Global cooling: the Snowball Earth transition in a climate model with drifting parameters

Bálint Kaszás[1,3], Tímea Haszpra[1,2], Mátyás Herein[1,2]

[1]Institute for Theoretical Physics, Eötvös Loránd University, Budapest, Hungary
[2]MTA-ELTE Theoretical Physics Research Group
[3]kaszasb@caesar.elte.hu

Motivation

The current configuration of our planet allows two stable climates

- A warm state, resembling today's climate
- An ice-covered Snowball Earth.

Drastic changes in solar irradiance (e. g. volcanic ash in the atmosphere) may trigger a transition to the Snowball state.
Conversely, the sudden melting can be induced by greenhouse gases.
The driving mechanism behind both the freezing and melting processes is the **ice-albedo feedback**.

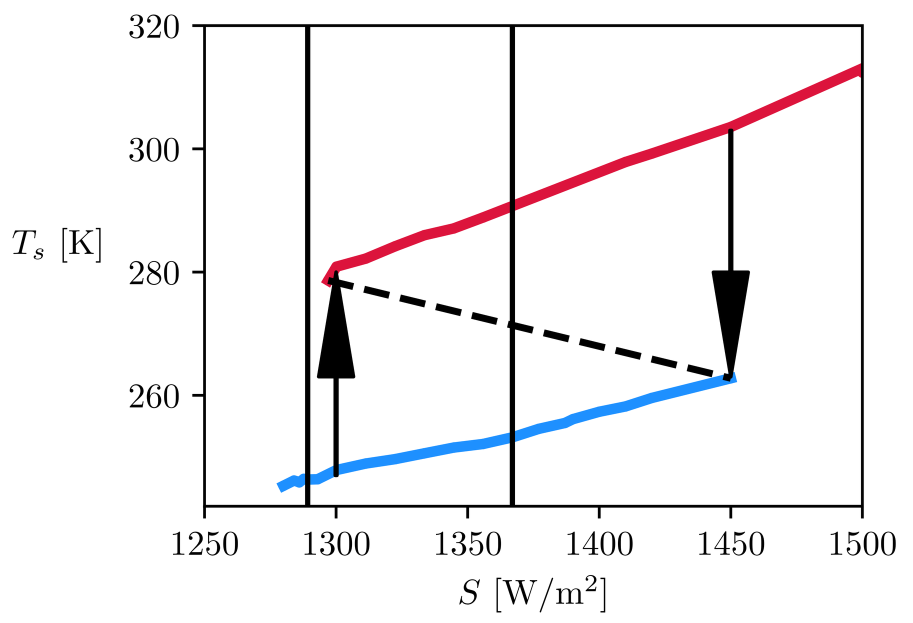
Plasim

The Snowball Earth transition is investigated in an intermediate-complexity climate model, **PlaSim** [1].

- T21 resolution, grid of $5^o \times 5^o$
- Atmosphere is coupled to a mixed layer ocean
- A dynamical system with 10^5 degrees of freedom

Introduction

Our goal is to investigate the transition between the two stable states (**attractors, from a dynamical point of view**), that coexist for a wide range of the solar constant S.



- Two dynamically different stable states exist. These are displayed on the **bifurcation diagram** [2, 3].
- Between the attractors, an unstable **edge state** is embedded in the basin boundary (dashed lines)
- At $S = S_{bif}$, the warm state loses stability
- **Assume a parameter drift scenario** $S(t)$ [see middle panel] for the solar constant

