DYNAMIC COUPLING OF THE CLIMATE AND MACROECONOMIC SYSTEMS

Patrice DUMAS[1,2,6], Michael GHIL[2,3,6],
Andreas GROTH[4,6], Stéphane HALLEGATTE[1,5,6]

RÉSUMÉ – *Le couplage entre les systèmes naturels et anthropiques a motivé plusieurs travaux de modélisation macro-économique visant à représenter ces deux systèmes dans un cadre de modélisation intégrée, ces travaux sont l'objet de cette revue de littérature. Ces interactions, et en particulier les conséquences économiques des événements extrêmes, sont étudiées à l'aide d'un modèle de déséquilibre possédant une dynamique cyclique endogène. Ce modèle réagit plus fortement aux catastrophes climatiques durant les phase de récession que durant les phases d'expansion. Ces résultats jettent un doute sur les évaluations des conséquances du changement climatique qui se fondent uniquement sur des modèles de croissance moyennés de long terme. Dans l'optique d'une validation du modèle, nous décrivons une méthode originale utilisant l'analyse multicanal du spectre singulier permettant d'extraire les composantes cycliques des observations économiques.*

MOTS CLÉS – Analyse multicanal du spectre singulier ; Cycle économique ; Dynamique macroéconomique ; Modélisation hors-équilibre ; Paradoxe de vulnérabilité

SUMMARY – *This review paper presents a modeling framework for macroeconomic growth dynamics that is motivated by recent attempts to formulate and study "integrated models" of the coupling between natural and socio-economic*

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1. Centre International de Recherche sur l'Environnement et le Développement, Paris, France

2. Département Terre - Atmosphère - Océan and Environmental Research and Teaching Institute, Ecole Normale Supérieure, Paris, France

3. Department of Atmospheric and Oceanic Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1565, USA

4. Laboratoire de Météorologie Dynamique (CNRS and IPSL), Ecole Normale Supérieure, Paris, France

5. Ecole Nationale de la Météorologie, Météo France, Toulouse, France

6. E-mail addresses : dumas@lmd.ens.fr (P. Dumas), ghil@lmd.ens.fr (M. Ghil), groth@lmd.ens.fr (A. Groth), hallegatte@centre-cired.fr (S. Hallegatte)

phenomena. The challenge is to describe the interfaces between human activities and the functioning of the earth system. We examine the way that this interface works in the presence of endogenous business cycle dynamics, based on a non-equilibrium dynamic model, and review the macroeconomic response to natural disasters. Our model exhibits a larger response to natural disasters during expansions than during recessions, and we raise questions about the assessment of climate change damages or natural disaster losses that are based purely on long-term growth models. In order to compare the theoretical findings with observational data, we present a new method for extracting cyclic behavior from the latter, based on multivariate singular spectral analysis.

KEYWORDS – Business cycle ; Macroeconomic dynamics ; Multivariate singular spectral analysis ; Nonequilibrium modeling ; Vulnerability paradox

1. INTRODUCTION AND MOTIVATION

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007) provides further evidence for global warming and for the significant contribution of anthropogenic greenhouse gases (GHGs) to this warming. Substantial uncertainties remain, however, regarding the degree of warming, and the part of natural variability in it. Even more controversial are the socio-economic consequences of climate change, as well as the costs of reducing GHG emissions and of adapting to a changing climate.

There are numerous difficulties in trying to study the coupled behavior of the socio-economic system and the climate system, each of which is highly complex and nonlinear, and poses variability on a wide range of time and space scales. The assessment of interactions between the two systems poses a difficult organizational problem to the IPCC : socio-economical scientists develop so-called "emission scenarios" that are passed on to the natural scientists, in order to simulate climate change according to these scenarios and to derive the future range of temperature increases. The results of these future-climate simulations are then used in impact and adaptation studies to evaluate the associated damages. So far, however, there is no real feedback taken into consideration in this exchange-of-information process. Although several "integrated assessment models" (e.g., Ambrosi et al., 2003; Nordhaus and Boyer, 1998; Stern, 2006) — used to compute optimal growth, including mitigation costs and climate change damages — are truly coupled, they disregard variability and represent both climate and the economy as a succession of equilibrium states with simple dynamics.

On the other hand, detailed dynamic modeling of these systems is still out of reach, as we do not yet understand their complex dynamics and coupling. For this reason, we advocate an approach based on a hierarchy of models, from simple, conceptual "toy models" all the way to complex detailed models. This approach has become fairly widespread in climate dynamics (Ghil, 2001; Ghil et al., 2008a) and it allows us to give proper weight to the understanding of the underlying mechanisms given by the simpler models, on the one hand, and to the realism of the more detailed models, on the other. In modeling physico-chemical, ecological, or socio-economic processes, this means starting with toy models and climbing up the modeling ladder, rung by rung, towards more complex models, while always comparing the results with increasingly detailed observational data.

The work presented here describes, on the level of toy models, the connection between a non-equilibrium economic model and extreme climatic events. After a brief description of the economic model and of its business cycles in the next section, we consider in Section 3. the impact of natural disasters on this model's dynamical behavior, and present some recent results concerning a vulnerability paradox that arises from the presence of cyclic behavior. The effect of using new technologies in the reconstruction process are considered in Section 4.. In Section 5., we address the problem of extracting relevant information about business cycles from observational data. Finally, we conclude in Section 6. with an outlook on ongoing and future research.

