Modeling continuum climate variability: Atmosphere, ocean, land, and ice

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Summary

Continuum temperature variability represents the response of the Earth's climate to deterministic external forcing. Scaling regimes range from days to ten-millennia with low frequency fluctuations characterizing long-term memory. Complex ocean-atmosphere climate models (ECHAM/MPIOM, HadCM3, and a CSIRO-AOGCM) reproduce this behavior quantitatively up to millennia *without* solar variability, interacting land-ice and vegetation components. First attempts to include ice-sheet dynamics into ECHAM were undertaken at MPI-M. Extending the spectral continuity beyond millennia to the ultra-low frequency domain is one aim of future research, in particular its conceptual and numerical modeling, which includes continental ice sheet dynamics. This will be achieved with the climate model Planet Simulator (University of Hamburg), an Ocean-Atmosphere General Circulation Model built to perform numerical experiments for understanding the dynamics of the climates of the Earth, Earth-like planets, and moons of the solar system. In Earth system analysis it is embedded in a modeling hierarchy ranging from complex state of the art and intermediate climate models. By using the spectrum of climate system components modules available at the University of Hamburg and the MPI-M, the role of different climate compartments, in particular the dynamics of land-ice shields and their interactions, will be assessed. Identification of a deterministic control on the continuum response allows insight into the climatic mechanisms governing interannual to ultra-long fluctuations. Thus, the proposed fellowship gives impetus for the MPI-M and the University of Hamburg towards climate system analysis and modeling for time scale ranges inaccessible so far.

1. Observed long and short term memory

The temporal variability of dynamical systems like weather or climate is conveniently characterized by its memory. Short-term memory shows finite integral correlation time-scale and is related to exponentially decaying auto-correlation between initial and future states. Long-term memory characterized by an infinite integral time-scale has a non-integrable power-law autocorrelation. Time variability can be represented by a power spectrum which, if it follows a power law scaling, $S(f) \sim f^{-\beta}$, characterizes long-term memory for an exponent range $0 < \beta < 1$, i.e. between white and flicker noise. Flicker or 1/*f*-noise ($\beta = 1$) is unique in the sense that it contains equal variability for all time scales without scale separation.

In the mid 1970s Brownian motion has entered climate research as a paradigm for the Earth's climate fluctuations. Based on Kutzbach and Bryson's (1974) observation that, in the Holocene, temperature variance density increases with decreasing frequency, Hasselmann (1976) introduced the Brownian motion analog for the climate system response on white noise atmospheric forcing. As the auto-correlation of this system decreases exponentially, there is no indication of long-term memory. Still, such simple concepts have stimulated an intensive red noise search in observed data and simulations of comprehensive general circulation models (GCM). However, scaling behavior different from the Lorentzian but with long-term memory, has recently been identified in many subsystems of the Earth's climate (see Pelletier and Turcotte, 1999, and below).

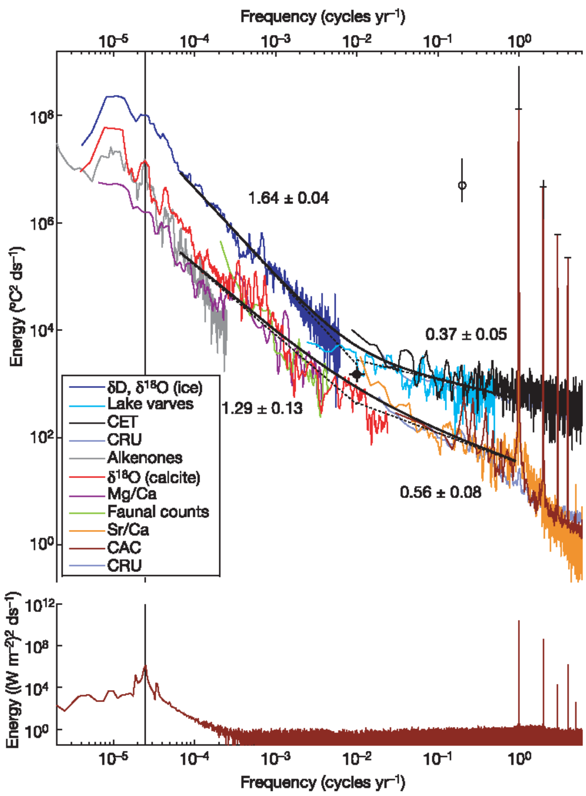

Fig. 1 [from Huybers, P. and W. Curry, 2006: Links between annual, Milankovitch and continuum temperature variability. *Nature*, 441, 329-332].

