale Supérieure, Paris France and Department of Atmospheric and Oceanic Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, USA*

Endogenous Business Cycles and the Economic Response to Exogenous Shocks

Summary

In this paper, we investigate the macroeconomic response to exogenous shocks, namely natural disasters and stochastic productivity shocks. To do so, we make use of an endogenous business cycle model in which cyclical behavior arises from the investment–profit instability; the amplitude of this instability is constrained by the increase in labor costs and the inertia of production capacity and thus results in a finite-amplitude business cycle. This model is found to exhibit a larger response to natural disasters during expansions than during recessions, because the exogenous shock amplifies pre-existing disequilibria when occurring during expansions, while the existence of unused resources during recessions allows for damping the shock. Our model also shows a higher output variability in response to stochastic productivity shocks during expansions than during recessions. This finding is at odds with the classical real-cycle theory, but it is supported by the analysis of quarterly U.S. Gross Domestic Product series; the latter series exhibits, on average, a variability that is 2.6 times larger during expansions than during recessions.

Keywords: Business cycles, Natural disasters, Productivity shocks, Output variability

JEL Classification: E01, E20, E32, E40, Q54

The authors are thankful to Benjamin Malin for his comments and suggestions on an earlier version of this article. This research was supported by the European Commission's Project No. 12975 (NEST) "Extreme events: Causes and consequences (E2-C2)".

Address for correspondence:

Stéphane Hallegatte
Centre International de Recherche sur l'Environnement et le Développement
and Ecole Nationale de la Météorologie, Météo-France
45bis, Av de la Belle Gabrielle
F-94736 Nogent-sur-Marne
France
Phone: +33 1 43 94 73 96
Fax: +33 1 43 94 73 70
E-mail: hallegatte@centre-cired.fr

1. Introduction and motivation

Economists have been aware of certain cyclical characteristics of economic evolution since the works of A. Smith (1776), D. Ricardo (1810), C. Juglar (1862) and many others. Two main theories have attempted, over the years, to explain the causes and characteristics of business cycles. The leading one today is known as the real business cycle (RBC) theory and assumes that economic fluctuations arise from exogenous shocks and that the economic system is otherwise stable (e.g., Slutsky, 1927; Frisch, 1933; Kydland and Prescott, 1982). The second one is the endogenous business cycle

(EBC) theory, which proposes that economic fluctuations are due to intrinsic processes that endogenously destabilize the economic system (e.g., Harrod, 1939; Samuelson, 1939; Goodwin, 1967; Chiarella *et al.*, 2005). Both theories have their successes and shortcomings, but the RBC theory is the one that garners consensus in the current economic literature.

The existence of these two alternative theories of economic fluctuations is a significant obstacle in any attempt to assess the economic cost of natural disasters (e.g., hurricanes or earthquakes) or other exogenous shocks (e.g., the implementation of climate policies aiming at reducing the emissions of greenhouse gases). Indeed, to carry out such an assessment, one has to decide first within which macroeconomic setting to work, as the underlying economic hypotheses can strongly influence the results. Overcoming the controversy between the RBC and EBC theories and achieving a constructive synthesis would thus reduce in a significant manner the uncertainty in the assessment of disaster and policy costs. On the other hand, investigating the consequences of exogenous shocks, like natural disasters, can also provide useful insights into economic behavior out of steady state in general and help achieve a unified theory of business cycles: the validation of RBC and EBC models against the history of past disasters could provide evidence in support of such a theory.

The purpose of this paper is to compare the two types of models in the way they treat external shocks and the effects these shocks have on the economic behavior they capture. In particular, we consider systematically the effect of exogenous shocks on EBC models.

In the next two sections, the RBC and EBC theories, respectively, will be described and discussed at some length. In Section 4a, a Non-Equilibrium Dynamic Model (NEDyM), already presented by Hallegatte *et al.* (2006a, b), will be used to show that, in the EBC framework, the particular phase of a business cycle matters in assessing the economic impacts of natural disasters: in NEDyM, this impact is increased by internal economic processes when the disaster occurs during an expansion phase, while the opposite is the case during a recession.

More generally, this result suggests that economic fluctuations due to exogenous shocks might be larger during expansions than during recessions. In Section 4b, we model therefore exogenous shocks in our EBC model, in order to investigate the interactions between exogenous and endogenous dynamics. In Section 4c we use National Bureau of Economic Research (NBER) data to compare the variance of U.S. Gross Domestic Production (GDP) during expansions and recessions. The large difference between the two can easily be interpreted in our extended EBC framework, while being at odds with classical RBC findings. The results are summarized and discussed in Section 5.

2. Real business cycle (RBC) theory

In a recent paper, Rebelo (2005) reviewed the main findings of RBC theory[1], which constitutes nowadays the mainstream approach to business cycles. Originating from the

[1] More generally, what is said here about RBC models is also valid for other Dynamic Stochastic General Equilibrium (DSGE; see for instance Smets and Wouters, 2005) models, in which exogenous shocks can be real or monetary.

ideas of Slutsky (1927) and Frisch (1933), this theory is based on the hypotheses of perfect markets and rational expectations. RBC theory states that business cycles are due to exogenous shocks in "real" (i.e. not purely monetary) variables and processes (e.g., sudden changes in technology, consumer preferences, oil prices or fiscal shocks), while the economic system can be modeled as a stable system that returns back to its steady state after having been perturbed by these exogenous shocks.

Among the numerous papers that followed this approach, Kydland and Prescott (1982) provided a break-through for economic theory in that (i) their paper proposed the first mathematical model for RBCs that was able to reproduce economic fluctuations; and (ii) it went beyond the qualitative comparison of model properties with stylized facts that had dominated theoretical work on macroeconomics up to that point. When properly calibrated and fed with productivity shock series built using Solow (1956) residuals, this RBC model and its followers do a fairly good job in reproducing statistical properties of economic series. RBC models, however, while reproducing rather well the standard deviation of most macroeconomic variables, encounter substantial difficulties in reproducing the co-movements of and correlations between variables (see for instance, Rotemberg and Woodford, 1996; Tables 1 and 3 in King and Rebelo, 2000; or Figures 1–4 in Ireland, 2003).

RBC models are also able to reproduce historical data for some variables in an impressive manner, as shown by King and Rebelo (2000). The historical fluctuations reproduced by these models are, however, entirely driven by exogenous productivity shocks. One needs to produce, therefore, a history of technological shocks in which one has to identify and describe the real shocks that cause each output variation. For instance, economic data show a strong recession in the United States in 1982. This recession must be related, according to RBC theory, to a productivity shock, which would correspond to a rather counter-intuitive technological regression: such a "real shock" has never been identified, described or explained, thus calling in question the findings of RBC theory. Moreover, the almost exclusive reliance of RBC model trajectories on exogenous productivity shocks makes them unsuited to economic forecasting (e.g., Rotemberg and Woodford, 1996), which is a definite drawback, since forecasting skills would provide a compelling validation of the theory.

While many stylized facts of the business cycle are well captured by basic RBC models, most of them — like the cycles' average duration or the fact that expansions are longer than recessions — are entirely forced by the technology shocks that are calibrated exogenously. In this sense, RBC theory mainly "transfers the issue" from explaining the fluctuations of economic variables to explaining the fluctuations of productivity, without achieving the latter, so far (see also King, 1995).

More recently, modified RBC models, sometimes incorporating New Keynesian features or monetary processes, have been proposed to explain additional stylized facts and correct some flaws of the basic model, through the introduction of innovative mechanisms: (i) varying capital utilization to reproduce realistic cycle amplitudes with small, nonnegative changes in productivity (King and Rebelo, 2000); (ii) introducing capital constraints to explain cycle asymmetry (e.g., Hansen and Prescott, 2005)[2]; (iii)

[2] Hansen and Prescott (2005), moreover, use a nonlinear solution method in their RBC model, making it thus able to capture nonlinear processes. As a consequence, shock responses in their model, unlike in classical RBC models, are not additive.

relying on monopolistic competition, price stickiness and monetary policies to explain business cycle persistence and correlation between nominal and real variables (e.g., Hairault and Portier, 1993; Ellison and Scott, 2000; Ireland, 2003; Christiano *et al.*, 2005); or (iv) matching friction in the labor market along with wage stickiness to explain the large response of employment to small changes in productivity and the co-movement of output and wages (Christiano *et al.*, 2005; Hall, 2005). In certain cases at least, the improvements so obtained are accompanied by loss or deterioration of some of the previously explained cycle features (e.g., Ellison and Scott, 2000; Ireland, 2003).

