Where are the coexisting parallel climates?
Large ensemble climate projections from the point of view of chaos theory

SCREEN CAPTURE WELCOME

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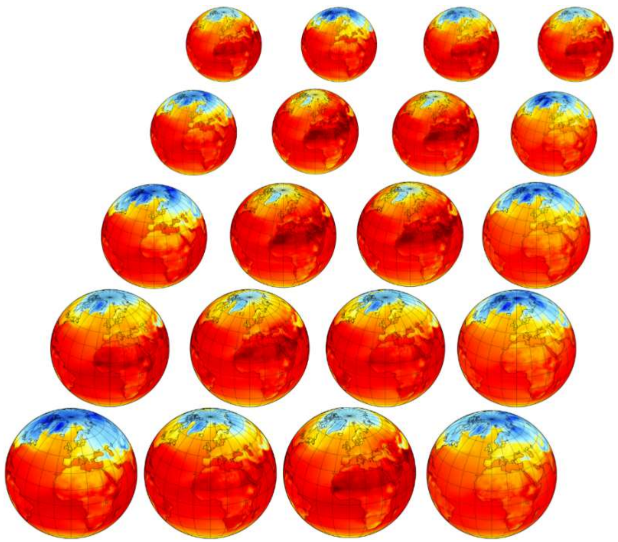

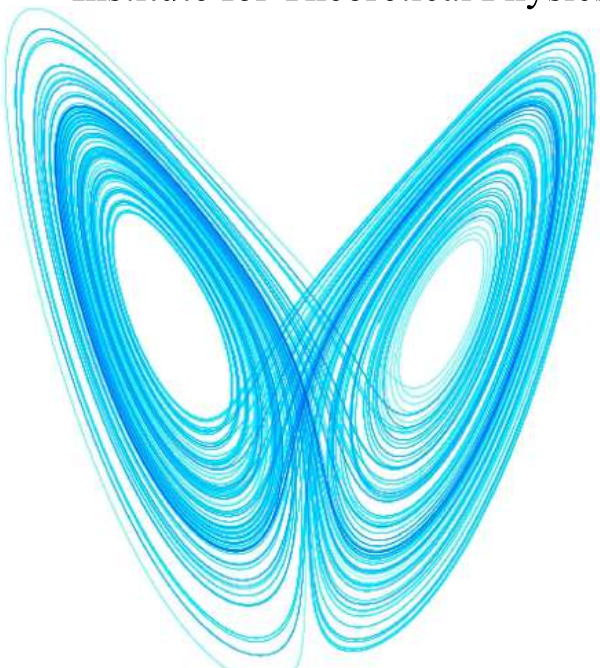

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Motivation – The Snapshot attractor view

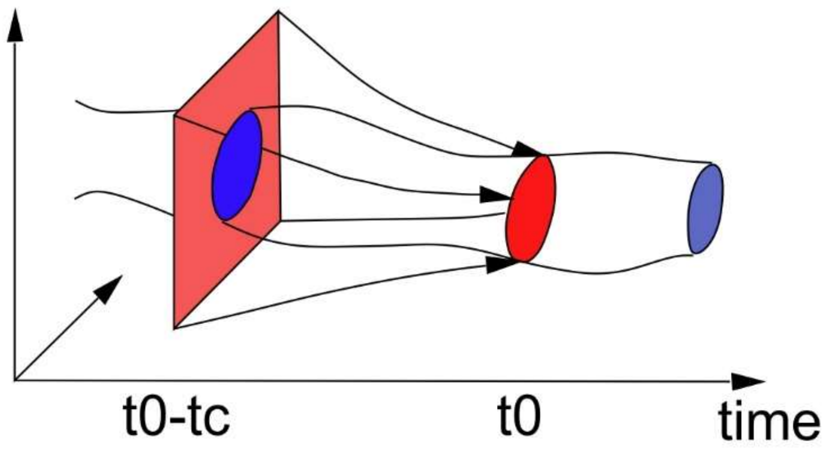
- What is climate (theoretically)?

„*The climate is what you expect, the weather is what you get*” /Robert Heinlein, 1973/
„Climate lasts all the time and weather only a few days” /*Mark Twain, 1887*/

- Question: if climate is what we „expect”, then what is the **expectation value**, what is the underlying **statistics (probability)**?

