COMPLEX Final Scientific Report, Volume 2

Non-linearities and System-Flips

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With contributions from the COMPLEX Consortium
http://owsgip.itc.utwente.nl/projects/complex/

COMPLEX (EU Project n°: 308601) is a 48-month project. We began collecting material for this report in Month 38 and started editing it together in Month 40. This report is a snapshot of the project taken in its final year. Please check the COMPLEX website for updates, executive summaries and information about project legacy.

Published by Sigtunastiftelsen, Sigtuna, Sweden
Human Nature Series
Editors: Nick Winder and Hans Liljenström
Graphic design: Regina Clevehorn, Sigtunastiftelsen
Printed by Kopieringshörnan I Uppsala AB, Uppsala 2016
ISBN: 978-91-976048-2-6
www.sigtunastiftelsen.se

5. The Climate System

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It is no surprise that state-of-the-art Global Climate Models (GCMs) and their recent extensions – Earth System Models (EMS) – based on strongly non-linear equations of geophysical fluid dynamics often demonstrate strongly non-linear behaviour. It should be noted however that already very simple climate models, like one-dimensional energy-balance models (EBMs) that were by design unable to resolve atmospheric/ocean dynamics, often demonstrated prominent nonlinear behaviour, including the existence of possible multiple equilibria (Budyko, 1969; Sellers, 1969). And even simpler zero-dimensional models broadly used as climate modules of Integrated Assessment models to calculate global mean surface air temperature changes caused by anthropogenic GHG emissions, e.g. the model NICCS (Hooss *et al.*, 2001), are usually nonlinear (CO_2 concentration typically enters the r.h.s. of temperature dynamic equation under a logarithm, therefore the CO_2 forcing is nonlinear etc.).

It should be noted in this respect that the entire modern theory of dynamic systems emerged from a seminal three-dimensional dynamic model of convection for which a strange attractor has been discovered by Lorenz (1963). Thus the modern theory of chaotic systems has its origin in geophysical fluid dynamics. In a recent review Ghil (2013) addresses two complementary approaches to modelling global climate system as a dynamic system – a deterministic nonlinear approach, which he calls “the Lorenz approach”, and a stochastic linear approach, which he calls “the Hasselmann approach” (in the latter the “slow” climate variability is caused by random forcing by “fast” “weather” events (Hasselmann, 1976)). He argues that the unification of both approaches towards a stochastic nonlinear climate theory is necessary to address problems of climate variability and climate sensitivity to external forcing.

An analysis of ocean circulation – an important element of the global climate system – from the viewpoint of modern theory of dynamic systems started with a simple two-box model of the North Atlantic circulation, in which two steady-state flow regimes were revealed (Stommel, 1961). These ideas have been significantly advanced in recent years in the numeric bifurcation analysis of realistic ocean models, which are able to address features such as the bistable regimes of the Gulf Stream and Kuroshio, or the El Niño – Southern Oscillation (ENSO) phenomenon (see a comprehensive review in (Dijkstra, 2005)). Finding steady-state solutions of a hierarchy of ocean models of increasing complexity, accompanied by a numeric analysis of their stability and associated bifurcation diagrams in the model parameter space, is a promising area for the further development of more realistic climate models, since the values of many ocean model parameters, especially with respect to sub grid dynamic processes, are often not known with sufficient accuracy (Dijkstra, 2005).

Thresholds

Rial *et al.* (2004) relate the concept of thresholds in climate system to a question of the balance of amplifying (positive) and controlling (negative) feedbacks. They propose a metaphor of a net feedback, arguing that countless feedbacks in the climate system can be reduced to a net negative feedback and a net positive feedback, According to this metaphor, in unperturbed conditions the net negative climate-driving feedback of the Earth is slightly stronger than the net positive feedback, at least for small values of external/internal forcing. However if the forcing grows beyond the point at which the two competing feedbacks are balanced, then the explosive amplification produced by positive feedbacks leads to strong nonlinear effects. The point of balance between the two competing feedbacks defines a runaway threshold.