Starting from the perfect-market and rational-expectation approach of Kydland and Prescott (1982), the most recent RBC models have thus had to incorporate frictions in markets and imperfections in expectations to reproduce more realistic business cycles, while still being mainly driven by exogenous shocks. Introducing frictions and imperfections, though, can also lead to macroeconomic models in which fluctuations arise endogenously, from intrinsic instabilities. The latter approach, recently embraced also by Hahn and Solow (1995), has led to the endogenous business cycle (EBC) theory, which is described in the next section.

3. An endogenous explanation of business cycles?

There are few, if any, systems of high complexity with stable behavior. Most physical and biological systems exhibit natural variability, i.e. they include destabilizing processes that make them deviate from equilibrium; limitations on resources, on the other hand, cause these deviations to remain bounded in amplitude. Examples of such systems are the global climate system or regional ecosystems dominated by predator–prey interactions.

Concerning the coupled ocean–atmosphere system, both short-term weather and longer-term climate variability arise from the interaction between the variability of exogenous forcing and the interplay of nonlinear feedbacks (Ghil et al., 1985; Ghil, 1994, 2002). Variations of external forcing do play a key role in the variability: indeed, the diurnal and seasonal cycles steer a large part of this variability and are clearly visible in the power spectrum of meteorological and oceanographic variables. Nonlinear feedbacks in the climate system though – such as those between cloud cover or surface properties and the radiative fluxes – are essential drivers of long-term and large-scale variability, even in the absence of exogenous forcing variations.

The same interaction can be observed in ecosystems. Loeuille and Ghil (2004) compared intrinsic (endogenous) and climatic (exogenous) factors in the population dynamics of North American mammals. They found that both types of factors have to be taken into account to understand the behavior of animal population series. Again, variability arises from the interplay of nonlinear, endogenous dynamics and responses to exogenous shocks.

The same combined explanation can be proposed for economic fluctuations and business cycles. Nobody would claim that exogenous real shocks do not play any role in business cycles; e.g., the strong economic expansion of the late 1990s was clearly driven by the rapid development of new technologies. But denying any role to endogenous fluctuations that are due to unstable and nonlinear feedbacks within the economic system itself seems also rather unrealistic. Even within the neoclassical tradition — with perfect markets and rational expectations — Day (1982), Grandmont (1985), Gale (1973), Benhabib and Nishimura (1979) proposed models in which endogenous fluctuations arise from savings behavior, wealth effects and interest rate movement, interactions between overlapping generations or interactions between different sectors.

As soon as market frictions, imperfect rationality in expectations or aggregation biases are accounted for, strongly destabilizing processes can be identified in the economic system. Their existence has been proposed and their importance noted by numerous authors: Harrod (1939) stated that the economy was unstable because of the absence of an adjustment mechanism between population growth and labor demand, even though Solow (1956) proposed later the choice of the labor–capital intensity by the producer as the missing adjustment process. Kalecki (1937) and Samuelson (1939) proposed simple business cycle models based on a Keynesian accelerator–multiplier and delayed investments. Later on, Kaldor (1940), Hicks (1950) and Goodwin (1951, 1967) developed business cycle models in which the destabilizing process was still the Keynesian accelerator–multiplier and the stabilizing processes were financial constraints, distribution of income or the role of the reserve army of labor. In Hahn and Solow (1995, chapter 6), fluctuations can arise from imperfect goods market, frictions in the labor market and from the interplay of irreversible investment and monopolistic competition.

Exploration of EBC theory was quite active in the middle of the 20th century and much less so over the last 30 years. A renaissance of this approach seems to occur, with Hillinger (1992), Chiarella and Flaschel (2000), Chiarella *et al.* (2002), Chiarella *et al.* (2005) and Hallegatte *et al.* (2006a,b) having recently proposed models of EBCs that rely on a much more mature dynamical system theory than available before this hiatus. These models reproduce business cycles characterized by certain realistic features and arising from nonlinear relationships between economic aggregates.

The renascent EBC models are not able, so far, to reproduce historical data as closely as RBC models do. This shortcoming can be easily explained by the fact that their calibration involves a much lower number of internal parameters, while RBC models use a long time series as tunable input. It is not surprising, moreover, that models with only a few state variables – typically less than a few dozen – were unable to reproduce the details of historical series that involve processes that lie explicitly outside the scope of an economic model (e.g., geopolitical tensions). Taking into account external shocks, as we do here, can only improve the match between historical data and the extended EBC models proposed herein.

More specifically, Hallegatte *et al.* (2006a) formulated a neoclassical model with myopic expectations, in which adjustment delays have been introduced in the labor and goods market clearings and in the investment response to profitability signals. In this NEDyM model, business cycles originate from the instability of the profit–investment relationship (a relationship similar to the Keynesian accelerator–multiplier) and are constrained by the interplay of three processes: (i) the increase of labor costs when the employment rate is high (a reserve army of labor effect); (ii) the inertia of production capacity and the consequent inflation in goods prices when demand increases too rapidly; and (iii) financial constraints on investment.

The main control parameter in the model is the flexibility of investment α_{inv}, which measures the investment adjustment time in response to profitability signals. For rapid adjustment, the model has a stable equilibrium, which was matched to the economic state of the European Union (EU-15) in 2001. As the adjustment time increases, this equilibrium loses its stability and the model then possesses a stable periodic solution; this "limit cycle," in the language of dynamical systems, is characterized by variables that oscillate around their equilibrium values.

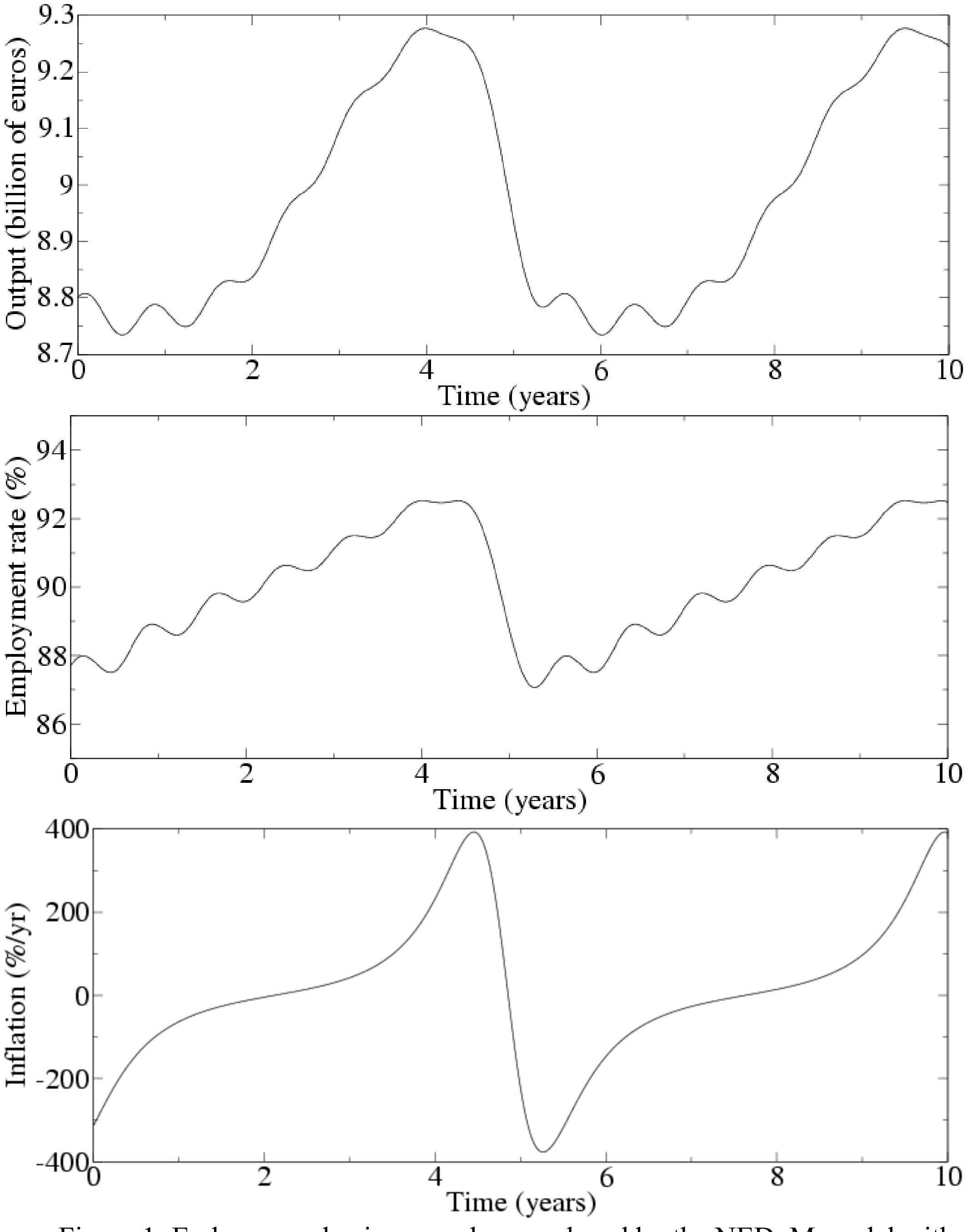

Figure 1: Endogenous business cycle reproduced by the NEDyM model with a flexibility of investment $\alpha_{inv} = 2.5$, in terms of output (top panel), employment (middle panel) and price inflation (bottom panel). After Hallegatte *et al.* (2006a).