2. ENDOGENOUS BUSINESS CYCLES IN A NON-EQUILIBRIUM MODEL

Ups and downs in prices and in economic activity have been discussed at least as far back as the seminal works of Smith (1776) and Ricardo (1810). To this day, the cyclical characteristics of economic behavior, referred to as business cycles, are explained by two main approaches. The dominant one today is known as *real business cycle (RBC)* theory and is implemented within Stochastic Dynamic General Equilibrium models ; in this context, "real" refers to the nature of the goods involved, to distinguish them from monetary and financial aspects of the economy. RBC theory originates from the works of Slutsky (1927) and Frisch (1933) ; Kydland and Prescott (1982) embedded this theory into the general equilibrium framework with rational expectations. In RBC theory, one assumes that economic fluctuations arise from exogenous shocks and that the economic system is otherwise stable. It follows that the system is entirely self-regulating and that there is no point in intervening in it.

The second approach is known as *endogenous business cycle (EnBC)* theory : it proposes that economic fluctuations are due to intrinsic processes that endogenously destabilize the economic system (e.g., Kalecki, 1937; Harrod, 1939; Kaldor, 1940; Samuelson, 1939; Hicks, 1950; Goodwin, 1967; Day, 1982; Grandmont, 1985; Chiarella et al., 2005). These intrinsic processes may involve various instabilities and nonlinear feedbacks within the economic system itself. It follows that socio-political intervention might help control the mean, period or other features of the cycles. Both theories have their successes and shortcomings, but it is RBC theory that garners consensus in the current economic literature.

The interplay between natural and economic variability depends to a considerable extent on the underlying economic mechanisms ; therefore, overcoming the controversy between the EnBC and RBC theories could facilitate the study of climate-economy interactions. Exogenous real shocks clearly do play an important role in business cycles ; e.g., the strong economic expansion of the late 1990s was obviously driven by the rapid development of new technologies. Increasing interest in RBC models since the work of Kydland and Prescott (1982) has led to good matches between multi-variable, detailed versions of such models and actual historical data, which have been compiled and become widely available during this time interval (e.g., King and Rebelo, 2000).

Endogenous fluctuations, however, have their part in generating and shaping the cycles, too. Even within the neoclassical tradition, with perfect markets and rational expectations, Day (1982), Grandmont (1985), Gale (1973), and Benhabib and Nishimura (1979) proposed models in which endogenous fluctuations arise from savings behavior, wealth effects and interest-rate movement, or from interactions between overlapping generations and between different sectors. Leading practitioners, like G. Soros, even blame the equilibrium paradigm for its role in helping bring about the current economic and financial crisis : "The currently prevailing paradigm, namely that financial markets tend towards equilibrium, is both false and misleading; our current troubles can be largely attributed to the fact that the international financial system has been developed on the basis of that paradigm." (Soros, 2008).

Market frictions, imperfect rationality in expectations or aggregation biases can give rise to strongly destabilizing processes within the economic system. Numerous authors have proposed accounting for such processes and noted their importance. Harrod (1939) stated that the economy was unstable because of the absence of an adjustment mechanism between population growth and labor demand, although Solow (1956) suggested later that such a mechanism was provided by the producer's choice of the labor–capital intensity. Kalecki (1937) and Samuelson (1939) proposed simple business cycle models based on a Keynesian accelerator-multiplier effect and on delayed investing. 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 an imperfect goods market, from frictions in the labor market, and from the interplay of irreversible investment and monopolistic competition.

EnBC theory was studied quite actively in the middle of the 20th century but much less so over the last quarter century or so. Still, Hillinger (1992), Jarsulic (1993), Flaschel et al. (1997), Nikaido (1996), Chiarella and Flaschel (2000), Chiarella et al. (2005) and Hallegatte et al. (2008b), among many others, have recently proposed EnBC models and further investigated their properties. The business cycles in these models arise from nonlinear relationships between economic aggregates and are consistent with certain realistic features of actual business cycles.

Due to the relatively limited recent interest in EnBC models, less progress has been made so far in matching their results to the historical data. Even so, Chiarella et al. (2006) showed that their model is able to reproduce historical series when utilization data are taken as input. It is not surprising, moreover, that EnBC models with only a few state variables — typically less than a few dozen — were unable to reproduce the details of historical information that involves processes lying explicitly outside the scope of an economic model (e.g., geopolitical events).

