Coupled Climate–Economics Modeling and Data Analysis: EnBCs and Fluctuation–Dissipation Theory

Michael Ghil  
ENS, Paris, & UCLA  
with C. Colon (IIASA) & G. Weisbuch (ENS), B. Coluzzi (Roma), A. Groth (Greifswald); P. Dumas (CIRAD), S. Hallegatte (World Bank) & J.-Ch. Hourcade (CIRED); L. Sella (CNR-IRCrES, Torino) & G. Vivaldo (CNR-IGG, Pisa)

Please visit these sites for more info.  
https://dept.atmos.ucla.edu/tcd/, http://www.environnement.ens.fr/  
& https://www.researchgate.net/profile/Michael_Ghil
Motivation

- Coupled climate and socio-economic modeling
- Coordinating EU project on extreme events
  - in the geosciences and the socio-economic sciences
- Novel tools for both data analysis and modeling
  - SSA-MTM Toolkit for time series analysis
  - key tools for nonlinear and random dynamics
  - combined modeling and data studies
Motivation – I

- Major cost in lives & goods of floods & other extremes
- Cost of reconstruction & infrastructure renewal
Motivation – II

- **The IPCC process**: Assessment Reports (AR1–AR5)
- **3 working groups**: various sources of uncertainties
  - Physical Science Basis
  - Impacts, Adaptation and Vulnerability
  - Mitigation of Climate Change
- **Physical and socio-economic modeling**
  - separate vs. coupled
- **Ethics and policy issues**
What is macroeconomics?

- **Economic subdisciplines**
  - macroeconomics: national or regional economy as a whole
  - microeconomics: individual households and firms
  - econometrics: methodology of both macro- & microeconomics

- **Macroeconomic variables and indicators**
  - gross domestic product (GDP) – produit intérieur brut (PIB)
  - production, demand
  - capital, profits (gross, net)
  - price level, wages
  - unemployment rate, number of employed workers
  - liquid assets (of banks, companies)
  - consumption, investment, stock

N. B. Some of these are in physical units, others are monetary; some are observable (time series), some are not
Outline

A. Endogenous business cycle (EnBC) model
   - sawtooth-shaped business cycles, 5–6-year period
   - impact of natural hazards
   - vulnerability paradox ➔ fluctuation-dissipation relation

B. U.S. macroeconomic indicators
   - methodology: singular-spectrum analysis (SSA) + multi-channel SSA (M-SSA)
   - BEA data confirm the vulnerability paradox

C. EU & World data
   - Italy, Netherlands and UK data, correlations with USA
   - 100 countries representing all economic regions
   - commonalities and differences

D. Concluding remarks & bibliography
The need for models with endogenous dynamics

“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.”

George Soros,
The New Paradigm for Financial Markets: The Credit Crisis of 2008 and What It Means,
BBS, PublicAffairs, New York, 2008
Outline

A. Endogenous business cycle (EnBC) model
   – sawtooth-shaped business cycles, 5–6-year period
   – impact of natural hazards
   – vulnerability paradox ➔ fluctuation-dissipation relation

B. U.S. macroeconomic indicators
   – methodology: singular-spectrum analysis (SSA) +
     multi-channel SSA (M-SSA)
   – BEA data confirm the vulnerability paradox

C. EU & World data – work in progress
   – Italy, Netherlands and UK data, correlations with USA
   – 100 countries representing all economic regions
   – commonalities and differences

D. Concluding remarks & bibliography
A tale of two theories: the “real” cycle and the endogenous cycle theories

- **In the real cycle theory**, business cycles and economic fluctuations arise from exogenous “real” (i.e. not monetary) shocks, like changes in productivity or in energy prices, or from fiscal shocks.

Aside from these exogenous shocks, the economic system is stable: all markets are at equilibrium, and there is no involuntary unemployment. Deviations from equilibrium are damped more or less rapidly. Acting on the economy, therefore (e.g., recovery policies), is not useful.

- **In endogenous business cycle (EBC) models**, cyclical behavior originates from endogenous instabilities in the economic system.

Several instabilities have been proposed:
- profitability-investment instability
- delays in investment
- income distribution

Acting on the economy can, therefore, have positive effects, by stabilizing it or by shifting its mean state.
The blessings of interdisciplinarity

Photo with lover
Duncan Grant

John M. Keynes’s home in Bloomsbury

photos M.G., May 2008
Macroeconomic indicators of the U.S.