The business cycle produced by the model with $\alpha_{inv} = 2.5$ (see Fig. 1) is far from perfect, in particular because the amplitude of the oscillation in monetary variables is too large; thus inflation, for instance, is too large by two orders of magnitude. The latter shortcoming of the NEDyM model is due to the fact that market adjustments are entirely made through prices in the model, and we will show in a subsequent paper that this can be corrected by taking into account reasonable mechanisms in the behavioral equations, following Gali (1999). Most observed qualitative features, though, are fairly well reproduced; e.g., the mean period is 5–6 years, the recessions are much more rapid than the expansions, the inflation and production are well correlated and the phase relations between variables are generally correct. Another interesting feature of the model's business cycles, to which we will return later on, is that the expansion phases exhibit shorter-period perturbations, whereas the recessions are quite smooth.

For even higher values of α_{inv}, the model exhibits also chaotic behavior, with Lyapunov times that lie between 0.09 and 0.11 yr $^{-1}$. It follows that, for any parameter set that produces similar behavior, in this or any other model, no economic forecast would be able to provide an accurate and reliable prediction over more than 10 years. In such a situation, assuming rational expectations[3] is still formally possible; but the assumption of perfect knowledge of future behavior can only extend out to the Lyapunov time, justifying the use of models with bounded rationality instead of perfect foresight.

4. Exogenous shocks in models with endogenous variability

As we have seen, both RBC and EBC models have their shortcomings, and thus it seems that an entirely satisfactory theory of the business cycle has still to be developed. Such a theory should be able to explain the properties of business cycles and output volatility without relying exclusively on the properties of exogenous shocks that are not fully understood.

Two strategies are thus possible. First, maintain the RBC framework but explain the exogenous shocks the model takes as input, and their characteristics, from scratch. Studying technological progress and innovation belongs to this strategy (see for example Rotemberg and Woodford, 1994). Second, following the EBC theory, it is possible to assume that business cycles originate from within the economic system, because of intrinsic destabilizing processes, but are also continuously perturbed by additional exogenous shocks. Even though the two approaches are complementary and together can contribute to explaining the actual business cycle process, this paper will now focus on the second one, through the introduction of exogenous shocks into our EBC model.

4a. The case of natural disasters

EBC models are just as able as RBC models to capture the effects of exogenous shocks, which are likely to contribute significantly to economic fluctuations. Even though EBC models have not reproduced, so far, a perfectly realistic business cycle and, therefore,

[3] Assuming rational expectation in an economic model amounts to assume that all agents (i) are able to make unbiased predictions; (ii) know all equations and behavioral rules of the model; (iii) know the true value of all deterministic exogenous forcings; (iv) know the true probability distributions governing all exogenous stochastic terms; and (v) know the realized values of all endogenous variables in the present and the past.

have not been able to provide realistic estimates of real or monetary economic variables, these models can help us understand the interactions between exogenous shocks and endogenous dynamics.

Benson and Clay (2004), for instance, have mentioned that the overall cost of a natural disaster might depend on the pre-existing economic situation. As an example, the Marmara earthquake in 1999 caused destructions amounting to between 1.5 and 3 percent of Turkey's GDP; its cost in terms of production loss, however, is believed to have been kept at a relatively low level by the fact that the country was experiencing a strong recession of –7% of GDP in the year before the disaster (World Bank, 1999). Indeed, the recovery effect from the additional activity due to reconstruction might have compensated, at least partly, the direct damages of the disaster.

To investigate this issue, we apply the NEDyM model of Hallegatte *et al.* (2006a), using a value of the investment flexibility α_{inv} of 2.5, for which the model exhibits perfectly periodic business cycles (see section 3 and Fig. 1). We introduce into this model the disaster-modeling scheme of Hallegatte *et al.* (2006b), in which natural disasters destroy the productive capital through the use of a modified production function and reconstruction investments are also included. We use the same parameter values as in these two models, of the economy and of disasters, and assume the same ability to fund and conduct reconstruction (f_{max} in the latter model). In our modeling framework, the economic shocks induced by natural disasters are one or two orders of magnitude smaller than observed economic fluctuations. The total cost of natural disasters is, indeed, difficult to assess in reality (Albala-Bertrand, 1993; Munich Re, 2005).

To evaluate how the cost of a disaster depends on the pre-existing economic situation, we apply the same loss of productive capital at different points in time, and we assess the total GDP losses, integrated over time and without discounting. Figure 2 shows in the top panel the model's business cycle, with respect to the time lag relative to the end of the recession. The bottom panel shows the overall cost of a disaster that causes destruction amounting to 3% of GDP, with respect to the time the disaster occurs, also expressed as a time lag relative to the end of the recession. We find that the total GDP losses caused by the disaster depend strongly on the phase of the business cycle in which the disaster occurs: the cost is minimal if the event occurs at the end of the recession and it is maximal if the disaster occurs in the middle of the expansion phase, when the growth rate is largest.

There is, therefore, a "vulnerability paradox":

- a disaster occurring when the economy is depressed results in lower damages, thanks to the recovery effect of the reconstruction, which activates unused resources; and
- a disaster occurring during the high-growth period results in larger damages, as it enhances pre-existing disequilibria, such as price and wage inflation, under-production, and lack of financial resources for investment.

Surprisingly, a robust economy with a high growth rate is thus much more vulnerable to natural disasters than a depressed economy that did not mobilize all its resources.

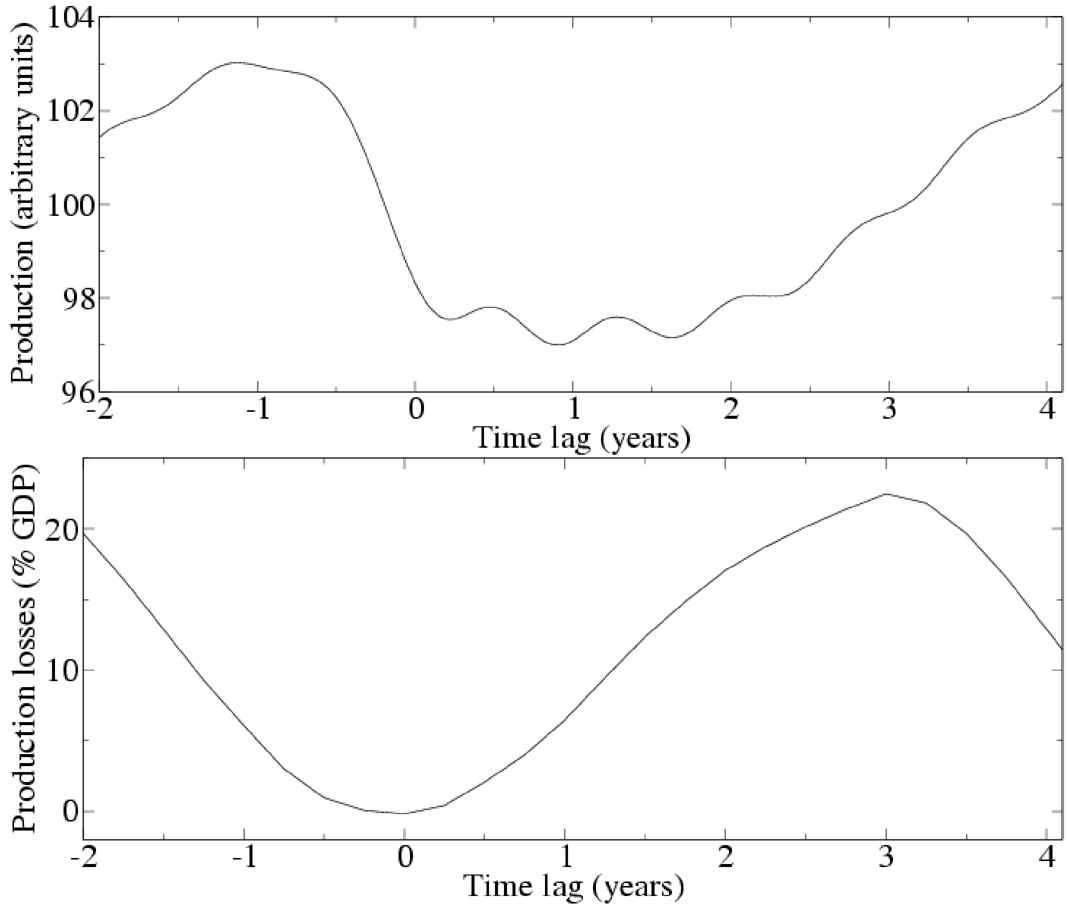

Figure 2: The effect of one natural disaster on an endogenous business cycle. Top panel: the business cycle in production, as a function of the time lag with respect to the cycle minimum. Bottom panel: total GDP losses due to one disaster, as a function of the same time lag.