The non-equilibrium dynamical model (NEDyM) of Hallegatte et al. (2008b) is a neoclassical model with myopic expectations, in which adjustment delays have been introduced in the clearing mechanisms of the labor and goods markets, as well as in the investment response to profitability signals. It is a toy model that represents an economy with one producer, one consumer, and one type of goods that is used both to consume and invest. NEDyM is based on the Solow (1956) model, in which all equilibrium constraints are replaced by dynamic relationships that involve adjustment delays. The model has 20 variables, which include production, capital, number

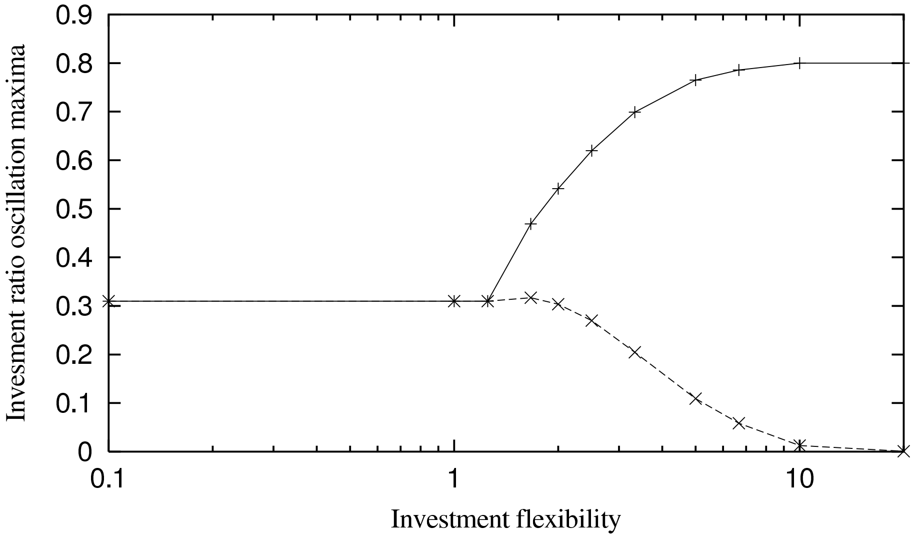

FIGURE 1. Bifurcation diagram of our non-equilibrium dynamic model (NEDyM). The abscissa displays the values of the investment parameter α. The model has a unique, stable equilibrium for low α values, and the figure shows the corresponding investment ratio value. For higher values, a Hopf bifurcation leads to a limit cycle whose minimum and maximum are shown in the figure. Transition to chaos occurs for even higher values (not shown). After Hallegatte et al. (2008b).

of workers employed, wages and prices. The evolution of these variables is governed by 8 ordinary differential equations and 12 algebraic relationships between the variables, such as a Cobb-Douglas production function that quantifies the labor-capital substitution rule. All model equations are summarized and explained succinctly in Appendix A of Hallegatte and Ghil (2008).

NEDyM's main control parameter is the investment flexibility α, which measures the adjustment speed of investments in response to profitability signals. This parameter describes how rapidly investment can react to a profitability signal : if α is very small, investment decreases very slowly when profits are small ; if α is very large, investment soars when profits are high and collapses when profits are small. Introducing this parameter is equivalent to allocating an investment adjustment cost, as proposed by Kydland and Prescott (1982) and Kimball (1995), among others ; these authors found that introducing adjustment costs and delays helps enormously in matching key features of macroeconomic models to the data.

In NEDyM, investment flexibility has a major influence on economic dynamics. For small α, i.e. slow adjustment, the model has a stable equilibrium, which matches the economic state of the European Union (EU-15) in 2001. As the adjustment flexibility increases, this equilibrium loses its stability and the model then poses a stable periodic solution ; this "limit cycle," in the language of dynamical systems (Guckenheimer and Holmes, 1987), is characterized by variables that oscillate periodically around their equilibrium values. Business cycles in NEDyM originate from the instability of the profit–investment relationship, a relationship similar to the Keynesian accelerator–multiplier. Furthermore, the cycles are constrained by the interplay of three processes : (i) a reserve army of labor effect, namely the increase of labor costs when the employment rate is high; (ii) the inertia of production capacity; and (iii) the consequent inflation in goods prices when demand increases too rapidly.

The model's bifurcation diagram apears in Fig. 1. For somewhat greater investment flexibility, the model exhibits chaotic behavior, because a new constraint intervenes, namely limited investment capacity. In this chaotic regime, the cycles become quite irregular, with sharper recessions and recoveries of variable duration.

The NEDyM business cycle is consistent with many stylized facts, such as the phasing, or comovements, of the distinct macroeconomic variables along the cycle. It also reproduces the observed asymmetry of the cycle, with the recession phase much shorter than the expansion phase, as can be seen in the top panel of Fig. 2. The amplitude of the price-and-wage oscillation, however is too large in NEDyM, calling for a better calibration of the parameters and further refinements of the model.

In the setting of the recent economic and financial crisis, the banks' and other financial institutions' large losses have clearly reduced credit access; this reduction obviously modifies investment flexibility. Our non-equilibrium EnBC model can thus help explain how this change in an important macroeconomic parameter can seriously perturb the entire economic system's behavior, by either increasing or decreasing the variability in macroeconomic variables. Additionally, these losses also lead to a reduction in aggregated demand; this, in turn, can lead to a reduction in economic production and a full-scale recession. While the latter processes are captured by NEDyM, detailed predictions are way beyond the province of such a toy model, and would require, in particular, the "tuning" of its parameters to actual economic data, as currently done for RBC models.

3. NATURAL DISASTERS IN A DYNAMIC ECONOMY

The dynamics of reconstruction are a major concern when considering the socio-economic consequences of natural disasters. Aside from the immediate damage caused by such a disaster, it is the length and other characteristics of the reconstruction period that will determine the disaster's full cost. Reconstruction may lead to an increase in productivity, by allowing for technical changes to be embedded into the reconstructed capital; technical changes could also sustain the demand and help economic recovery. At the same time, economic productivity may be reduced during reconstruction because some vital sectors are not functional, and reconstruction investments crowd out investment into new production capacity.