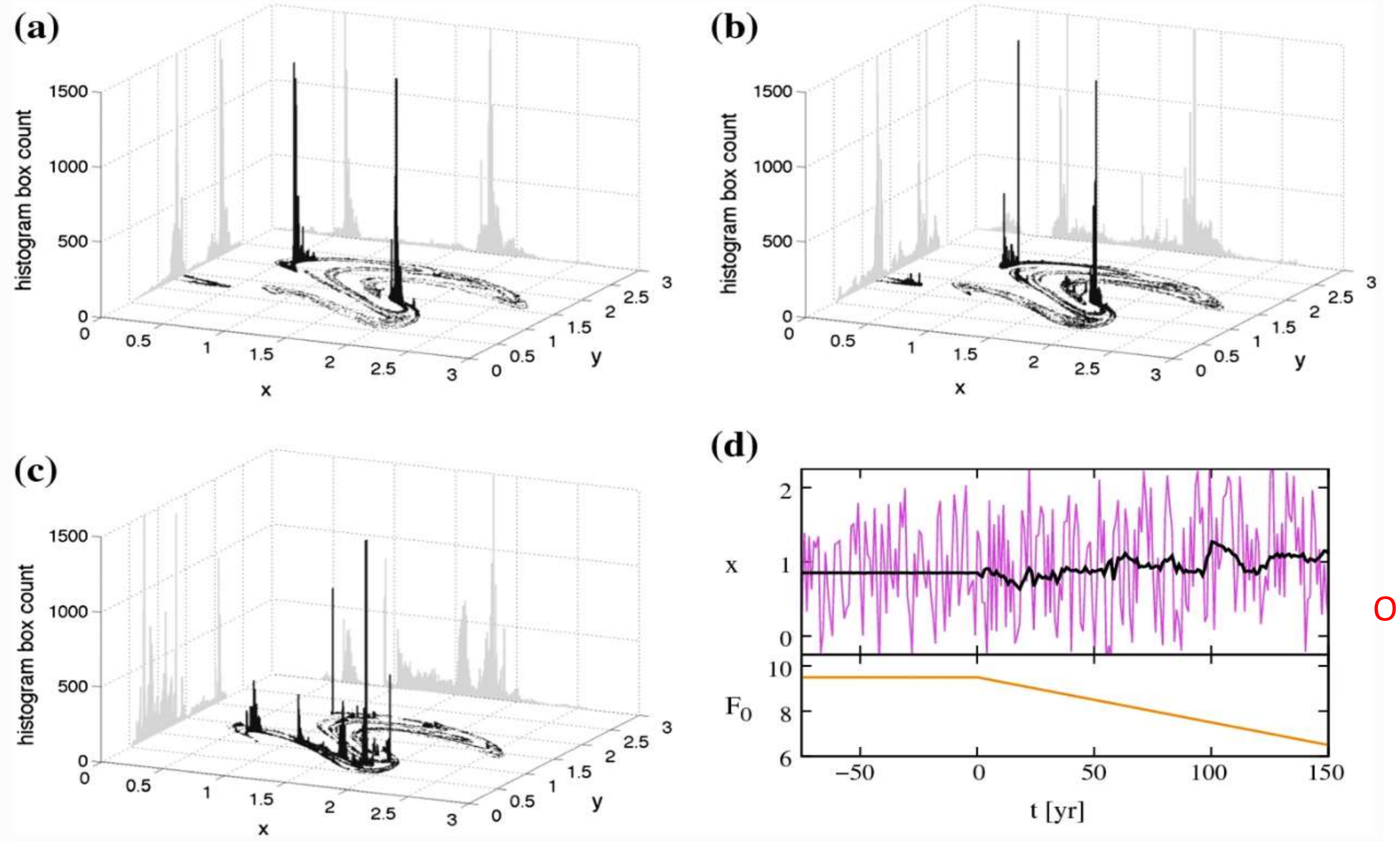
- An appropriate mathematical concept is that of snapshot/pullback attractors (Romeiras et al., 1990; Ghil et al., 2008; Bódai, Tel, 2012; Drótos et al., 2015; Herein et al., 2016; 2017).
- These are attractors (to which ENSEMBLEs of trajectories converge) in systems whose essential parameters are changing. .. its natural probability distribution is also changing.