However, even below this critical runaway level, the negative impacts of human induced climate change can become so strong at some critical adaptation threshold that societies are no longer able to respond to the climate change impacts at an acceptable cost. Thus mitigation policies should be implemented such that this critical adaptation threshold is not exceeded. The inevitable uncertainty in the scientific and socioeconomic determination of the adaptation threshold has inevitably lead to discussions within the academic community. However, in the Copenhagen Accord (UNFCCC, 2010) this threshold, based on recommendations, among others, of Bruckner *et al.* (1999), was set at 2 degrees C. Jaeger & Jaeger (2011) provide an interesting overview of the history of emergence of 2C target, including a review of the criticism of this target. Whether the 2C threshold is well justified as a mitigation policy target or not, there is now increasing scepticism on the chances of retaining the global mean surface air temperature at or below this limit (Anderson & Bows, 2011; Peters *et al.*, 2013). At the same time, some recent studies (Mann, 2009; Smith *et al.*, 2009) have revised the climate change impacts associated with 2C temperature rise above the pre-industrial level towards higher severity levels. On this basis, Anderson and Bows (2011) suggest redefining the 2C limit as a threshold not between "acceptable" and "dangerous" climate change, but between "dangerous" and "extremely dangerous" climate change.

Irreversibilities

In IPCC AR5 WGI (2013, final draft) abrupt climate change is defined as a large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems.

The IPCC AR5 WGI (2013, final draft) defines a perturbed state as irreversible on a given timescale if the recovery timescale from this state due to natural processes is significantly longer than the time it takes for the system to reach this perturbed state.

The concept of abrupt climate change is closely related to the concept of egrodicity (or supposed non-ergodicity) of the global climate system. The dynamic system is called ergodic if its behavior does not depend on its initial state and if its statistics as $t \to \infty$ does not depend on its initial position in phase space (Karol, 1988), If the climate system is ergodic, then for given external conditions there can be only one climate state; otherwise, dependent on the initial conditions, the climate system can move to different asymptotic regions in the phase space, so that multiple climate states may be possible for single given external conditions, the actual climate depending on the history of the system. Lorenz (1976) called ergodic climate systems "transitive" and non-ergodic climate systems "intransitive"; referring to paleoclimate evidence, he also proposed a hypothesis of "almost-intransitivity" of highly nonlinear climate systems. According to this hypothesis, the phase space of the global climate system is divided into separate regions. The trajectories of the climate system remain within a certain area over a finite time interval, but from time to time they move from one region to another. Lorenz (1976) provided an example of "almost-intransitive" dynamic system.

It should be noted that abrupt climate changes can be defined not only in the time domain (as above), but also in the frequency domain, where they can be manifested as changes in dominant oscillations or shifts in the phase between different climate signals (Lohmann, 2011). One example, suggested by modelling studies (e.g. Timmermann *et al.*, 1999) is a possible change in El Niño events caused by global warming

Irreversible changes in the climate system may be triggered if the forcing exceeds certain thresholds. E.g. a recent modelling study by Robinson *et al.* (2012) suggests that an irreversible decay of the Greenland ice sheet (that would lead to 6 to 7 m sea level rise) could start when the global average temperature exceeds 1.5C above preindustrial level (with a range of 0.8 to 3.2degrees C); These estimates are substantially lower than those reported previously in IPCC AR4 Other model simulations suggest that not only the level of the forcing matters, but also its rate of its change (Stocker, 1999). For instance, simulations with a coupled climate model reported in (Stocker & Schmittner, 1997) produced irreversible changes of the Atlantic thermohaline circulation at CO_2 concentration of 750 ppm if CO_2 increases by 1% per year, while at a slower rate of only 0.5% per year the system withstands the increase of CO_2 concentration up to the same level. The sensitivity to the rate of increase of the CO_2 concentration is governed in this case by the rate increase of the heat uptake of the ocean.