The Figure shows a patch-work of spectral estimates based on instrumental and proxy records of surface temperature variability, and insolation at 65°N. The origin of the data is indicated. The upper (lower) curve is based on high-latitude data (tropical sea surface temperatures). Power-law estimates between 1.1-100 years and 100-15.000 years periods are indicated by dashed lines. The sums of the power-laws fitted to the long- and short-period continuum are indicated by the black curve. The mark at 1/100 years indicates the region mid-way between the annual and Milankovitch periods. At the bottom is the spectrum of insolation at 65°N sampled monthly over the past million years (vertical black line: 41-kyear obliquity period).

Recently Huybers and Curry (2006) demonstrate that climate variability exists at all timescales and climate processes are intimately coupled, so that understanding variability at any one timescale requires some understanding of the whole. Records of the Earth's surface temperature illustrate this interdependence with continuum variability which follows power-law scaling (Figure 1). Modes of interannual variability are relatively well understood, but controls on continuum variability are unknown and often interpreted as stochastic processes. It has been shown that power-law relationships of surface temperature variability exist, scaling with annual and Milankovitch cycles (23,000 and 41,000 year). The annual cycle dominates monthly to decadal, while millennial to longer cycles are linked with Milankovitch cycles. That is, from annual to Milankovitch periods, a continuum temperature variability represents the response of the Earth climate variability to its deterministic insolation forcing. The identification of a deterministic control on the continuum response allows insight into the climatic mechanisms governing interannual to long-period fluctuations.

2. Modelling climate variability: Atmosphere, ocean, land, and ice

A focus of research during the last years was (i) detection of long-term memory in compartments of the global climate system, (ii) its reproducibility by simple and complex models and (iii) its impact on the behavior of trends and extremes. Before results are summarized two remarks on the analysis of long-term memory and on non-stationary time series are in order.

Analysis of long-term memory: Stationary long-term memory (LTM) is typically based on scaling low frequency behavior of the power spectrum $S(f) \sim f^{-\beta}$. The state of the art method for the analysis of LTM processes is the Detrended Fluctuation Analysis (DFA, Peng et al. 1994) since it integrates the time series and yields a fluctuation function $F(t) \sim t^{\alpha}$ with a scaling that is directly linked to the power spectrum scaling by $\beta = 2\alpha - 1$.

Non-stationarity and 1/f-noise: The analysis by Huybers and Curry (2006) reveals that the climate is non-stationary beyond millennia since the low frequency power spectra scale as $S(f) \sim f^{-\beta}$ with exponents $\beta > 1$. The limiting case $\beta = 1$ is 1/*f* or flicker noise representing a spectral law found in wide fields of natural science, however, still awaiting satisfactory explanations in terms of simple models. The 1/*f*-spectrum also appears in finite frequency ranges without relation to non-stationarity.

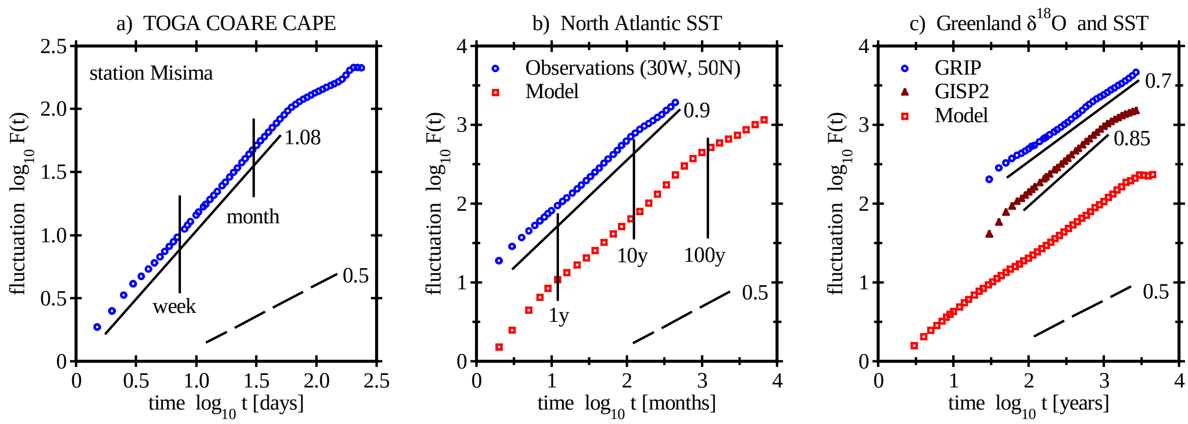

Figure 2: Climate variability in (a) tropical data (TOGA-COARE) in the short-term range of days to months, (b) mid-latitude sea surface temperature (SST) in the annual to decadal time range, and (c) Greenland ice core and SST in the decadal to millennial time range. The panels show the fluctuation function (by DFA); its power law scaling is marked by slopes α corresponding to spectral power law scaling $\beta = 2\alpha - 1$.