  - Trajectories evolving from the „distant past”
  - A set to which the system evolves after a long enough time (tc)
  - Variability: the characteristic size of the attractor
  - Instantaneously permitted parallel climate realization



Schematic view of the convergence to snapshot attractor (after Sévellec, F., & Fedorov, A. V. 2015)

Illustration of the time-dependence of a snapshot attractor – Lorenz’84 system



$$\frac{dx}{dt} = -y^2 - z^2 - ax + aF$$
$$\frac{dy}{dt} = xy - bxz - y + G$$
$$\frac{dz}{dt} = bxy + xz - z \ .$$

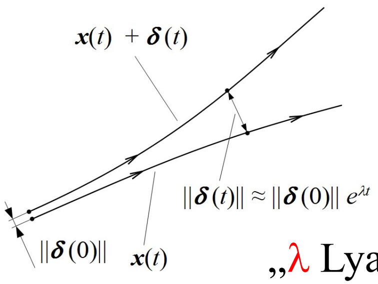
One trajectory is not „relevant”

A conceptual climate model (Lorenz'84) with x as the speed of westerlies (over a hemisphere), and y as the strength of cyclonic activity. The forcing parameter: decrease of the temperature contrast (F) after the onset of the climate change in year 0. (a) 25 years (b) 50 years (c) 85 years after climate change (d) One member (magenta), ensemble average (black) and forcing (orange) after Tél et al., 2020.

Results

<u>Consequences (Chaos analogy)</u>

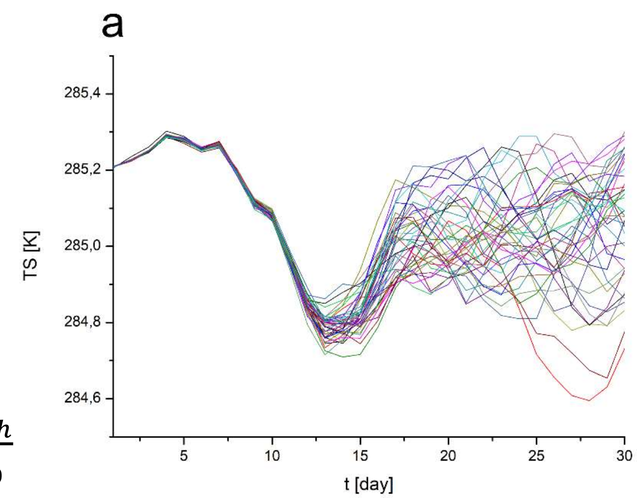
- parallel climate realizations in CESM1-LE (Kay et al., 2015)
- Driven pendulum



$$\Delta r = e^{\lambda t} \cdot \Delta r_0$$

$$t_p = \frac{1}{\lambda} ln \frac{\Delta r_{th}}{\Delta r_0}$$

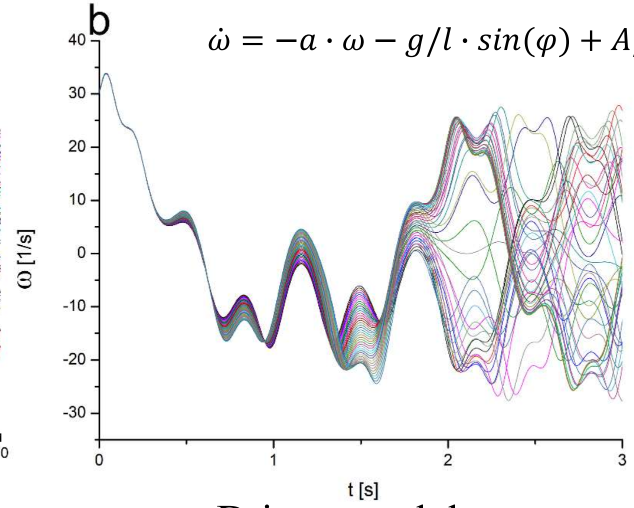
„λ Lyapunov exponent”