Extreme weather events in the recent past have destroyed only a small amount of capital by comparison with annual investments (Münich Re, 2004), which suggests a recovery spread out over at most a couple of months. But past experience also shows that short-term constraints can reduce the pace of reconstruction. For example, the 10 billion euros of reconstruction expenditures after the 2002 summer floods in Germany correspond to only 10 days of German investments, but have in fact been spread out over more than 3 years. Using the equilibrium version of NEDyM, Hallegatte et al. (2007) showed that to simulate the correct length of the reconstruction period requires setting a limit on the ability to mobilize investment under these circumstances. This delay in mobilizing reconstruction capital can lead to substantial indirect losses from natural and other disasters.

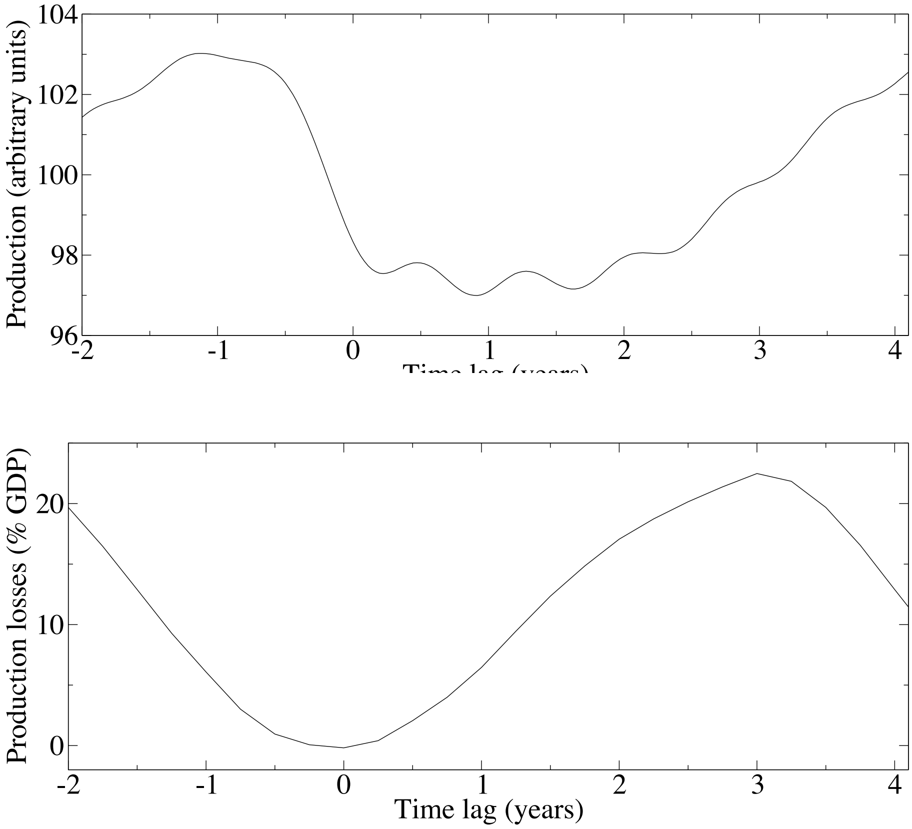

FIGURE 2. The effect of a single natural disaster on an endogenous business cycle. Upper panel : the business cycle in terms of annual production, as a function of time, starting at the cycle minimum (time lag = 0). Lower panel : total production losses due to a disaster that instantaneously destroys 3 % of gross domestic product (GDP), shown as a function of the cycle phase in which the disaster occurs, measured as a time lag with respect to the cycle minimum. A disaster occurring at the cycle minimum causes a limited indirect production loss, while a disaster occurring during the expansion leads to a much larger loss. From Hallegatte and Ghil (2008).

The state of the economy may also influence the consequences of natural disasters, by interfering with reconstruction dynamics. In the model version in which business cycles are present, Hallegatte and Ghil (2008) found a remarkable “vulnerability paradox” : the indirect costs caused by extreme events during a growth phase of the economy are much higher than those that occur during a deep recession. Figure 2 illustrates this paradox, by showing in its upper panel a typical business cycle and in the lower panel the corresponding losses for disasters hitting the economy in different phases of this cycle.

This apparent paradox, however can be easily explained : disasters during high-growth periods enhance pre-existing disequilibria. Inventories are low and cannot compensate the reduced production ; employment is high, and hiring more employees induces wage inflation ; and the producer lacks financial resources to increase his/her investment. The opposite holds during recessions, as mobilizing investment and labor is much easier.