Of course, this conclusion is valid only for one and the same economy in different phases of its business cycle. If two economies at different stages of economic development are compared, it is very likely that the poorer one will be more vulnerable because of other factors: lower ability to predict the disaster and warn the population, lower ability to fund mitigation actions like the construction of flood protection systems, poorer quality of housing, as well as weaker ability to provide post-disaster relief and to fund and conduct reconstruction.

4b. Modeling generic shocks in EBC models

Natural disasters are but one of many possible shocks on the economy. The kind of results shown Fig. 2 might therefore also be valid for other types of real shocks: oil-price shocks, fiscal shocks or technology shocks, among others. Section 4a suggests, indeed, that the amplitude of economic fluctuations due to exogenous real shocks might depend on the phase of the endogenous business cycle, even though natural disasters and other shocks imply very different economic processes. To investigate this issue, the NEDyM model is modified to take into account exogenous shocks in productivity in addition to its endogenous dynamics.

In NEDyM, production Y is determined by a Cobb-Douglas (1927) function:

$$Y = A\,K^{\lambda}\,L^{\mu}\ , \qquad (1)$$

where K is productive capital, L is labor, A is total factor productivity, and where constant returns imply $\lambda+\mu=1$. To introduce productivity shocks, the productivity A is modified through the addition of a factor ξ:

$$Y = \xi\,A\,K^{\lambda}\,L^{\mu}, \qquad (2)$$

driven according to a red-noise or Ohrenstein-Uhlenbeck process :

$$\mathrm{d}\xi = \alpha_{\xi}\,(1-\xi)\,\mathrm{d}t + \sigma \mathrm{d}\upsilon\ , \qquad (3)$$

where t is time and $\mathrm{d}\upsilon$ is a Wiener process (also called white noise). The parameter α_{ξ} in the Langevin equation (3) is such that productivity has a characteristic auto-correlation time of one month, while σ is chosen empirically such that the impact on production of these exogenous shocks is one order of magnitude smaller than the endogenous fluctuations.

A particular realization $\xi(t)$ of this red noise is reproduced in Fig. 3. It has, to a very good approximation, mean zero over sufficiently long time intervals and a standard deviation that is, indeed, much smaller than the amplitude of the business cycle in Fig. 1a.

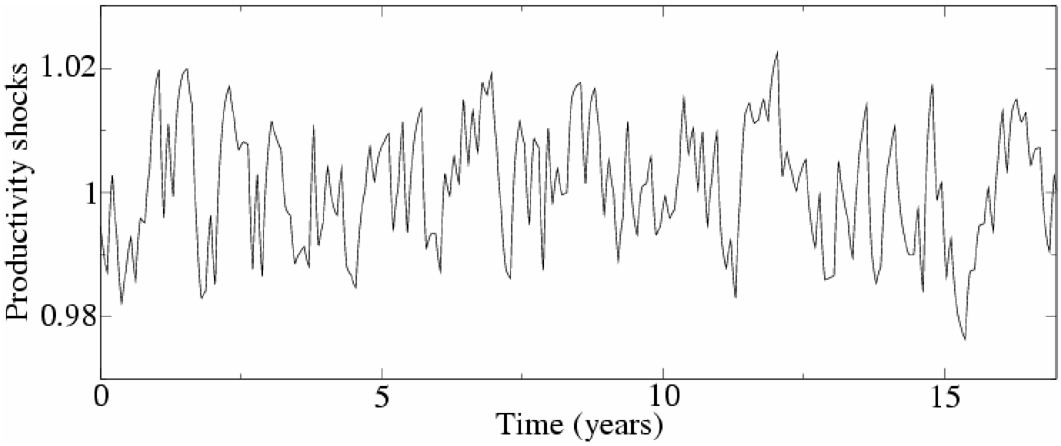

Figure 3: Productivity shocks $\xi(t)$ in NEDyM, as given by Eqs. (2) and (3), for $\sigma = 1.6\ 10^{-3}$.

Using this modified productivity ξA, the NEDyM model yields a business cycle composed of (i) the EBC shown in Fig. 1; plus (ii) the nonlinear effects of the exogenous productivity shocks on coupled model behavior. Indeed, given the NEDyM model's nonlinearities, the effects of the multiple exogenous shocks are neither additive nor simply superposed on the model's steady-state behavior, as in classical RBC models (see Section 2); instead, these exogenous effects interact in a complex manner with the endogenous out-of-equilibrium behavior, as we will see below.

An annualized quarterly production series from the NEDyM model is reproduced in Fig. 4. Of course, the productivity shocks being purely stochastic at this stage of our study, we do not expect the model output series to get any closer to a given historical series.

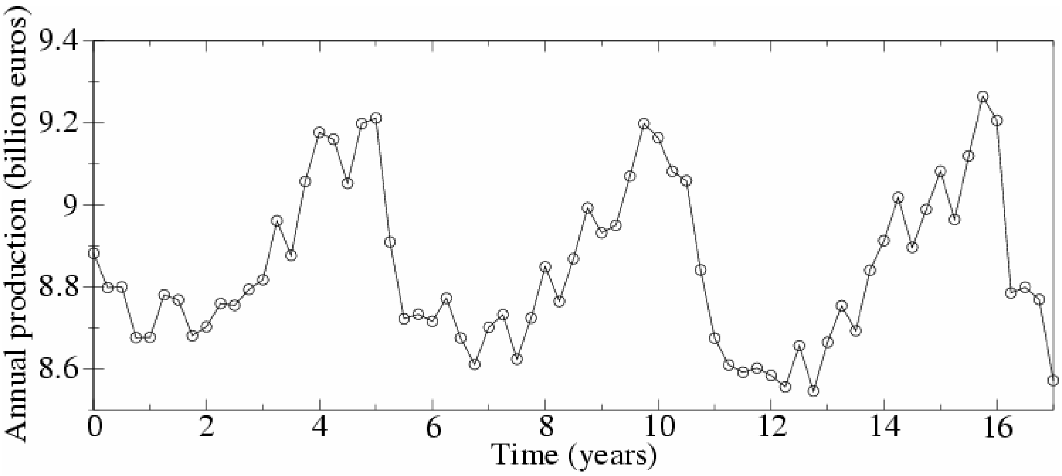

Figure 4: Annualized quarterly production over three NEDyM business cycles with exogenous productivity shocks.

To verify our hypothesis, namely that exogenous shocks lead to more output variability during the expansion phase than during the recession phase, a 150-year anomaly series is created, as the difference between the model's simulated production with exogenous shocks (Fig. 4) and without them (Fig. 1a). These anomalies can be considered as the additional effect of the exogenous shocks on production and they are reproduced in Fig. 5. The time series so obtained contains 26 periods of the model's main business cycle.

The first interesting observation in Fig. 5 is the existence of a near-periodic oscillation in the anomaly series, with a period around 70 years. It follows that the exogenous productivity shocks, though null on average over a few years [see Eq. (3) and Fig. 3], not only perturb the model over the very short term but also excite one or several slow modes of the economic system that are probably damped and therefore not visible in the unperturbed model simulation; see the power spectrum of the business cycle in Fig. 6 of Hallegatte *et al.* (2006a; not shown here).