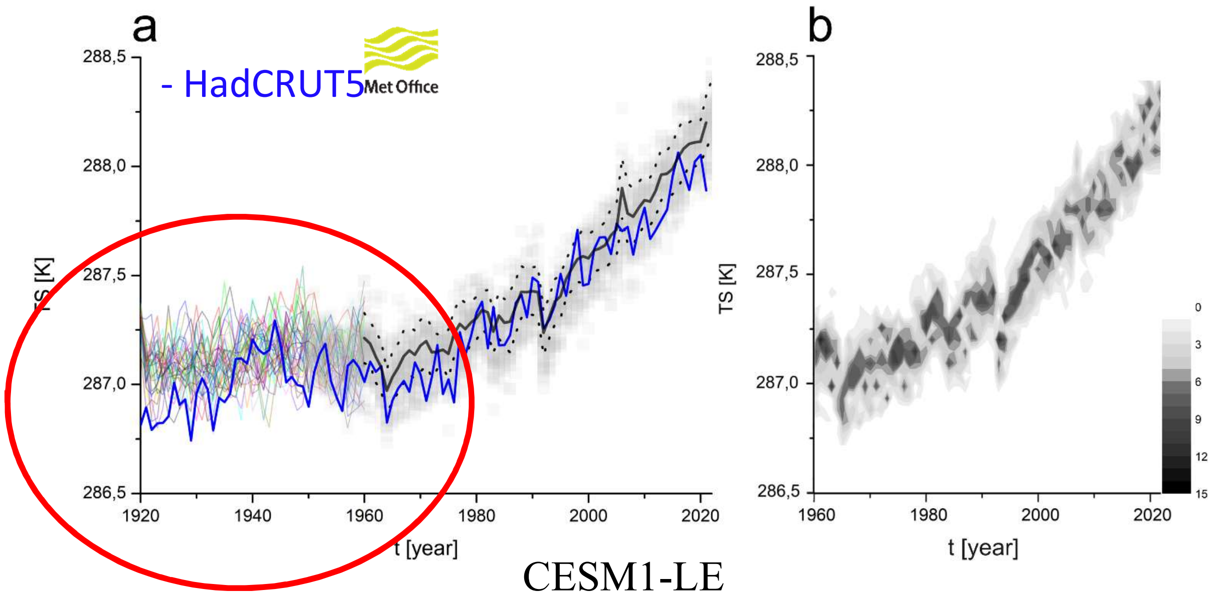
CESM1-LE

$$\dot{\varphi} = \omega,$$

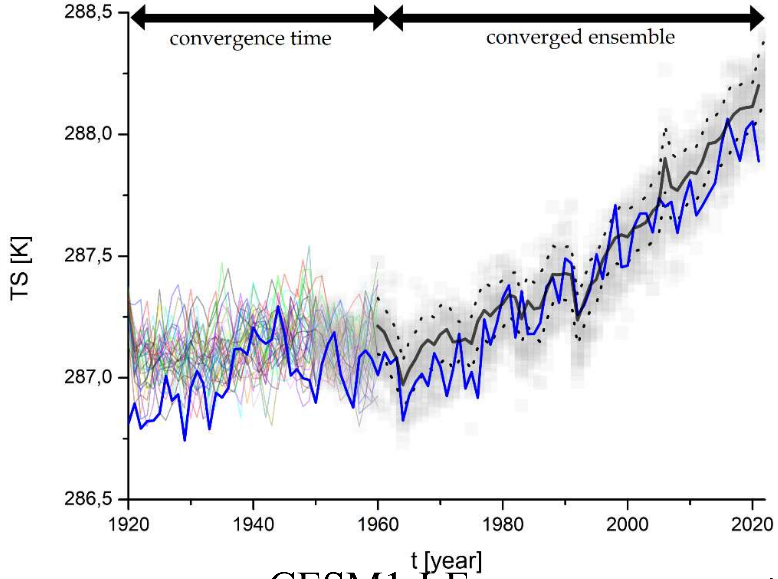
$$\dot{\omega} = -a \cdot \omega - g/l \cdot sin(\varphi) + A/l \cdot \omega^2 \cdot cos(\Omega\, t) \cdot cos(\varphi)$$



Driven pendulum



CESM1-LE



CESM1-LE

Herein et al., 2023

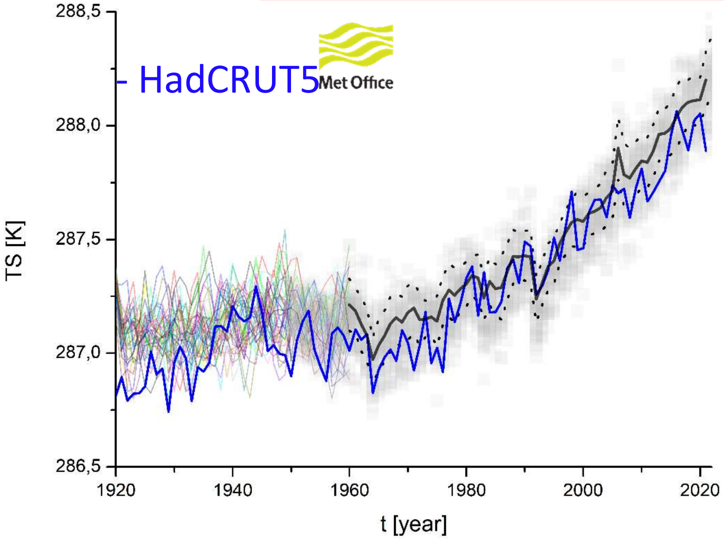
Consequences (credible models - Where are parallel climates at all?)