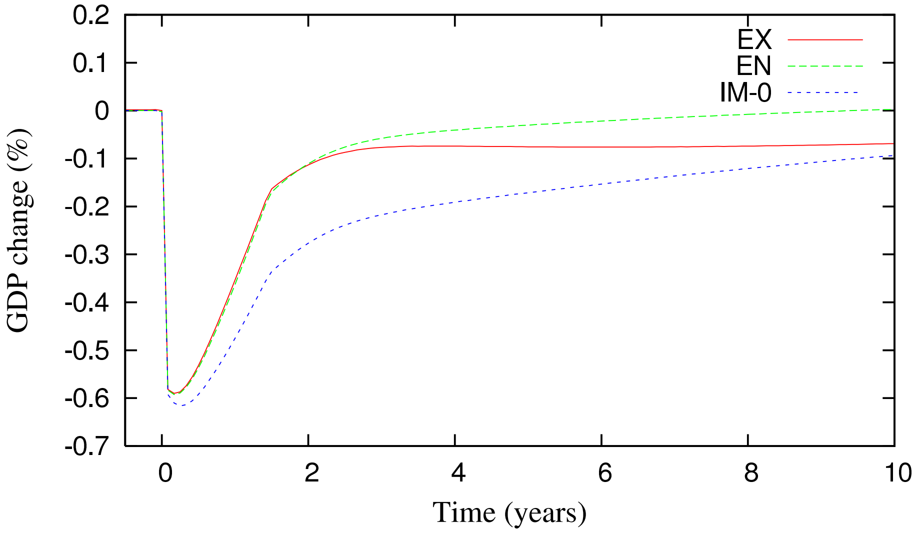

FIGURE 3. GDP changes in response to a disaster that initially destroys capital amounting to 2.5% of GDP, according to one of three hypotheses : exogenous technical change only (EX) ; endogenous technical change with perfect productivity effect (EN) ; and endogenous technical change with imperfect productivity effect (IM-0). From Hallegatte and Dumas (2008).

4. TECHNOLOGICAL AND LONG-TERM EFFECTS

New and more productive capital may be used to replace facilities destroyed by extreme events. It is possible, therefore, that capital replacement leads to the use of more productive technologies. Short-term constraints, however — as well as the possibility to salvage parts of the previous capital — may prevent the inclusion of the most efficient technology and thus inhibit the full manifestation of this modernization effect in the actual aftermath of a disaster .

Hallegatte and Dumas (2008), still relying on NEDyM, modeled the inclusion of new technologies into the capital used in reconstruction. These authors allowed the fraction of reconstruction capital that is invested in new technologies to take on different values. A fraction of 1 means that the entire reconstruction capital is more productive than before, while a fraction of 0 corresponds to reconstruction with the previous technologies.

The consequences of taking technical change into account in modeling recovery from a disaster differ widely from case to case. They may be positive when this fraction is high and hence technical change is accelerated, or negative when little new technology is used ; in the latter case, the crowding-out effect of reconstruction actually slows down technical change. The three curves in Fig. 3 show how gross domestic product (GDP) changes after a disaster that destroys capital amounting to 2.5% of GDP. The EX curve corresponds to a case with no upgrading of technology. In the EN case, all of the reconstruction capital embodies technical change, and thus achieves a faster recovery. In the IM-0 case, technical change is embodied in new investments, but reconstruction investments are made using unchanged technology. In this case, the crowding-out effect of reconstruction investments leads to productivity that recovers much more slowly.

In this setting, the long-term effect of a sequence of extreme events depends on the behavior of the economy : an economy that is in stable equilibrium and has no flexibility ($\alpha = 0$, see again Fig. 1) or very little is more vulnerable than a more flexible economy that is still at or near equilibrium (e.g., $\alpha = 1.0$). Clearly, if investment flexibility is null or very low, the economy is incapable of responding to the natural disasters through investment increases aimed at reconstruction ; total production losses, therefore, are quite large. Such an economy behaves according to a pure Solow (1956) growth model, where the savings, and therefore the investment, ratio is constant ; see Table 1 in Hallegatte and Ghil (2008).

When investment can respond to profitability signals without destabilizing the economy, i.e. when α is non-null but still lower than the critical bifurcation value of $\alpha = 1.39$, the economy has a new degree of freedom to improve its situation and respond to productive capital shocks. Such an economy is much more resilient to disasters, because it can adjust its level of investment in the disaster's aftermath. If investment flexibility α is larger than 1.39, though, the economy undergoes an endogenous business cycle and, along this cycle, the economy crosses phases of high vulnerability, as shown in Fig. 2. As a consequence, production losses due to disasters that occur during expansion phases are strongly amplified, while they are reduced when the shocks occur during the recession phase. On average, however, (i) expansions last much longer than recessions, in our NEDyM model as well as in reality ; and (ii) amplification effects are larger than damping effects. It follows that the total effect of the cycle is strongly negative, with an average production loss that is almost as large, for $\alpha = 2.5$, as for $\alpha = 0$.

These results suggest the existence of an optimal investment flexibility ; this flexibility allows the economy to react in an efficient manner to exogenous shocks, without provoking endogenous fluctuations that would make it too vulnerable to such shocks. According to our model, therefore, stabilization policies may not only help prevent recessions from being too strong and costly ; they may also help control expansion phases, and thus prevent the economy from becoming too vulnerable to unexpected shocks, like natural disasters or other supply-side shocks. Examples of the latter are energy-price shocks, like the oil shock of the 1970s, and production bottlenecks, for instance when electricity production cannot satisfy the demand from a growing industrial sector (Hallegatte and Ghil, 2008).