a) Atmosphere: 1/f-scaling ranges from clouds to ENSO

The tropical convective variability reveals 1/*f*-noise for a 1-30-day period (Yano et al. 2001, Yano et al. 2004) as detected in convective available potential energy (Figure 2a), which measures the degree of convective instability, boundary layer moisture, wind speed and temperature during a 4-month period over the western Pacific (Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment, TOGA-COARE). A first theoretical explanation of the 1/*f*-noise observed is a conceptual boundary layer recharge-discharge model based on pulse-like events. Moreover, pulses are discovered, which consist of 1/*f*-noise in wide range of time scales, so that the 1/f-noise variability extends continuously from clouds via the Madden-Julian (or 30-60 day) oscillation to ENSO (El Nino-Southern Oscillation, Yano et al. 2004). This has important implications for global climate modeling, particularly for ENSO predictions and the stochastic parameterization of subgrid-scale processes (Fraedrich 2005).

Precipitation: A final conclusion about long-term memory of precipitation is not yet available, because it is a notoriously 'difficult' variable to be observed and simulated. Observed time series, although carefully prepared, cannot be considered as reliable for long-term analysis since their lengths are mostly not sufficient and the effect of changes in measurement methods cannot be ignored. In simulations, the specific choice of parameterization schemes has a strong impact and deviations of 50% in mean quantities hint at fundamental problems.

b) Ocean-Atmosphere: Temperature scaling in observations and climate models

Power-law scaling of near surface air temperature fluctuations and its geographical distribution is analyzed in 100 years observations and in a 1000 year simulation of the present-day climate with a complex atmosphere-ocean model (Fraedrich and Blender 2003). In observations and simulation, DFA leads to the scaling exponent corresponding to $\beta = 1$ over the oceans (Figure 2b), $\beta = 0$ over the inner continents, and $\beta = 0.3$ in coastal transition regions. Scaling up to decades is demonstrated in observations and coupled atmosphere-ocean models with complex and mixed-layer oceans. Only with the complex coupled ocean-atmosphere model the simulated power laws extend up to centuries.

The 1/*f*-spectrum of the ocean surface temperature in the Atlantic and Pacific mid-latitudes is explained by a vertical diffusion energy balance model consisting of a shallow mixed layer on top of a deep ocean forced by stochastic surface fluxes (Fraedrich et al., 2004). A 1000 year climate simulation is employed for testing: Given its total surface heat flux forcing at the air-sea interface, the impact of horizontal surface advection and the internal thermal diffusivities can be estimated.

The spectral variability of the meridional overturning circulation (MOC) in the Atlantic Ocean reveals no consistent result in two coupled atmosphere-ocean general circulation models, GFDL and ECHAM5/MPIOM (Zhu et al. 2006). In the interannual to decadal frequency range, the spectra are dominated by scaling, $S(f) \sim f^{-\beta}$, with nontrivial exponents, mostly β=1, in agreement with 1/*f* or flicker noise. For the lowest frequencies, some spectra show stationary long-term memory, while others reveal spectra increasing with frequency. None of the spectra can be considered uniquely as red noise explained by an ocean integrating a white stochastic atmospheric forcing.

c) Land: Droughts, floods, and river discharges

The long-term memory of the surface temperature and possibly run-off (Fraedrich and Bantzer 1991, Fraedrich et al. 1997 analyzing Nile data) is outstanding since other prominent key variables like pressure and precipitation (Fraedrich and Larnder 1993) indicate much less memory. Long-term memory analysis of the components of the hydrological cycle in East Asia in a high resolution GCM simulation reveals specific differences between the variables that describe processes (precipitation, evaporation, and local runoff) and those describing storage (soil wetness, soil temperature, and, similar, atmospheric near-surface temperature). The simulated river flows of the Yangtze reveal LTM with scaling exponents β=0.3…0.4 extending beyond the decadal time scale (similar to observations, and that of the rivers Nile and Huang He, see Jiang et al. 2005, Blender and Fraedrich 2006, Wang et al. 2006). Patterns, variability and extremes of dryness and wetness, also under global change conditions, are determined in Europe and China using the Standardized Precipitation Index (SPI, Bordi et al. 2003, Bordi et al. 2004).

d) Ice core: Variability in a 10k year simulation

A GCM simulation reveals the quantitative agreement of the simulated sea surface temperature with the GISP2 and GRIP $\delta^{18}O$ records during the Holocene. The 10.000 year simulation is performed with the coupled CSIRO atmosphere-ocean model under present-day conditions. Up to 1000 years DFA-scaling leads to a spectral exponent $\beta = 0.5$ in ice-free sea surface temperature south of Greenland consistent with the ice core temperature proxy data (Figure 2c, note that the ice core data differ slightly). The LTM of the surface temperature is coupled to the intense low frequency variability of the Atlantic MOC. In the Pacific and Antarctic ocean LTM is not simulated, which is in agreement with ice core proxy data during the Holocene in Antarctic.