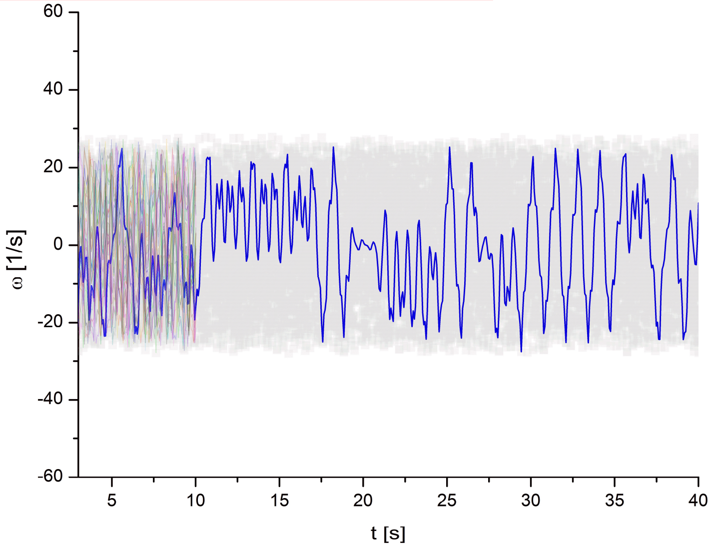
- A model is credible if: **1. observed signal wanders within the band of the ensemble**
- **2. the climate model must be a converged one!**

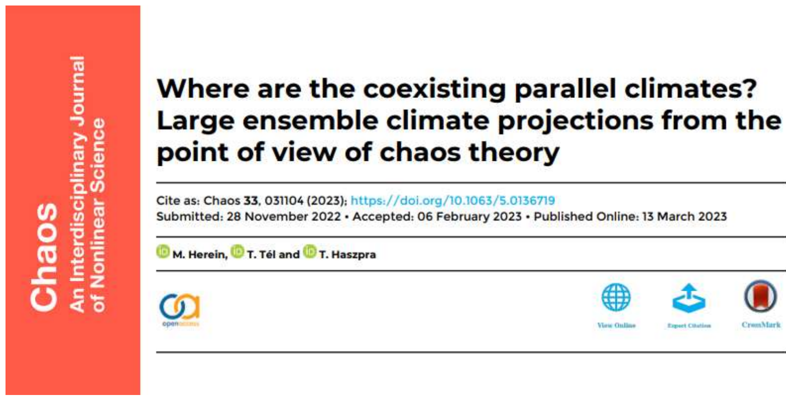
- Meaning: **being credible** (globally at least) requires the agreement between simulated and measured quantities
- in nonlinear science, we can say that they are present indeed in any credible ensemble simulation, even if not in an individual sense, rather in the form of the probabilities generated by the dynamics.

- It is valid for PAST and FUTURE EQUALLY!
- consider using only converged **SMILES** (Single model initial-condition large ensembles)
- „..concept, .. referred to as the “Theory of Parallel Climate Realizations” (Tél et al., 2020)... has enormous implications." C. Deser Earth Future