The long-term consequences of natural disasters also depend on the reconstruction capacity and this dependency exhibits a threshold effect (**?**) : for each value of the capacity to fund reconstruction, GDP losses remain moderate if the intensity and frequency of natural disasters remain below a certain threshold. Above this threshold GDP losses increase sharply. Moreover, if the time between two large disasters is too short, there is not enough time for reconstruction, and damages may increase sharply. This threshold effect could at least partially explain why repeated natural disasters seem to prevent the development of several poor countries. As an example, Guatemala experienced an impressive series of weather catastrophes that severely inhibited economic development : Hurricane Mitch in 1998, 3 years of drought from 1999 to 2001, and Hurricane Michelle in 2001. In another Central American country, the Honduran prime minister said that Hurricane Michelle by itself "puts the country's economic development back 20 years" (IFRCRCS, 2002).

Applied to the specific issue of climate change, the results reviewed in this section highlight the importance of short-term constraints on the economy in the assessment of long-term damages. Taking into account the presence of business cycles will modify this assessment and may point to larger GDP losses than those suggested by the use of optimization strategies based on equilibrium models (e.g., Ambrosi et al., 2003; Nordhaus and Boyer, 1998; Stern, 2006). Moreover, the allocation of capital between reconstruction and other types of investment after a large natural disaster can play an important role in both short- and long-term production losses. Optimizing this allocation, therefore, is an important factor in dealing with the expected change in the distribution of extreme events, due to global warming.

5. EXTRACTING CYCLICAL BEHAVIOR FROM MACROECONOMIC DATA

As already discussed above, besides a long-term increase in production and material well-being, macroeconomic data exhibit short-term fluctuations with a cyclical character, referred to as business cycles. In this section, we focus on extracting the fundamental dynamical behavior and typical stylized facts of a business cycle. This is an essential step in order to assess the NEDyM model's reliability and to infer possible modifications that would improve its explanatory and predictive capabilities. Beyond their application to this model, the methodology we introduce here into the macroeconomic literature might have further and even greater benefits.

The data set we use is quarterly U.S. macroeconomic data from the Bureau of Economic Analysis for 1947 to 2005 ; see http ://www.bea.gov/. According to a common procedure, we first remove the trend and convert the data to relative values by dividing the data points by the corresponding trend values. A typical filter used in the economic literature for extracting the trend is the Hodrick-Prescott filter (Hodrick and Prescott, 1997). Next, all time series are normalized by their standard deviation. The six time series we use are GDP, investment, consumption, employment rate (in %), total wage, and change in private inventories. These series, detrended and normalized, are shown in the upper panel of Fig. 4.

It is quite obvious that these time series exhibit fluctuations of varying amplitude and period. These fluctuations could be induced by external shocks, such as political events, or by intrinsic macroeconomic processes, as seen in Section 2. Whatever the causes, a predominantly cyclical behavior is clearly apparent. In order to extract the essential cyclicity from a short, noisy time series, like that in Fig. 4, we decompose the data set into its spectral components, with the help of single- and multi-channel singular spectral analysis (SSA and M-SSA).

The use of M-SSA for multivariate time series has been proposed in the context of nonlinear dynamics by Broomhead and King (1986), for the purpose of reconstructing the dynamics of a system from the time series it produces. These authors thus provided an extension and robust application of the Mañé-Takens idea of reconstructing dynamics from a time series (Mañé, 1981; Takens, 1981). M. Ghil, R. Vautard and associates first proposed to apply the SSA methodology to the spectral analysis of short and noisy time series, for which standard methods derived from Fourier analysis do not work well (Vautard and Ghil, 1989; Ghil and Vautard, 1991; Vautard et al., 1992). SSA and M-SSA have already proven their advantages in a variety of applications, such as climate dynamics, meteorology, oceanography, as well as the