In summarizing, the group at the University of Hamburg has successfully demonstrated

(1) that a complex ocean-atmosphere climate model (CSIRO) *without* an interacting land-ice component is able to create fluctuations captured in millennial ice core data;

(2) long-term memory scaling (from years to centuries) and its land-ocean difference both in observations and modeling, which is solely due to ocean-atmosphere coupling. The theoretical concept is based on a vertically diffusive energy balance model with a deep ocean under a shallow mixed layer forced by stochastic atmospheric fluxes;

(3) scaling regimes continuing to higher frequencies (from days to years). The conceptual theory is based on random pulses affecting a boundary layer recharge-discharge mechanism, whose variability follows a 1/*f*-noise spectrum in a range which exceeds the duration of the pulses' life-cycles.

Extending the spectral continuity beyond millennia into the ultra-low frequency domain is one aim of future research, in particular its conceptual and numerical modeling, which includes continental ice sheet dynamics.

3. The Planet Simulator

The Planet Simulator is built to support numerical experiments for understanding the dynamics of the climate of the Earth, Earth-like planets, and moons of the solar system. In this sense the Planet Simulator can be used as a simplified virtual laboratory to study fundamental dynamical and thermo-dynamical issues, to identify feedbacks responsible for the long-term stability of the climate, and to explore the causes of sudden losses of stability or abrupt change, like the impact of volcanic eruptions and the consequences of a thermohaline circulation breakdown. The Planet Simulator can be used to run climate and paleo-climate simulations for time scales up to ten thousand years or more in an acceptable real time. The priorities in development are set to speed, easy handling and portability. Its modular structure allows a problem dependent configuration. Adaptions exist for the climates of Mars and of Saturn's moon Titan. Common coupling interfaces enable the addition of ocean models, ice models, vegetation, and other compartments.

Features of the model environment developed at the Meteorological Institute (University of Hamburg) are: (i) The models are embedded in a hierarchy of complexity and share the same philosophy and coding principles: the Planet Simulator, the Portable University Model of the Atmosphere (PUMA) and the Shallow Atmosphere Model (SAM). (ii) In addition to the standard terrestrial version, Planet Simulator Earth, configurations for Mars and Titan are available. (iii) An interactive mode with a Model Starter (MoSt) and a Graphical User Interface (GUI) can be used to select a model configuration from the available hierarchy and to inspect atmospheric fields while changing model parameters on the fly. This is especially useful for teaching, debugging and tuning of parameterizations. (iv) The code is portable, scalable, modular and open source to instigate capacity building, that is, collaboration in research, cooperation in teaching (e-learning), and progress in community model building. The complete model hierarchy including sources and documentation is available at www.mi.uni-hamburg.de/plasim.

The Planet Simulator is coupled to models for the compartments ocean (including sea ice), vegetation, and land ice. For ocean simulations, for example, three models can be selected: (i) LSG (Large Scale Geostrophic, note that the model is nevertheless not quasigeostrophic), which is a three-dimensional dynamic model based on the primitive equations (Maier-Reimer et al. 1993), (ii) the University of Victoria (Canada) model UVic based on MOM (Geophysical Fluid Dynamics Laboratory, Princeton), and (iii) a mixed layer model with prognostic depth. Vegetation is simulated by SimBa, a biome model which uses a continuous, macroscopic description of vegetation properties. Land ice is simulated by the model SICOPOLIS (Simulation COde for POLythermal Ice Sheets), a three-dimensional, dynamic-thermodynamic ice-sheet model (Greve 1997a, b, implemented for Planet Simulator Mars); the model is based on the shallow-Ice approximation, which determines for an arbitrary ice shield the evolution of thickness, density, velocity, temperature, water content, and the age of the ice. Thus, the Planet Simulator should be considered as an open system in transit based on a dynamical core of the primitive equation atmosphere in the traditional spectral form and sigma coordinates (like PUMA). The data structure is fully compatible with the ECHAM model (MPI for Meteorology).

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