agreement between simulated and measured quantities



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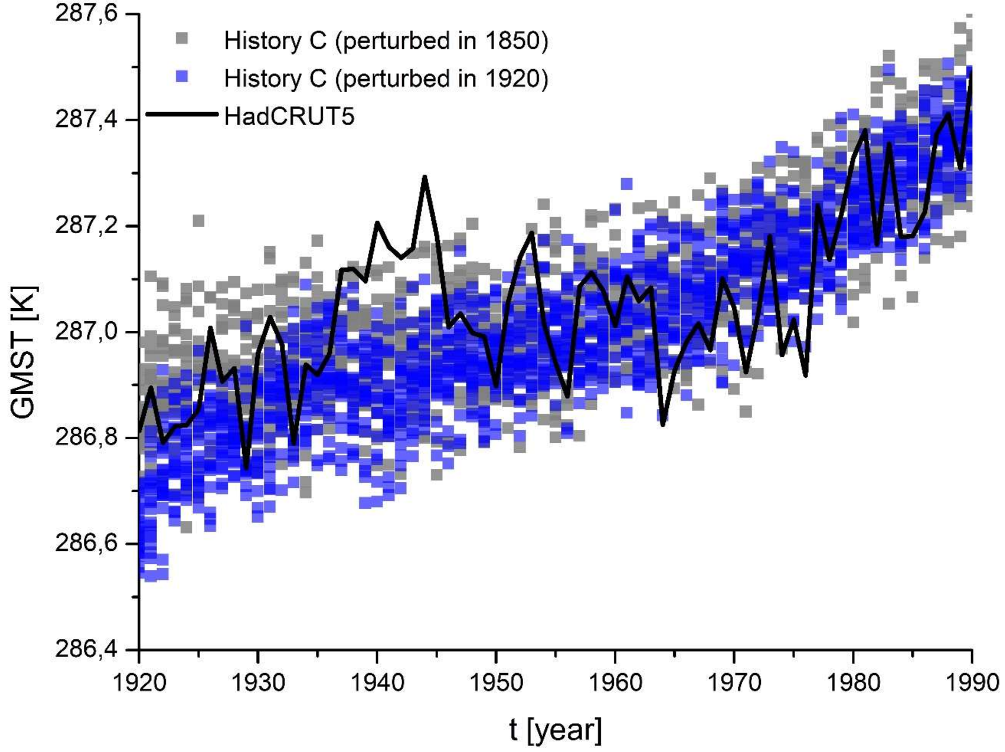
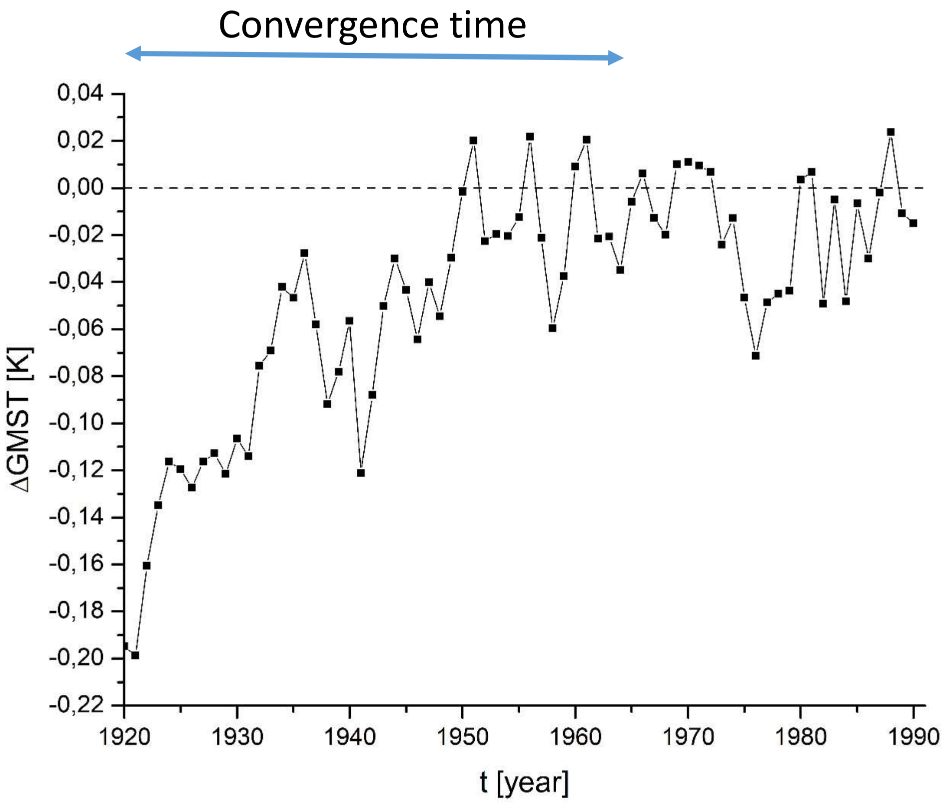
Parallel climates in CESM1-LE and for a driven pendulum (Herein et al., 2023)