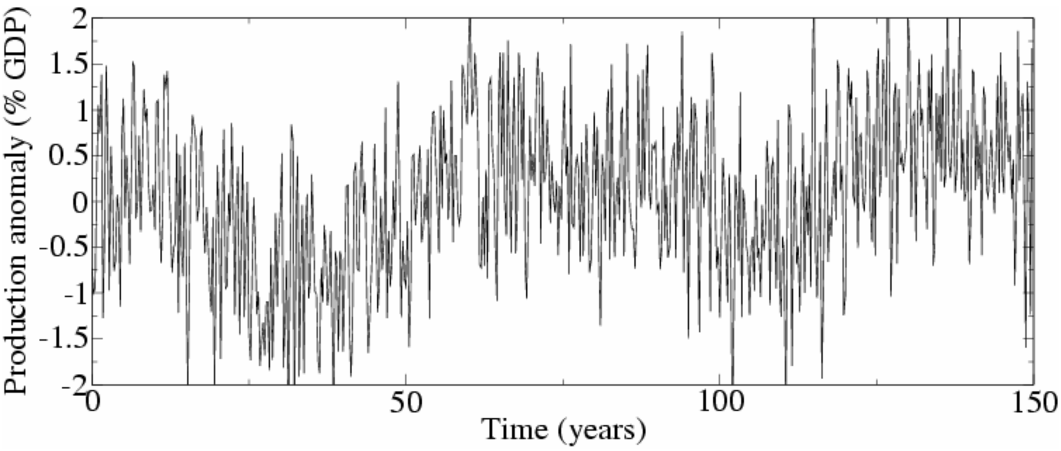

Figure 5: NEDyM production anomalies, over 150 years.

The multidecadal oscillation of Fig. 5 might be related to Kondratieff (1935) cycles and it highlights the complexity of the interactions between endogenous dynamics and exogenous shocks in nonlinear systems. These interactions make it much more difficult to disentangle the effects of endogenous and exogenous processes in the economic system than classic RBC models would suggest; they will be investigated in a follow-up paper.

Returning to the validation of our hypothesis, the variance of the anomaly is computed separately for the 26 expansion phases and the 26 recession phases, as defined in the unperturbed solution of Fig. 1. The variance of the anomaly is then averaged first over the expansion and then over the recession phases: The mean variance over the former is found to be 2.4 times larger than over the latter. The exogenous productivity shocks thus do generate a significantly larger output variability during expansions than during recessions in our EBC model.

4c. Validation using U.S. economic data

To verify whether this model result is validated by actual economic data, we used the NBER table of quarterly U.S. GDP, from 1948 to 2002 (www.nber.org). First we detrended the data set in a very simple manner: two parameters α and β were determined by minimizing the mean-square relative differences, over the 54 years, between observed GDP and the exponential function $g(i) = \alpha \exp(\beta i)$, where i is the quarter, counted from the beginning of the time series. The relative deviation $BC(i)=[GDP(i)-g(i)]/g(i)$ is an approximation of the business cycles superimposed on the exponential growth; it is shown in Fig. 6.

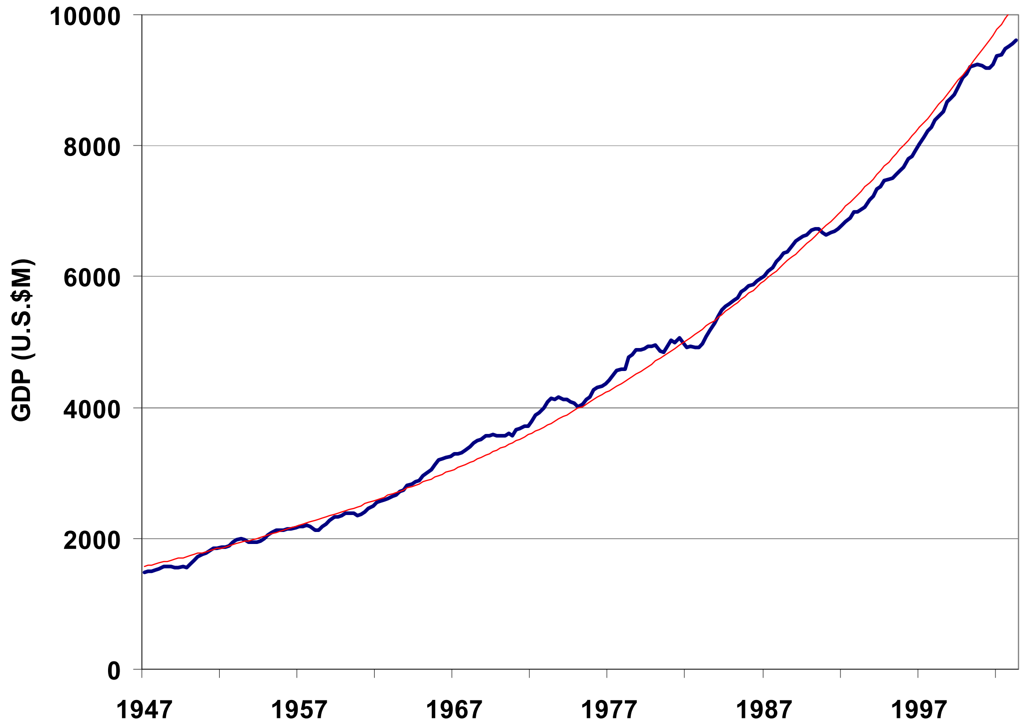

Figure 6: NBER data for quarterly GDP (in blue), and the least-square fitted trend (in red). Abscissa in years from 1947, ordinate in $M.

This detrending method is much simpler than the classical Hodrick and Prescott (1997) filter, which we did not use, because we are interested also in the record's lower-frequency fluctuations that are removed by this filter. Still, the detrended GDP so obtained is, in most even though not in all cases, consistent with the NBER official recession intervals (see Fig. 7). Recall that NBER defines a recession as “a significant decline in economic activity spread across the economy, lasting more than a few months, normally visible in real GDP, real income, employment, industrial production, and wholesale-retail sales”.

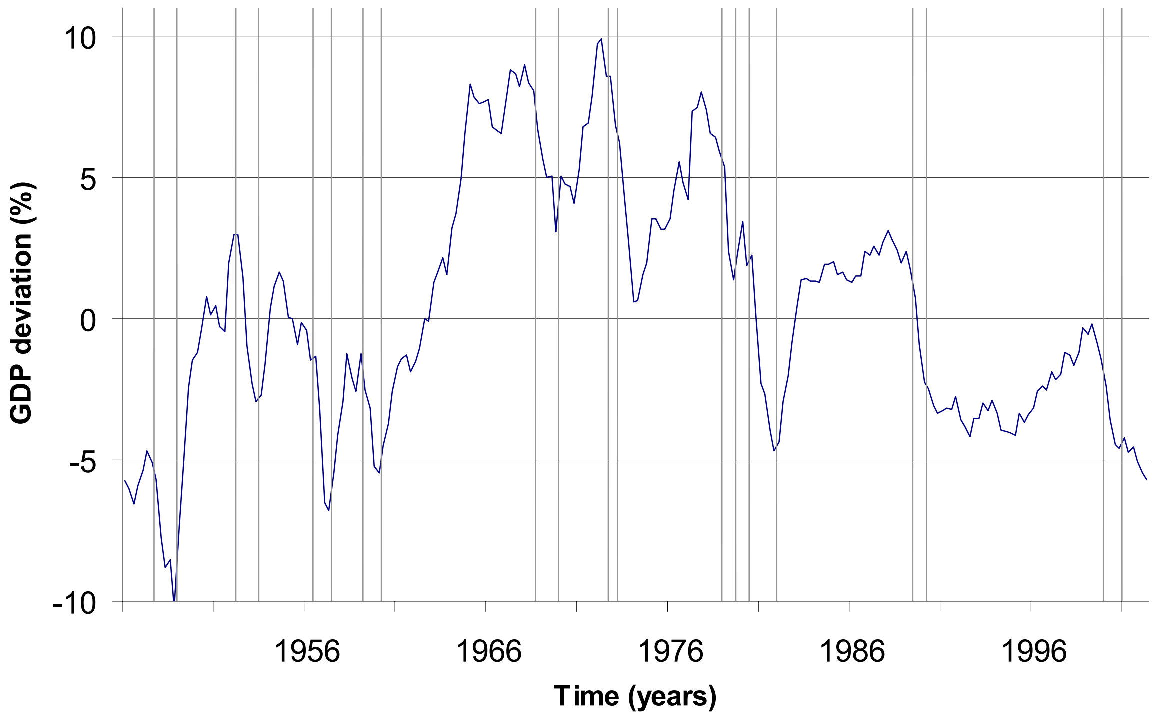

Figure 7: GDP relative deviation from trend (in blue) and the NBER reference recessions, indicated by thin vertical lines.