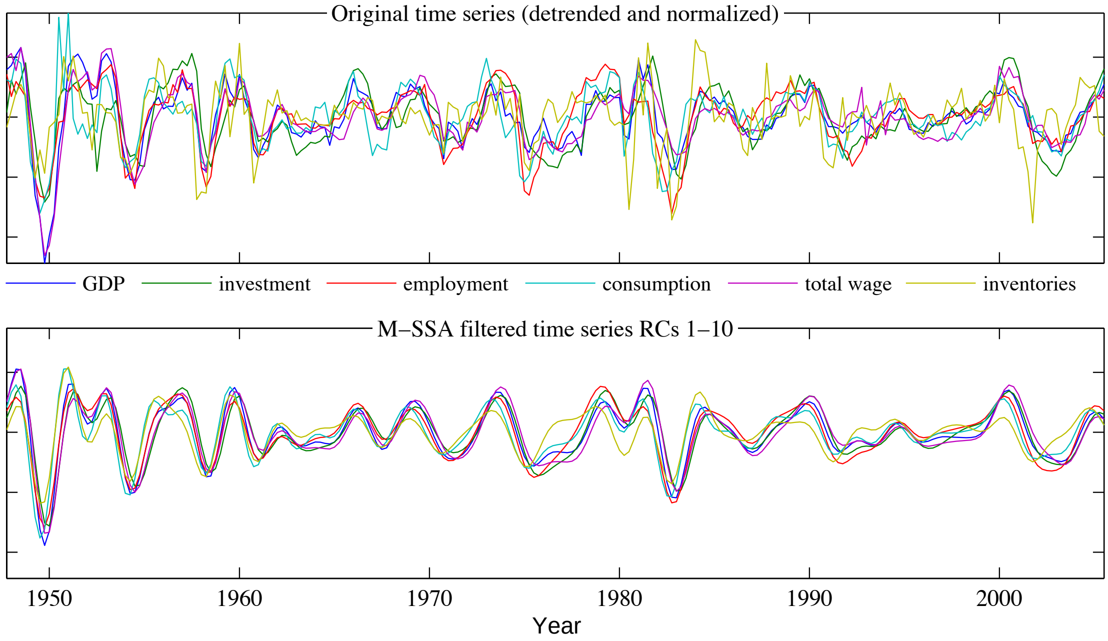

FIGURE 4. Extracting cyclicity from macroeconomic time series. Upper panel : six U.S. economic indicators for 1947–2005 (see text for source and details) ; lower panel : the data-adaptively filtered versions of the time series in the upper panel, by using M-SSA with a maximal time lag for the correlation functions of $M = 40$ quarters.

biomedical sciences. Ghil et al. (2002) provide an overview and a comprehensive set of references ; see also free software at http ://www.atmos.ucla.edu/tcd/ssa/.

The SSA and M-SSA methodology combines two useful features : (i) it determines the data set's major directions in phase space — i.e., the directions of dominant variability — with the help of principal component analysis ; and (ii) it extracts major spectral components with the help of data-adaptive filters. In particular, M-SSA provides a separation of the different spectral components in a multivariate data set. To do so, it first estimates all pairs of auto- and cross-correlation functions up to a predefined time lag. With this information, a grand block matrix is constructed that contains information on all the dependencies between the macroeconomic time series. Next, this matrix is decomposed into its eigenvalues and eigenvectors. The eigenvectors represent an orthonormal basis for the original phase space of the system, while the eigenvalues capture the variance along each eigenvector. With the help of this decomposition, various aspects of the time series can be studied in depth by considering only a subset of leading eigenvalues and corresponding eigenvectors.

The results of applying M-SSA to the six macroeconomic time series of interest are shown in the lower panel of Fig. 4. The time series all represent major U.S. economic indices for 55 years or 220 quarters, and we use a maximum lag of $M = 40$ quarters. Thus our grand lag matrix has a size of N by N, with $N = LM = 240$, where $L = 6$ is the number of channels. In this case, the first 10 of the 240 eigenvalues capture almost 75 percent of the total variance of the original time series. The reconstruction based on projecting the time series onto the 10 leading eigenvectors is the one shown in the lower panel of Fig. 4.

The behavior of the six time series in the lower panel is not only smoother, but also more coherent than for the raw data in the upper panel, because M-SSA looks for common spectral components, contained in all time series. This is a significant advantage in contrast to univariate smoothing algorithms, including the application of single-channel SSA (not shown).

The reconstructed time series clearly exhibit the individual business cycles and typical stylized facts : The period of expansion is in almost all cases longer than the period of recession, and the leads and lags between the individual time series coincide with the stylized facts reported in the literature. A quantitative analysis (not shown here) confirms that changes in business inventories lead GDP, and that employment and personal income are coincidental with GDP, as discussed, for instance, by Zarnowitz (1985). The analysis of Fiorito and Kollintzas (1994) gives slightly different results, with employment lagging GDP by one quarter, while consumption and investment are coincidental with GDP. The differences between our results and previous analyses arise — at least partly — from the fact that previous authors have focused only on the peaks, while our analysis takes the full cycle trajectory into account to decide whether a variable leads or lags another one. This improves the statistical significance of the results.

The results in Fig. 4 show that the cyclical behavior, while pervasive, is not regular in amplitude or period, and that the shape of the cycle is not fixed at all. This irregularity suggests a more mature view of business cycles — in which a single, stylized cycle is replaced by amplitude, period and shape modulation — and supports the idea of chaotic behavior in the economy ; see, for instance, Chiarella (1988); Day and Shafer (1985), as reviewed by Rosser Jr. (1999) and Hallegatte et al. (2008b).

6. SUMMARY AND OUTLOOK

In this research-and-review paper, we set out to combine three strands of research : (i) the formulation and study of a nonequilibrium model of endogenous business cycles (EnBCs)(Hallegatte et al., 2008b) ; (ii) the application of this NEDyM model to the investigation of the impact of global warming and extreme events on the economy (Hallegatte and Dumas, 2008; Hallegatte and Ghil, 2008; Hallegatte et al., 2007) ; and (iii) the quantitative extraction of business cycles from data. Sections 2., 3. and 5. of the paper dealt respectively with each one of these strands ; the latter presented only preliminary results of work in progress. We also addressed briefly in Section 4. the impact of including technological innovation in the reconstruction efforts.