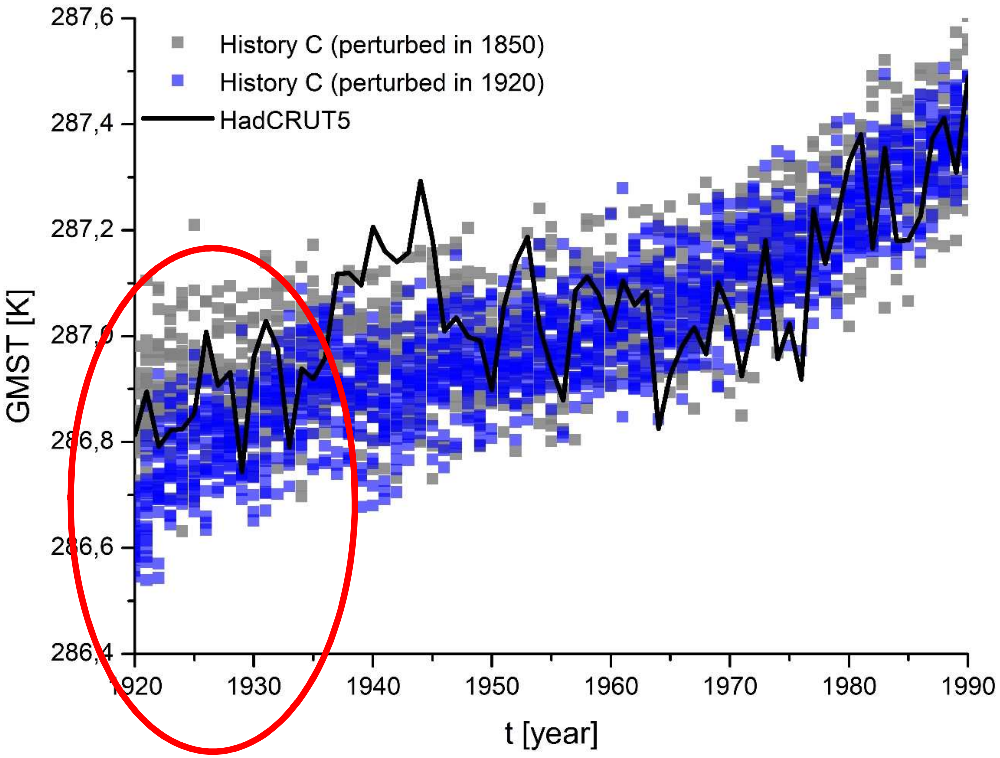
The importance of „being" converged

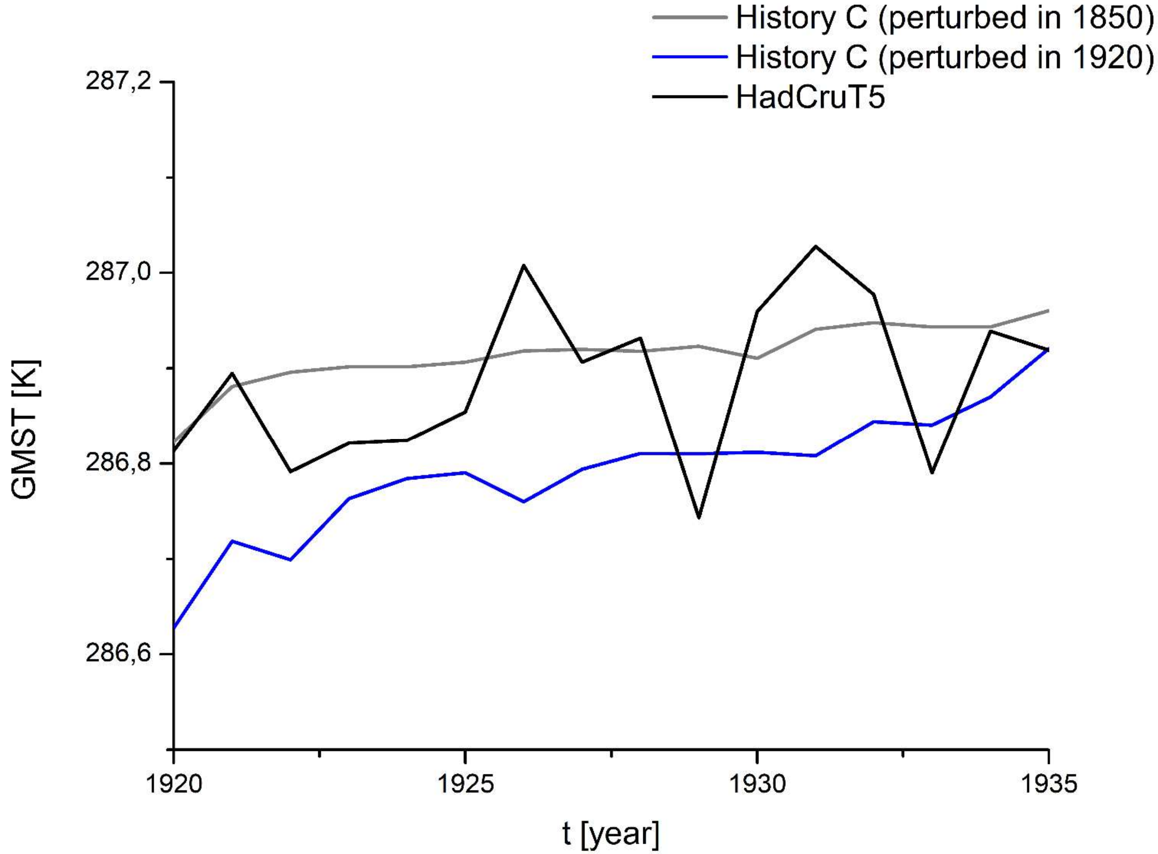
- To illustrate convergence we run climate model PlaSim (T21, LSG ocean, historical+Keeling forcing)
- converged (grey) and un-converged (blue) ensembles