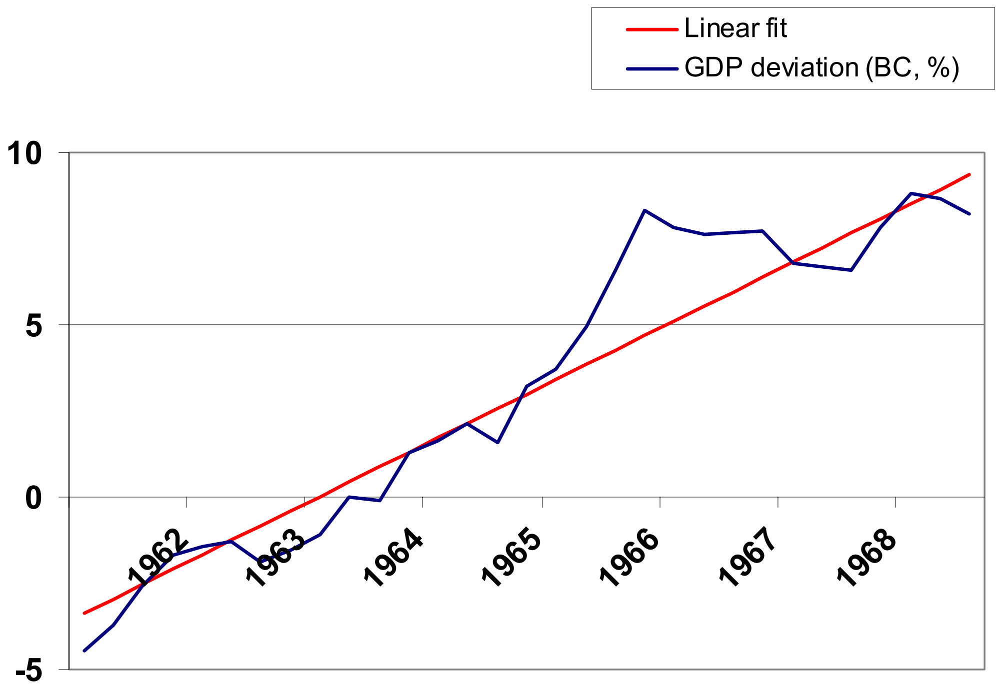

Figure 8: One expansion phase and the linear trend fitted to it. Abscissa in quarters, ordinate in $M.

The relative deviations BC(i) of GDP are used — for each recession and each homogenous expansion phase, following the NBER reference dates – to fit a local linear trend by least-squares. An illustrative example for one expansion phase is plotted in Fig. 8.

Next we calculate second-order fluctuations, defined as the differences between BC(i) and the piecewise linear fits to each recession and each expansion phase. The results are plotted in Fig. 9.

Of course, there is no reason to believe that endogenous dynamics should generate expansions and recessions that are linear in time; this is not even the case in our simple NEDyM model (see again Fig. 1a). There is, therefore, no rigorous basis to assume that our calculation performs an exact separation of second-order fluctuations arising from real shocks, on the one hand, from smoother economic evolution due to endogenous dynamics, on the other. This lack of piecewise linearity of the business cycle explains why it is not possible to compute historical second-order fluctuations using exactly the same method we applied to the model output, in which we can separate rigorously exogenous fluctuations from endogenous evolution. Our preliminary results are, however, quite suggestive and more elaborate calculations will be carried out in follow-up work.

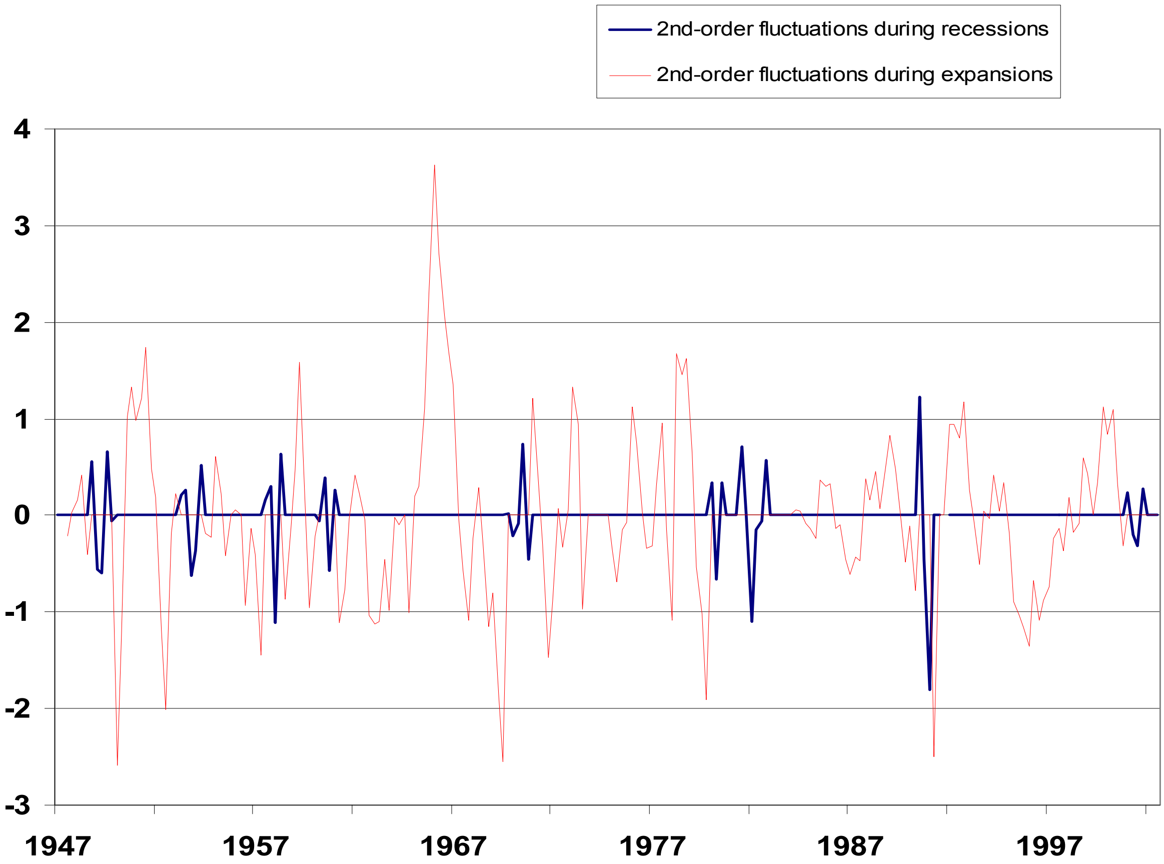

Figure 9: Fluctuation in U.S. GDP (in % of baseline) during expansions (red) and during recessions (blue); see text for details.

It is clear from Fig. 9 that the second-order fluctuations, so defined, are much larger during expansion phases than during recession phases. This is confirmed by the computation of the variances, which equal 0.34 during recessions and 0.87 during expansions. There is, therefore, a factor 2.6 between the two variances, compared with a factor 2.4 in our simple EBC model (see Section 4b). The closeness of these two numbers, 2.4 and 2.6, for such a simple model, is probably fortuitous, but striking nonetheless.
In our EBC framework, this property of the variability can be explained in two ways: (i) by the higher output variability of the endogenous dynamics during expansion phases than during recession phases, as observed in NEDyM; or (ii) by the higher sensitivity of the economy to exogenous shocks during the expansion phase, because these shocks are amplified by pre-existing tensions. These results are much more difficult to interpret within the classical RBC framework, in which model responses to shocks are additive and symmetric, since the intrinsic model dynamics is stable.

5. Concluding remarks

In this paper, we compared the way in which the two main theories of business cycles, namely the real business cycle (RBC) theory and the endogenous business cycle (EBC) theory, handle the effect of exogenous shocks on the economy. It has been shown in Section 2 that RBC models, built on the effect of such shocks, cannot reproduce realistic business cycles without introducing market frictions and imperfections in expectation. Such departures from the perfect neoclassical hypotheses, though, can also lead to macroeconomic models in which fluctuations arise even in absence of exogenous shocks.