- **GDP**
- **Price**
- **Exports**
- **Employment**
Macroeconomic modeling

Two main areas of research

- GDP
- Long-term growth (trend)
- Short-term fluctuations (residuals after trend removing)
Mean periodicity =
(2008 – 1937)/12 = 5.9 years

Source: NBER;
graphics: TIME Magazine
NEDyM (Non-equilibrium Dynamic Model)

• Represents an economy with one producer, one consumer, one goods that is used both to consume and invest.

• Based on the Solow (1956) model, in which all equilibrium constraints are replaced by dynamic relationships that involve adjustment delays.

• The NEDyM equilibrium is neo-classical and identical to that in the original Solow model. If the parameters are changing slowly, NEDyM has the same trajectories as the Solow model.

• Because of market adjustment delays, NEDyM model dynamics exhibits Keynesian features, with transient trajectory segments, in response to shocks.

• NEDyM possesses endogenous business cycles!

Hallegatte, Ghil, Dumas & Hourcade (J. Econ. Behavior & Org., 2008)
The basic Solow (1956) model represents market equilibrium + productive capital evolution:

- $Y$—production;
- $A$—total productivity;
- $K$—productive capital;
- $C$—consumption;
- $L$—labor;
- $L_f$—labor at full employment;
- $S$—consumer savings;
- $I$—investment;
- $\Gamma$—investment ratio; and
- $\tau_d$—depreciation time.

The equations governing this long-term growth model are, with $\dot{X} = dX/dt$:

1. $$Y = f(K, L) = AL^\lambda K^\kappa, \quad C + I = Y, \quad L = L_f, \quad S = \Gamma Y, \quad I = S,$$
   \hspace{1cm} \text{(1a)}

2. $$\dot{K} = I - K/\tau_d.$$
   \hspace{1cm} \text{(1b)}

The NEDyM model introduces adjustment delays into the Solow model of Eqs. (1).

The most important ones are:

(a) **Goods market.** To allow for \{supply\} $\neq$ \{demand\}, introduce an inventory $H \leq 0$ with

$$\dot{H} = Y - (C + I).$$

This excess or shortfall of production affects prices $p$

$$\dot{p} = -\alpha_p p H / Y.$$

Hence conventional market clearing conditions (Walras, 1874) are verified only over the long term.
The NEDyM model (Hallegatte et al., *JEBO*, 2008) – Variables & Equations - II

(b) **Labor market.** The producer sets the optimal labor demand $L_e$ that maximizes profits, as a function of wages $w$ and marginal labor productivity $\partial f / \partial L$, with $f$ the Cobb-Douglas function of Eq. (1a):

$$\frac{w}{p} = \frac{\partial f}{\partial L} \bigg|_{(L_e, K)}.$$  

(4)

Thus $L(t) \neq L_f$; instead

$$\dot{L} = \left(\frac{1}{\tau_{\text{emp}}}\right)(L_e - L),$$  

(5)

and wages also evolve to eventually restore full employment,

$$\dot{w} = \frac{w}{\tau_{\text{wage}}} \frac{(L - L_f)}{L_f}.$$  

(6)

(c) **Household behavior.** In NEDyM, a household not only consumes $C$ and invests their savings $S$ but can also temporarily hoard $M$, with $M \sim H$ in Eq. (2) above.

(d) **Producer behavior.** Instead of $I = S$, as in Eq. (1a), NEDyM describes an investment behavior à la Kalecki (*RES*, 1937), with a stock of liquid assets $F$ that is distributed as dividends $D$:

$$\dot{F} = p(C + I) - wL + S - D - pI.$$  

(7)

Please see the full list of variables and parameters in Tables 1–3 of Hallegatte et al. (*JEBO*, 2008) and the equations collected in Appendix A of Hallegatte & Ghil (*EcolEc*, 2008).
Hopf bifurcation from stable equilibrium to a limit cycle ("business cycle")
$\alpha_{\text{inv}} = 1.7$: purely periodic behavior (limit cycle)

$\alpha_{\text{inv}} = 2.5$: transition to chaos (irregular behavior)
$\alpha_{\text{inv}} = 10$: irregular orbit (kinky torus)

$\alpha_{\text{inv}} = 20$: very asymmetric business cycle (relaxation oscillation)
Endogenous dynamics: an alternative explanation for business cycles
Endogenous business cycles (EnBCs) in NEDyM

- Business cycles originate from the profit–investment relationship (oscillations with a 5–6-year period) – Fukuyama (1989–92)?!
  - higher profits => more investments => larger demand => higher profits

- Business cycles are limited in amplitude by three processes:
  - increase in labor costs when employment is high;
  - constraints in production and the consequent inflation in goods prices when demand increases too rapidly;
  - financial constraints on investment.