In Section 2., we showed that NEDyM does indeed produce EnBCs, due essentially to the instability of the profit–investment relationship. This relationship is similar to the Keynesian accelerator–multiplier, while the cycles are constrained by the interplay of several processes, including the reserve army of labor effect, the inertia of production capacity, and the consequent inflation in goods prices when demand increases too rapidly. The NEDyM business cycle is consistent with many stylized facts described in the macroeconomic literature, such as the phasing, or comovements, of the distinct macroeconomic variables along the cycle. It also reproduces the observed asymmetry of the cycle, with the recession phase much shorter than the expansion phase ; see again the top panel of Fig. 2. The amplitude of the price-and-wage oscillation, however is too large in NEDyM, calling for a better calibration of the parameters and further refinements of the model.

The model's main control parameter is the investments flexibility. As this parameter increases, model solutions go from a single stable equilibrium, consistent with the Solow (1956) balanced-growth model, to regular, periodic business cycles (see again Fig. 1) and on to irregular, chaotic ones. The reduction in credit access associated with the recent economic and financial crisis obviously diminishes investment flexibility, and NEDyM can thus help explain how this change in an important macroeconomic parameter is bound to seriously perturb the behavior of the entire economic system. To proceed from such a qualitative result to quantitative, detailed predictions, however, requires the "tuning" of the model's parameters to actual economic data, as currently done for real business cycle (RBC) models.

In a nonequilibrium model that does take into account short-term variability, the state of the economy may also affect the consequences of natural disasters, by interfering with reconstruction dynamics ; such effects were reviewed in Section 3.. In the version of NEDyM in which business cycles are present, we found indeed a remarkable *vulnerability paradox* : the indirect costs caused by extreme events during a growth phase of the economy exceed those that occur during a recession ; see once more Fig. 2. The explanation of this apparent paradox, given in Section 3., is probably related to a greater instability of the economy during expansions. We thus expect to find greater variability during expansion phases in time series of economic indicators, which motivated in part our study of the latter.

The results reviewed in Sections 3. and 4. highlight the importance of short-term constraints on the economy in the assessment of long-term damages. Taking into account the presence of business cycles modifies this assessment and points to larger GDP losses than those suggested by the use of optimization strategies based on equilibrium models (e.g., Ambrosi et al., 2003; Nordhaus and Boyer, 1998; Stern, 2006). Moreover, the allocation of capital between reconstruction and other types of investment after a large natural disaster seems to play an important role in both short- and long-term production losses. Global warming is expected to change the distribution of natural hazards ; optimizing this allocation of capital, therefore, will be an important factor in adaptation to future climate change.

The preliminary results of Section 5. dealt with six indicators for the U.S. economy from 1947 to 2005 ; see again Fig. 4. These results, based on a systematic application of multi-channel singular spectral analysis (M-SSA), show that cyclic behavior is pervasive, but not regular in amplitude or period, and that the shape of the cycle is not fixed at all. This irregularity suggests replacing the hunt for the "stylized facts" of a truly typical business cycle by a more sophisticated approach, in which a single, stylized cycle is replaced by amplitude, period and shape modulation of such a cycle. Our results also seem to support the idea of chaotic behavior in the economy (e.g., Day & Shafer, 1985 ; Chiarella, 1988 ; Rosser, 1999, and Hallegatte et al. (2008b).

Our "toy" model, however, is still lacking a suitable calibration of its parameters on economic data. To estimate these parameters, we expect to rely on the "data assimilation" approach. Its use is common by now in the geosciences(Bengtsson et al., 1981; Ghil, 1997; Kondrashov et al., 2008) ; it has been used in the econometric context (Harvey, 1989) but is only starting to be applied to macroeconomic models (Lemoine and Pelgrin, 2004). Preliminary results (not reported here) were obtained by applying data assimilation methods, such as Kalman filtering (Kalman, 1960; Ghil et al., 1981) to the NEDyM model, using at first synthetic data produced by the model itself — the so-called "identical-twin" approach (Bengtsson et al., 1981) ; these results were encouraging but not conclusive. Such methods could be used with the business cycles reconstructed from actual economic indicators in Section 5. to get a better representation of the economic dynamics, to assess the quality of the model, and to suggest possible improvements to it.

Economic planning and adaptation at the local level require also a better understanding of economic processes on smaller scales. Hallegatte et al. (2008a) and Hallegatte (2008) studied the processes that have slowed down reconstruction in the building sector's response to hurricane destructions in Florida, and inter-sectorial relationships in reconstruction dynamics during the response to Hurricane Katrina in Louisiana, respectively. More broadly, understanding business network disruptions may necessitate the representation of individual firms or production units in much greater detail. Such a representation is possible, for instance, in agent-based models that allow one to analyze how failure in some part of the system propagates, dissipates and interacts with similar failures elsewhere. Work along these lines has started with a client-supplier network (Henriet and Hallegatte, 2008) and is proceeding with a model based on the theory of Boolean delay equations (Ghil et al., 2008b).

Finally, work on truly coupled climate-economy models has started by coupling a very simple, linear climate model to a two-sector dynamic economic model (Dumas, 2006). In this model, the infrastructure and housing sector are separated from the rest of the economy ; it is these two sectors that are vulnerable to extreme events and inert. While the macroeconomic modeling in this coupled climate-economy model is less advanced than in NEDyM, it allows one to represent, in one unified framework, climate prediction and adaptation to climate change impacts, while taking into account the natural variability of both the climate system and the economy.

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