The alternative EBC theory, discussed in Section 3, follows the latter path and explains economic fluctuations — first and foremost, but not exclusively — by intrinsic economic mechanisms that destabilize the economy and cause endogenous fluctuations. Numerous models have been built on this idea, both in the Keynesian and neoclassical traditions. These EBC models can reproduce some of the stylized facts of the business cycles, even though no such model is able, so far, to reproduce historical data as closely as RBC models do. EBC theory, too, can take into account the additional fluctuations caused by exogenous shocks like oil crises, technological changes, or natural disasters. The thrust of the present paper is precisely to examine systematically the effect of such shocks.

The EBC model formulated and initially analyzed by Hallegatte *et al.* (2006a) was briefly summarized in Section 4a and its endogenous business cycles illustrated in Fig 1. This Non-Equilibrium Dynamical Model (NEDyM) was then used to assess the economic cost of a natural disaster and the sensitivity of this cost to the pre-existing economic situation when the disaster occurs. In this model, the cost of a disaster is strongly dependent on the phase of the business cycle in which it occurs (see Fig. 2): while a disaster occurring at the end of a cycle's recession has a relatively small cost, this cost is greatly increased by economic processes and pre-existing disequilibria when the disaster occurs at a time of rapid growth.

There is, therefore, a "vulnerability paradox," as a healthy economy with high growth appears to be more vulnerable to disasters than a depressed economy in which some resources are unused. This conclusion, however, applies only to a given economy and does not extend to the comparison of two distinct economies: an overall flourishing economy is clearly more robust than an overall weak economy.

In Section 4b we found this result to be valid for other exogenous shocks, like productivity shocks, as well: in NEDyM, the additional output variability due to exogenous shocks on productivity is 2.4 larger during expansions than during recessions (see Figs. 3–5). This property of EBC models suggests that economic aggregates might exhibit a larger observed variability during expansion phases than during recession phases.

To examine this hypothesis, we studied in Section 4c the record of U.S. GDP from 1948 to 2002 in the NBER data base. We found that the discrepancy between output variance during expansions and recessions is amazingly close when comparing the historical data with our simple NEDyM model: a factor of 2.6 in variances, rather than 2.4 (see Figs. 6–9). This striking similarity is probably fortuitous — especially when considering the slightly different methods that had to be used, for technical reasons, in computing the variances in the data and in the model — but worth noting nonetheless.

The greater variability of output during expansion phases cannot be easily understood in a classical RBC framework, in which the stability of the basic equilibrium renders the response to shocks independent of the timing of their occurrence and shock responses are basically additive. In the EBC framework, the enhancement of fluctuations during growth phases and their suppression during recessions can be explained either by the higher variability of the endogenous dynamics during the former or by the higher sensitivity of the economy to exogenous shocks when pre-existing tensions amplify them.

In fact, the two explanations within the EBC framework are complementary, but not identical: the fluctuation–dissipation theorem of statistical mechanics states that, in a physical system near equilibrium, the decay of internal fluctuations follows the same behavior in time as the response of the system to an external impulse. To the extent that RBC models are near-equilibrium models and do not distinguish between internal variability in one phase or another of the business cycle, the theorem should apply to these models as is.

It is well known, however, that considerable deviations from the fluctuation–dissipation theorem occur for systems far from steady state, such as EBC models. Thus, for instance, interesting attempts to learn about climate sensitivity by applying this theorem to meteorological data (Leith, 1975; Bell, 1985) have not been very successful, precisely because of the nonlinear, large-scale, deterministic component of natural climate variability (Ghil et al., 1985; Ghil, 2002). In future work we plan, therefore, to examine more carefully the full explanation of these asymmetries in economic variability and in the sensitivity of the macroeconomic system during different phases of the observed business cycle.

According to the results of Sections 4b and 4c, economic fluctuations and sensitivity thus depend on the phase of the business cycle, in NEDyM as well as in the NBER data sets. Moreover, the interaction between NEDyM's endogenous business cycle, with its 5–6-year period, and the short-term exogenous productivity shocks generates lower-frequency oscillations, with a period longer than 50 years, and points to a possible mechanism for the generation of long period fluctuations (see Fig. 5). Nonlinear interactions in EBC models may thus help disentangle the effects of different processes — endogenous and exogenous, natural and socio-economic — on economic aggregates. These findings suggest a consistent research agenda to build a theory of economic fluctuations that can embrace both endogenous dynamics and the exogenous drivers of the business cycle.

References

Albala-Bertrand, J., 1993. The Political Economy of Large Natural Disasters with Special Reference to Developing Countries. Oxford: Clarendon Press.

Bell, T. L., 1985. Climatic sensitivity and fluctuation–dissipation relations. In *Turbulence and Predictability in Geophysical Fluid Dynamics and Climate Dynamics*, M. Ghil, R. Benzi and G. Parisi (Eds.), North-Holland, 424–440.

Benson, C., and E. Clay , 2004. Understanding the Economic and Financial Impact of Natural Disasters. The International Bank for Reconstruction and Development. The World Bank, Washington D.C.

Benhabib, J., and K. Nishimura, 1979. The Hopf-bifurcation and the existence of closed orbits in multi-sectoral models of optimal economic growth. *Journal of Economic Theory* 21, 421–444.

Chiarella, C., and P. Flaschel, 2000. The Dynamics of Keynesian Monetary Growth. Cambridge University Press.

Chiarella, C., P. Flaschel, G. Gong, and W. Semmler, 2002. Nonlinear Phillips curves, complex dynamics and monetary policy in a Keynesian macro model. School of Finance and Economics, University of Technology, Sydney, Working Paper number 120.

Chiarella C., P. Flaschel, and R. Franke, 2005. Foundations for a Disequilibrium Theory of the Business Cycle, Cambridge University Press, Cambridge, 523 pp.

Christiano, L.J., M. Eichenbaum, and C.L. Evans, 2005. Nominal rigidities and the dynamic effects of a shock to monetary policy, *Journal of Political Economy* 113, 1–45.

Cobb, C., and P. Douglas, 1928. A theory of production. *The American Economic Review* 18 (1), 139–165.

Day, R., 1982. Irregular growth cycles. *American Economic Review* 72, 406–414.

Ellison, M. and A. Scott, 2000. Sticky prices and volatile output, *Journal of Monetary Economics* 46, 621–632.

Frisch, R., 1933. Propagation Problems and Impulse Problems in Dynamic Economics. Economic Essay in honor of Gustav Cassel, London: George Allen and Unwin.

Gale, D., 1973. Pure exchange equilibrium of dynamic economic models. *Journal of Economic Theory* 6, 12–36.

Gali, J., 1999. Technology, employment, and the business cycle: Do technology shocks explain aggregate fluctuations? *American Economic Review* 89, 249–271.

Ghil, M., 1994: Cryothermodynamics: The chaotic dynamics of paleoclimate, *Physica D*, **77**, 130–159.

Ghil, M., 2002. Natural climate variability, in *Encyclopedia of Global Environmental Change*, Vol. 1 (M. MacCracken & J. Perry, eds.), Wiley & Sons, Chichester/New York, 544–549.

Ghil, M., R. Benzi, and G. Parisi (Eds.), 1985: *Turbulence and Predictability in Geophysical Fluid Dynamics and Climate Dynamics*, North-Holland Publ. Co., Amsterdam/New York/Oxford/ Tokyo, 449 pp.

Goodwin, R., 1951. The non-linear accelerator and the persistence of business cycles. *Econometrica* 19, 1–17.

Goodwin, R., 1967. A growth cycle. In C. Feinstein (Ed.), Socialism, Capitalism and Economic Growth, Cambridge University Press, Cambridge.

Grandmont, J.-M., 1985. On endogenous competitive business cycles. *Econometrica* 5, 995–1045.

Hahn, F., and R. Solow, 1995. A Critical Essay on Modern Macroeconomic Theory. The MIT Press, Cambridge, Massachussetts and London, England.

Hairault, J.-O., and F. Portier, 1993. Money, New-Keynesian macroeconomics and the business cycle, *European Economic Review* 37, 1533–1568.

Hall, R.E., 2005. Employment fluctuations with equilibrium wage stickiness. *The American Economic Review*, 95(1), 50–65.

Hallegatte S., M. Ghil, P. Dumas, and J.-C. Hourcade, 2006a. Business cycles, bifurcations and chaos in a neoclassical model with investment dynamics. Accepted by *Journal of Economic Behavior and Organization*, preprint available at http://www.centre-cired.fr/forum/article.php3?id_article=36&lang=en.

Hallegatte S., J.-C. Hourcade, P. Dumas, 2006b. Why economic dynamics matter in assessing climate change damages: illustration on extreme events. Accepted by *Ecological Economics*, preprint available at http://www.centre-cired.fr/forum/article77.html?lang=en.