- EnBC models need to be calibrated and validated
  - harder than for real business cycle models (RBCs):
    - fast and slow processes => need a better definition of the business cycles => study of BEA & NBER data!
Catastrophes and the state of the economy – I

A vulnerability paradox: When does a disaster cause greater long-term damage to an economy, during its expansion phase or during a recession?

Catastrophes and the state of the economy – II

A vulnerability paradox:
A disaster that affects an economy during its recession phase...

**Business cycle**

**Economic losses due to a disaster, as a function of the pre-existing economic situation**

**Limited losses if the disaster affects an economy in recession**
Catastrophes and the state of the economy – III

...causes fewer long-term damages than if it occurs during an expansion!

Einstein (1905) formulated the problem of the **Brownian motion** of a large particle immersed in a fluid formed of many small ones as follows:

\[ du = -\lambda u dt + \eta(t), \]  

(8)

Here the random force \( \eta(t) \) is assumed to be a “white noise”: it has mean zero \( \mathcal{E}[\eta(t; \omega)] = 0 \) and autocorrelation \( \mathcal{E}[\eta(t; \omega)\eta(t + s; \omega)] = \sigma^2 \delta(s) \); \( \delta(s) \) is a Dirac function, \( \sigma^2 \) is the variance of \( \eta(t) \), \( \omega \) a realization of \( \eta(t) \), and \( \mathcal{E} \) is the expectation operator.

Equation (8) is the Langevin equation, with \( \eta = \sigma dW \) and \( W(t) \) a **Wiener process**. Einstein’s main result is that

\[
\mathcal{E}[u^2] = \frac{\tau^*}{2\lambda}, \quad \mathcal{E}[x^2] = \frac{\tau^*}{\lambda^2 t}.
\]  

(9)

Here \( x(t) = x_0 + \int_0^t u(s)ds \) is the displacement of the particle and \( \tau^* = \int_{-\infty}^{+\infty} \sigma^2 \delta(s)ds \). There are two remarkable features in Eqs. (9) above.
First, the variance of the displacement is proportional to time, \( \mathcal{E}[x^2] \propto t \). Hence, stochastic differential equations (SDEs) distinguish between the time differential \( dt \) and the stochastic differential \( dW \), since \( \int_0^t ds = t \), while \( \int_0^t dW(s) = t^2 \); in other words, \( dW \propto (dt)^{1/2} \).

Second, the friction coefficient \( \lambda \) characterizes a dissipation of the fluctuations, since \( \mathcal{E}[u(t)] = \mathcal{E}[u_0] \exp(-\lambda t) \). More generally, the dissipation constant is \( D = \lim_{t \to \infty} \mathcal{E}[(x(t) - x(0))^2] \), and one gets

\[
\mu = \frac{D}{kT} = \frac{1}{kT} \int_0^\infty \mathcal{E}[u(t_0)u(t_0 + t)]dt; \tag{10}
\]

here \( \mu = 1/\lambda \) is the mobility of the particles, \( T \) is the temperature of the thermal bath, and \( k \) is the Boltzmann constant. This is the original version of the FDT.

Hence, for a system in thermodynamic equilibrium, the decay of fluctuations is the same, whether caused by an external shock or by an internal anomaly. And we know typically much more about the former than about the latter. It is this knowledge we wish to apply to the macroeconomy now.
# Long-term averaged GDP losses due to natural disasters (*)

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Economic dynamics</th>
<th>Mean GDP losses (% of baseline GDP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No investment flexibility $\alpha_{inv} = 0$</td>
<td>Stable equilibrium</td>
<td>0.15%</td>
</tr>
<tr>
<td>Low investment flexibility $\alpha_{inv} = 1.0$</td>
<td>Stable equilibrium</td>
<td>0.01%</td>
</tr>
<tr>
<td>High investment flexibility $\alpha_{inv} = 2.5$</td>
<td>Endogenous business cycle</td>
<td>0.12%</td>
</tr>
</tbody>
</table>

(*) calibrated on the disasters that impacted the EU in the last 30 years (Hallegatte, Hourcade & Dumas, 2007; Munich-Re, 2004)
Outline

A. Endogenous business cycle (EnBC) model
   – sawtooth-shaped business cycles, 5–6-year period
   – impact of natural hazards
   – vulnerability paradox \(\rightarrow\) fluctuation-dissipation relation