The lack of convergence





Conclusions

• „Where are „parallel climates at all??” – „present indeed in any credible ensemble simulation, even if not in an individual sense, rather in the form of the probabilities generated by the dynamics”

•Due to chaos -> „butterfly effect” – none of the trajectories are distinguished

•BUT still we have one measured reality only

•Credible models: only converged ensembles, in harmony with observations

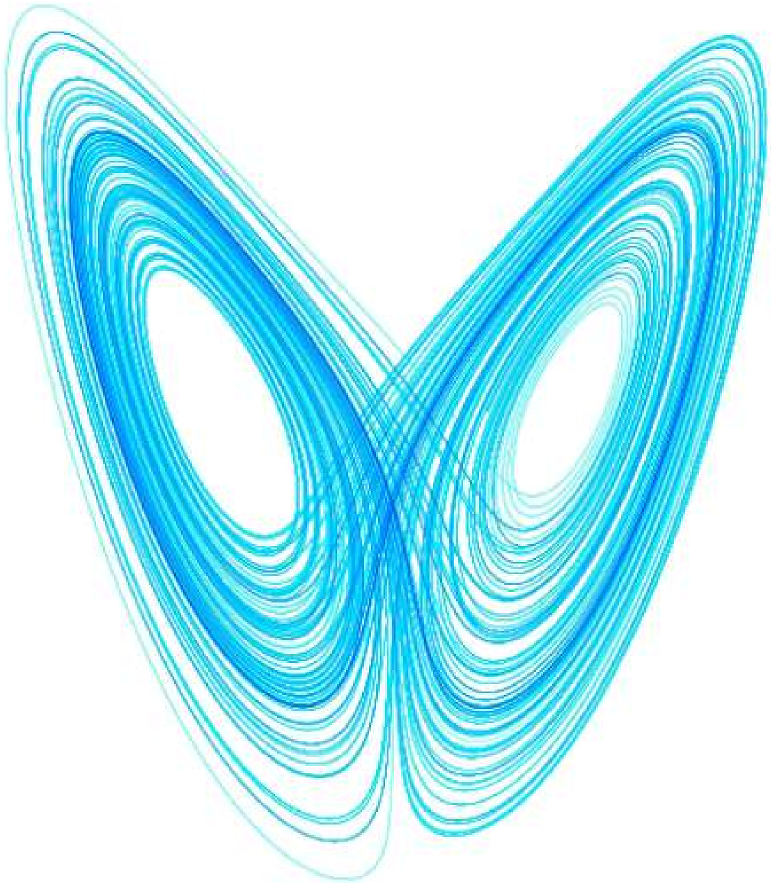
•**TRUE EVEN in chaos related experiments!**

•Convergence time: at least decades

•Climate ensembles should be generated in the „distant past”

•Lack of convergence can lead to misleading results

- **Co-existing „climates”: today’s Earth, slushball, snowball ?**
- **Co-existing „climate states” – splitting of the snapshot attractor**



Ongoing research / Further prospectives

- AMO/PDO-SEOF – PDO-ENSO coupling in the snapshot picture
- Arctic-Tropic, teleconnection strength changes? (Tímea Haszpra, Dániel Topál)
- TSI changes and climate response (Imre M. Jánosi, Tímea Haszpra, Gábor Drótos)
- Geoengineering, Solar Shield Management (Tímea Haszpra)
- Snowball dynamics (co-existing climate attractors)
- Chaos and climate (Warmer climates are less predictable?) (Tamás Tél, Dániel Jánosi)
- Schumann Resonance – climate feedback (Tamás Bozóki)
- Tidally-locked exoplanets (Miklós Vincze)

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The theory of parallel climate realizations as a new framework for teleconnection analysis

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Teleconnections are striking features of the Earth climate system which appear as statistically correlated climate-related patterns between remote geographical regions of the globe. In a changing climate, however, the strength of teleconnections might change, and an appropriate characterization of these correlations and their change (more appropriate than detrending the time series) is lacking in the literature. Here we present a novel approach, based on the theory of snapshot attractors, corresponding in our context to studying parallel climate realizations. Imagining an ensemble of parallel Earth systems, instead of the single one observed (i.e., the real Earth), the ensemble, after some time, characterizes the appropriate probabilities of all options permitted by the climate dynamics, reflecting the internal variability of the climate. We claim that the relevant quantities for characterizing teleconnections in a changing climate are correlation coefficients taken over the temporally evolving

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