Hansen, G.D., and E. C. Prescott, 2005. Capacity constraints, asymmetries, and the business cycle, *Review of Economic Dynamics*, 8(4), 850-865.

Harrod, R., 1939. An essay on dynamic economic theory. *Economic Journal* 49, 14–33.

Hicks, J., 1950. The cycle in outline. A Contribution to the Theory of the Trade Cycle. Oxford, Oxford University Press, Ch. 8, 95–107.

Hillinger, C., 1992. Cyclical Growth in Market and Planned Economies. Oxford University Press.

Hodrick, R.J. and E.C. Prescott, 1997. Postwar U.S. business cycles: an empirical investigation. *Journal of Money, Credit and Banking* 29, 1–16.

Ireland, P.N., 2003. Endogenous money of sticky prices? *Journal of Monetary Economics* 50, 1623–1648

Juglar, C., 1862. Des Crises commerciales et leur retour périodique en France, en Angleterre, et aux Etats-Unis, Strasbourg, Imprimerie de Veuve

Kaldor, N., 1940. A model of the trade cycle. *Economic Journal* 50, 78–92.

Kalecki, M., 1937. A theory of the business cycle. *Review of Economic Studies* 4, 77–97.

King, R.G., 1995. Quantitative theory and econometrics. *Economic Quarterly* 81(3), Federal Reserve Bank of Richmond

King, R., and S. Rebelo, 2000. Resuscitating real business cycles. In J. Taylor and M. Woodford (eds.), *Handbook of Macroeconomics*, North-Holland: Amsterdam, 927–1007.

Kydland, F. E. and E.C. Prescott, 1982. Time to build and aggregate fluctuations. *Econometrica* 50, 1345–70.

Kondratieff, N.D., 1935. The long waves in economic life. *Review of Economic Statistics*. 17(6), 105–115

Leith, C. E., 1975. Climate response and fluctuation dissipation. *J. Atmos. Sci.* **32**, 2022-2026.

Loeuille, N., and M. Ghil, 2004. Intrinsic and climatic factors in North-American animal population dynamics. *BMC Ecology* 2004, **4**:6, doi:10.1186/1472-6785-4-6.

Munich-Re, 2005. Topics. Annual Review: Natural Catastrophes 2004. Munich Reinsurance Group, Geoscience Research Group, Munich, Germany.

Rebelo, S., 2005. Real business cycle models: Past, present, and future. *Scandinavian Journal of Economics*, 107, 217–238.

Ricardo, D., 1810. The High Price of Bullion, a Proof of the Depreciation of Bank Notes, London: John Murray.

Rotemberg, J.J. and M. Woodford, 1994. Is the business cycle a necessary consequence of stochastic growth? National Bureau of Economic Research, Working paper No. 4650

Rotemberg, J.J. and M. Woodford, 1996. Real-Business-Cycle Models and forecastable movement in output, hours, and consumption. *American Economic Review* 86, 71–89

Samuelson, P., 1939. A synthesis of the principle of acceleration and the multiplier. *Journal of Political Economy* 47, 786–797.

Smets, F. and R. Wouters, 2005. Comparing shocks and frictions in US and euro area business cycles: a Bayesian DSGE Approach, *Journal of Applied Econometrics* 20 (2), 161–183

Smith, A., 1776. An Inquiry into the Nature and Causes of the Wealth of Nations. (Reprinted London: Methuen, 5th edn., Ed., E. Cannan, 1904).

Slutsky, E., 1927. The summation of random causes as a source of cyclic processes, III(1), Conjuncture Institute, Moscow, Reprinted in *Econometrica* 5, 105–146.

Solow, R., 1956. A contribution to the theory of economic growth. *The Quarterly Journal of Economics* 70 (1), 65–94.

World Bank, 1999. Turkey: Marmara earthquake assessment, World Bank Working Paper.

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/Feem/Pub/Publications/WPapers/default.htm
http://www.ssrn.com/link/feem.html
http://www.repec.org
http://agecon.lib.umn.edu
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2007

NRM	1.2007	*Rinaldo Brau, Alessandro Lanza, and Francesco Pigliaru*: How Fast are Small Tourist Countries Growing? The 1980-2003 Evidence
PRCG	2.2007	*C.V. Fiorio, M. Florio, S. Salini and P. Ferrari:* Consumers' Attitudes on Services of General Interest in the EU: Accessibility, Price and Quality 2000-2004
PRCG	3.2007	*Cesare Dosi and Michele Moretto*: Concession Bidding Rules and Investment Time Flexibility
IEM	4.2007	*Chiara Longo, Matteo Manera, Anil Markandya and Elisa Scarpa*: Evaluating the Empirical Performance of Alternative Econometric Models for Oil Price Forecasting
PRCG	5.2007	*Bernardo Bortolotti, William Megginson and Scott B.* Smart: The Rise of Accelerated Seasoned Equity Underwritings
CCMP	6.2007	*Valentina Bosetti and Massimo Tavoni*: Uncertain R&D, Backstop Technology and GHGs Stabilization
CCMP	7.2007	*Robert Küster, Ingo Ellersdorfer, Ulrich Fahl* (lxxxi): A CGE-Analysis of Energy Policies Considering Labor Market Imperfections and Technology Specifications
CCMP	8.2007	*Mònica Serrano* (lxxxi): The Production and Consumption Accounting Principles as a Guideline for Designing Environmental Tax Policy
CCMP	9.2007	*Erwin L. Corong* (lxxxi): Economic and Poverty Impacts of a Voluntary Carbon Reduction for a Small Liberalized Developing Economy: The Case of the Philippines
CCMP	10.2007	*Valentina Bosetti, Emanuele Massetti, and Massimo Tavoni*: The WITCH Model. Structure, Baseline, Solutions
SIEV	11.2007	*Margherita Turvani, Aline Chiabai, Anna Alberini and Stefania Tonin*: Public Policies for Contaminated Site Cleanup: The Opinions of the Italian Public
CCMP	12.2007	*M. Berrittella, A. Certa, M. Enea and P. Zito*: An Analytic Hierarchy Process for The Evaluation of Transport Policies to Reduce Climate Change Impacts
NRM	13.2007	*Francesco Bosello, Barbara Buchner, Jacopo Crimi, Carlo Giupponi and Andrea Povellato*: The Kyoto Protocol and the Effect of Existing and Planned Measures in the Agricultural and Forestry Sector in the EU25
NRM	14.2007	*Francesco Bosello, Carlo Giupponi and Andrea Povellato*: A Review of Recent Studies on Cost Effectiveness of GHG Mitigation Measures in the European Agro-Forestry Sector
CCMP	15.2007	*Massimo Tavoni, Brent Sohngen, and Valentina Bosetti*: Forestry and the Carbon Market Response to Stabilize Climate
ETA	16.2007	*Erik Ansink and Arjan Ruijs*: Climate Change and the Stability of Water Allocation Agreements
ETA	17.2007	*François Gusdorf and Stéphane Hallegatte*: Compact or Spread-Out Cities: Urban Planning, Taxation, and the Vulnerability to Transportation Shocks
NRM	18.2007	*Giovanni Bella*: A Bug's Life: Competition Among Species Towards the Environment
IEM	19.2007	*Valeria Termini and Laura Cavallo*: "Spot, Bilateral and Futures Trading in Electricity Markets. Implications for Stability"
ETA	20.2007	*Stéphane Hallegatte and Michael Ghil*: Endogenous Business Cycles and the Economic Response to Exogenous Shocks

(lxxxi) This paper was presented at the EAERE-FEEM-VIU Summer School on "Computable General Equilibrium Modeling in Environmental and Resource Economics", held in Venice from June 25th to July 1st, 2006 and supported by the Marie Curie Series of Conferences "European Summer School in Resource and Environmental Economics".

2007 SERIES

CCMP	*Climate Change Modelling and Policy* (Editor: Marzio Galeotti)
SIEV	*Sustainability Indicators and Environmental Valuation* (Editor: Anil Markandya)
NRM	*Natural Resources Management* (Editor: Carlo Giupponi)
KTHC	*Knowledge, Technology, Human Capital* (Editor: Gianmarco Ottaviano)
IEM	*International Energy Markets* (Editor: Matteo Manera)
CSRM	*Corporate Social Responsibility and Sustainable Management* (Editor: Giulio Sapelli)
PRCG	*Privatisation Regulation Corporate Governance* (Editor: Bernardo Bortolotti)
ETA	*Economic Theory and Applications* (Editor: Carlo Carraro)
CTN	*Coalition Theory Network*