B. U.S. macroeconomic indicators
   – methodology: singular-spectrum analysis (SSA) + multi-channel SSA (M-SSA)
   – BEA data confirm the vulnerability paradox

C. EU & World data – work in progress
   – Italy, Netherlands and UK data, correlations with USA
   – 100 countries representing all economic regions
   – commonalities and differences

D. Concluding remarks & bibliography
# Singular Spectrum Analysis (SSA) – I

<table>
<thead>
<tr>
<th>Spatial EOFs (PCA)</th>
<th>Temporal EOFs (SSA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion</td>
<td>Expansion</td>
</tr>
<tr>
<td>$\Phi(t, x) = \sum_k a_k(t)e_k(x)$</td>
<td>$X(t, s) = \sum_k a_k(t)e_k(s)$</td>
</tr>
<tr>
<td>Covariance</td>
<td>Covariance</td>
</tr>
<tr>
<td>$C_\Phi(x, y) = \langle \Phi(t, x)\Phi(t, y) \rangle_t$</td>
<td>$C_X(s, u) = \langle X(t)X(t +</td>
</tr>
<tr>
<td>Eigendecomposition</td>
<td>Eigendecomposition</td>
</tr>
<tr>
<td>$C_\Phi e_k = \lambda_k e_k$</td>
<td>$C_X e_k = \lambda_k e_k$</td>
</tr>
<tr>
<td>Eigenelements</td>
<td>Eigenelements</td>
</tr>
<tr>
<td>$e_k(x)$</td>
<td>$e_k(s)$</td>
</tr>
<tr>
<td>$x$ – space</td>
<td>$s$ – time lag</td>
</tr>
<tr>
<td>$\lambda_k$ pairs $\rightarrow$ oscillations</td>
<td>$(nonlinear)$ sine + cosine pair</td>
</tr>
</tbody>
</table>

- Colebrook (1978); Weare & Nasstrom (1982); Broomhead & King (1986; BK); Fraedrich (1986); Vautard & Ghil (1989; VG).

- BK + VG: Analogy between Mañé-Takens embedding and the Wiener-Khinchin theorem.
▶ Truncation of the expansion to the $S$ leading EOFs
$\Rightarrow$ data-adaptive filter.
▶ Nearly equal eigenvalues $\Rightarrow$ nonlinear, anharmonic oscillation.
Singular Spectrum Analysis (SSA) decomposes (geophysical & other) time series into **Temporal EOFs** (T-EOFs) and **Temporal Principal Components** (T-PCs), based on the series’ lag-covariance matrix.

Selected parts of the series can be reconstructed, via **Reconstructed Components** (RCs).

- SSA is good at isolating oscillatory behavior via paired eigenelements.
- SSA tends to lump signals that are longer-term than the window into
  - one or two trend components.

**Selected References:**
- Vautard & Ghil (1989, *Physica* D);
Stylized Facts of a Business Cycle – I

Need a more objective, quantitative description of the “typical business cycle.” To do so we use two complementary approaches:
1. synchronization methods from dynamical systems (“chaos”); and
2. Advanced methods of time series analysis (SSA and M-SSA)

9 variables:
gross domestic product (GDP), investment, consumption, employment rate (in %), price, total wage, imports, exports, and change in private inventories.

Groth, Ghil, Hallegatte and Dumas, submitted

Raw data, detrended and standardized

(a) Pre-processed time series

(b) RCs 1–32 of M–SSA

9-channel SSA ($D = 9$, $M = 24$ quarters)

Adaptive filtering, via multichannel singular-spectrum analysis (M-SSA);
vertical shaded bars are NBER-defined recessions
Consider the local variance fraction $V_{K}(t)$ with $D = 9$, $M = 100$, and $A_{k}(t)$ the PCs:

$$V_{K}(t) = \frac{\sum_{k \in K} A_{k}(t)^2}{\sum_{k=1}^{DM} A_{k}(t)^2}$$

The “signal” fraction is largest during the recessions

The “noise” fraction is largest during the expansions

Vertical shaded bars are NBER-defined recessions

Groth, Ghil, Hallegatte and Dumas, submitted
Outline

A. Endogenous business cycle (EnBC) model
   - sawtooth-shaped business cycles, 5–6-year period
   - impact of natural hazards
   - vulnerability paradox → fluctuation-dissipation relation

B. U.S. macroeconomic indicators
   - methodology: singular-spectrum analysis (SSA) + multi-channel SSA (M-SSA)
   - BEA data confirm the vulnerability paradox

C. EU & World data
   - Italy, Netherlands and UK data, correlations with USA
   - 100 countries representing all economic regions
   - commonalities and differences

D. Concluding remarks & bibliography
World Economic Activity (Groth & Ghil, *Chaos*, 2018) – Dataset

We analyze macroeconomic data from the *World Development Indicators (WDI)* database of the World Bank. Annual datasets for a comprehensive collection of development data. Five variables were selected, all given in constant 2010 US$

1. **Gross domestic product (GDP)** at market prices;
2. **gross fixed capital formation (GDI)**; *
3. **final consumption expenditure (CON)**;
4. **exports (EXP)** of goods and services;
5. **imports (IMP)** of goods and services.

We restricted ourselves to the interval 1970–2015 of length $N = 46$ years, for which we have 104 economies with no missing values from at least one of these five macroeconomic indicators. The total number $D = 336$ of input time series for the analysis lies, therewith, between the (number of economies $= 104) \times (5$ variables) $= 520$ and half this number, $260 \leq D \leq 520$.

*formerly gross domestic fixed investment*
World Business Cycle

Synchronization of macroeconomic indicators from over 100 countries; mean period = 7–11 years
Outline

A. Endogenous business cycle (EnBC) model
   - sawtooth-shaped business cycles, 5–6-year period
   - impact of natural hazards
   - vulnerability paradox \( \Rightarrow \) fluctuation-dissipation relation

B. U.S. macroeconomic indicators
   - methodology: singular-spectrum analysis (SSA) +
     multi-channel SSA (M-SSA)
   - BEA data confirm the vulnerability paradox

C. EU & World data – work in progress
   - Italy, Netherlands and UK data, correlations with USA
   - 100 countries representing all economic regions
   - commonalities and differences

D. Concluding remarks & bibliography
Conclusions and outlook: a hierarchy of economic models and data analysis methods

1. The highly idealized, aggregate NEDyM model exhibits fairly realistic, endogenous business cycles (EnBCs): period = 5–6 yr, sawtooth shape, good phasing of indices.

2. NEDyM displays a vulnerability paradox:
   - extreme-event consequences depend on the state of the economy;
   - they are more severe during an expansion than a recession.

3. This paradox is supported by
   - consequences of Izmit (Marmara) earthquake, 1999;
   - reconstruction process after the 2004 and 2005 hurricane seasons in Florida.

   data assimilation (M. Bocquet, P. Dumas, A. Groth).


6. Need more detailed, regional and sectorial models: C. Colon, B. Coluzzi, M. G., S.H., and G. Weisbuch have used simplified, Boolean models to study the economy as a network of businesses (suppliers and producers, etc.).

7. Compare aggregate models with agent-based models (ABMs) and with the data, US + EU + global.
The place of BDEs in dynamical systems theory

Flows
- \( x \) continuous, \( t \) continuous
- (vector fields, ODEs, PDEs, FDEs/DDEs, SDEs)

Maps
- \( x \) continuous, \( t \) discrete
- (diffeomorphisms, OΔEs, PΔEs)

Automata
- \( x \) discrete, \( t \) discrete
- (Turing machines, real computers, CAs, conservative logic)

BDEs, kinetic logic
- \( x \) discrete, \( t \) continuous

\( \Delta t \) ("P-map", time-one map)
- Suspension
- Interpolation, smoothing
- \( \Delta t \) (discretization, thresholds, saturation)

\( \Delta x \) (discretization, thresholds, saturation)
- Interpolation, smoothing
- Suspension?
- \( \Delta t \) ("P-map")

after A. Mullhaupt (1984) and M. Ghil et al. (2008)

Ghil, Zaliapin & Coluzzi, 2008:
Some general references on macroeconomics

Arrow, K.J., and G. Debreu. Existence of an equilibrium for a competitive economy.


Nikolaidi, M., 2019: Climate-economy modelling: an introduction,
A few references


The deeper motivations of economic modeling

“Really, Karl! Can’t I mention the high price of kohlrabi without getting a manifesto?”
Reserve slides
A day in the life of the Lorenz (1963) model’s random attractor, or LORA for short; see SI in Chekroun, Simonnet & Ghil (2011, *Physica D*)
### Table SPM.2. Recent trends, assessment of human influence on the trend and projections for extreme weather events for which there is an observed late-20th century trend. (Tables 3.7, 3.8, 9.4; Sections 3.8, 5.5, 9.7, 11.2–11.9)

<table>
<thead>
<tr>
<th>Phenomenon and direction of trend</th>
<th>Likelihood that trend occurred in late 20th century (typically post 1960)</th>
<th>Likelihood of a human contribution to observed trend</th>
<th>Likelihood of future trends based on projections for 21st century using SRES scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warmer and fewer cold days and nights over most land areas</td>
<td>Very likely</td>
<td>Likely</td>
<td>Virtually certain</td>
</tr>
<tr>
<td>Warmer and more frequent hot days and nights over most land areas</td>
<td>Very likely</td>
<td>Likely (nights)</td>
<td>Virtually certain</td>
</tr>
<tr>
<td>Warm spells/heat waves. Frequency increases over most land areas</td>
<td>Likely</td>
<td>More likely than not</td>
<td>Very likely</td>
</tr>
<tr>
<td>Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas</td>
<td>Likely</td>
<td>More likely than not</td>
<td>Very likely</td>
</tr>
<tr>
<td>Area affected by droughts increases</td>
<td>Likely in many regions since 1970s</td>
<td>More likely than not</td>
<td>Likely</td>
</tr>
<tr>
<td>Intense tropical cyclone activity increases</td>
<td>Likely in some regions since 1970</td>
<td>More likely than not</td>
<td>Likely</td>
</tr>
<tr>
<td>Increased incidence of extreme high sea level (excludes tsunamis)</td>
<td>Likely</td>
<td>More likely than not</td>
<td>Likely</td>
</tr>
</tbody>
</table>

a. = assessment; b. = assessment of contribution; c. = likely; d. = virtually certain; e. = more likely than not; f. = likely; g. = likely.
F. Bretherton's "horrendogram" of Earth System Science

Earth System Science Overview, NASA Advisory Council, 1986
Global warming and its socio-economic impacts—II

Temperatures rise:
• What about impacts?
• How to adapt?

AR5 vs. AR4

A certain air of *déjà vu*: GHG “scenarios” have been replaced by “representative concentration pathways” (RCPs), more dire predictions, but the uncertainties remain.

*Source: IPCC (2013), AR5, WGI, SPM*
Climate models (atmospheric & coupled) : A classification

• **Temporal**
  - stationary, (quasi-)equilibrium
  - transient, climate variability

• **Space**
  - 0-D (dimension 0)
  - 1-D
    - vertical
    - latitudinal
  - 2-D
    - horizontal
    - meridional plane
  - 3-D, GCMs (General Circulation Model)
  - Simple and intermediate 2-D & 3-D models

• **Coupling**
  - Partial
    - unidirectional
    - asynchronous, hybrid
  - Full

→ **Hierarchy**: back-and-forth between the simplest and the most elaborate model, and between the models and the observational data
Global warming and “global weirding”

“CLIMATE STRANGE
FORGET GLOBAL WARMING—AND
GET READY for GLOBAL WEIRDING
BY BRYAN WALSH”


“The New Rule: For the next few (?) years, global warming will lead to
colder, more brutal winters.”

- Oh, thank you for the latest prediction from a science journalist — based on interesting but still rather tentative, & hotly debated, suggestions from a few media-loving (& vice-versa) researchers.

- And if this is so certain, why wasn’t it predicted by IPCC(*) and other models BEFORE it happened?

(*) Intergovernmental Panel on Climate Change
Concluding remarks, I – RDS and RAs

Summary
• A change of paradigm from closed, autonomous systems to open, non-autonomous ones.
• Random attractors are (i) spectacular, (ii) useful, and (iii) just starting to be explored for climate applications.

Work in progress
• Study the effect of specific stochastic parametrizations on model robustness.
• Applications to intermediate models and GCMs.
• Implications for climate sensitivity.
• Implications for predictability?
Concluding remarks, II –
Climate change & climate sensitivity

What do we know?
• It’s getting warmer.
• We do contribute to it.
• So we should act as best we know and can!

What do we know less well?
• By how much?
  – Is it getting warmer …
  – Do we contribute to it …
• How does the climate system (atmosphere, ocean, ice, etc.) really work?
• How does natural variability interact with anthropogenic forcing?

What to do?
• Better understand the system and its forcings.
• Explore the models’, and the system’s, robustness and sensitivity
  – stochastic structural and statistical stability!
  – linear response = response function + susceptibility function!!
Climatic uncertainties & moral dilemmas

Feed the world today or...

see also Hillerbrand & Ghil, Physica D, 2008, 237, 2132–2138,