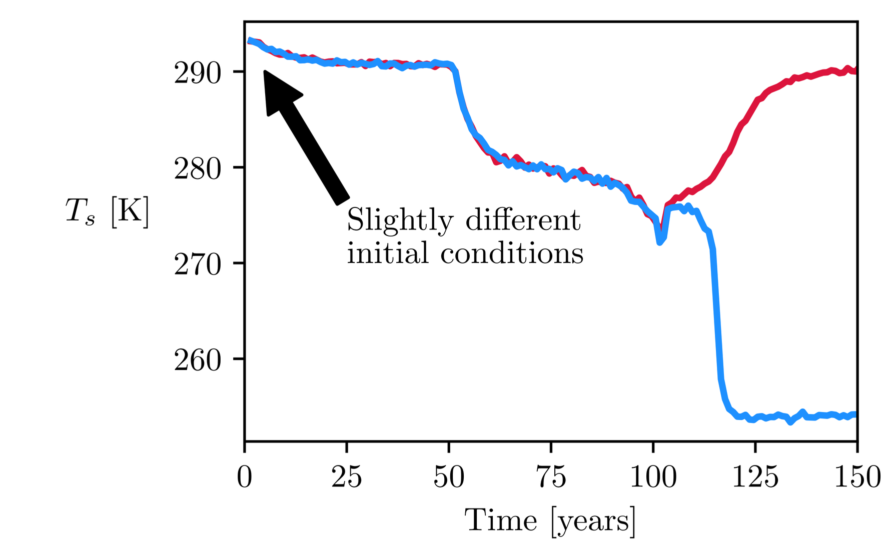
References, Acknowledgements

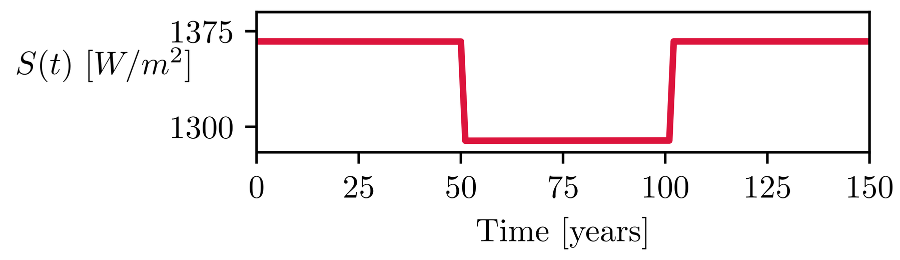
[1] K. Fraedrich et al., Meteorol. Z. **14**:299–304 (2005)
[2] V. Lucarini et al., Q. J. Royal Meteorol. Soc. **136**:2–11 (2010).
[3] A. Tantet et al., Nonlinearity **31**:2221–2251 (2018)
[4] M. Herein et al., Sci. Rep. **7**:44529 (2017).
[5] M. D. Chekroun et al., Physica D **240:** 1685–1700 (2011).

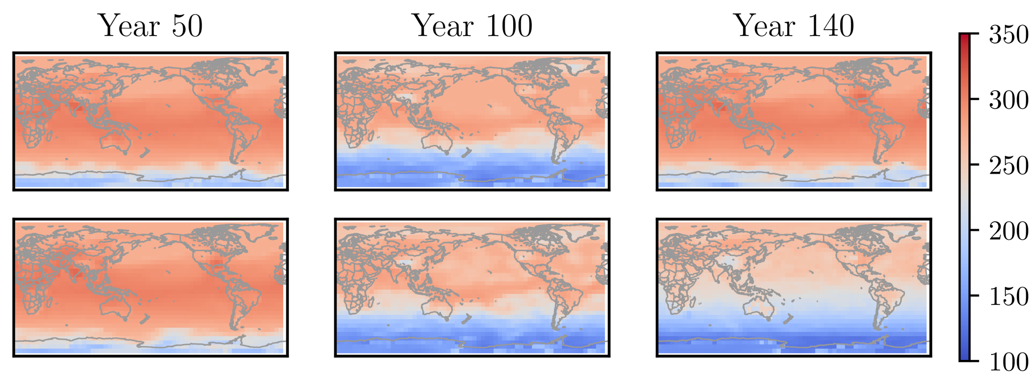
This work was supported by the ÚNKP-18-2 (B. K.) and ÚNKP-18-4 (T. H.) New National Excellence Program of the Ministry of Human Capacities.

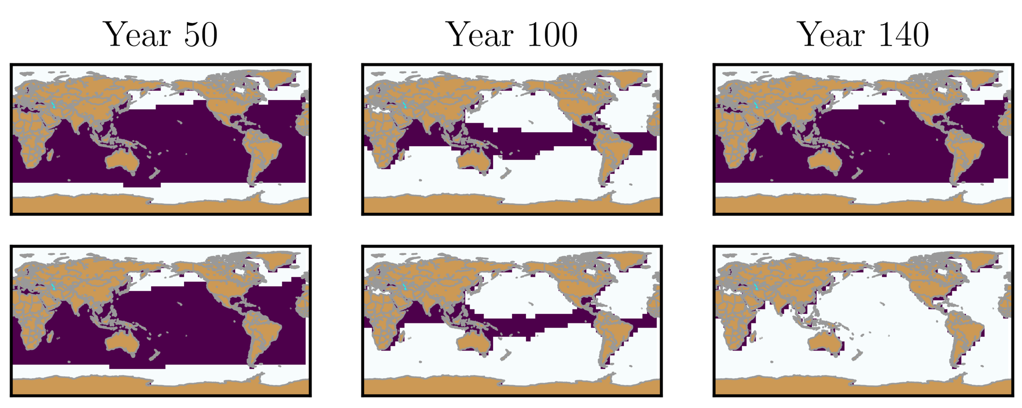
Photography encouraged

Individual simulations





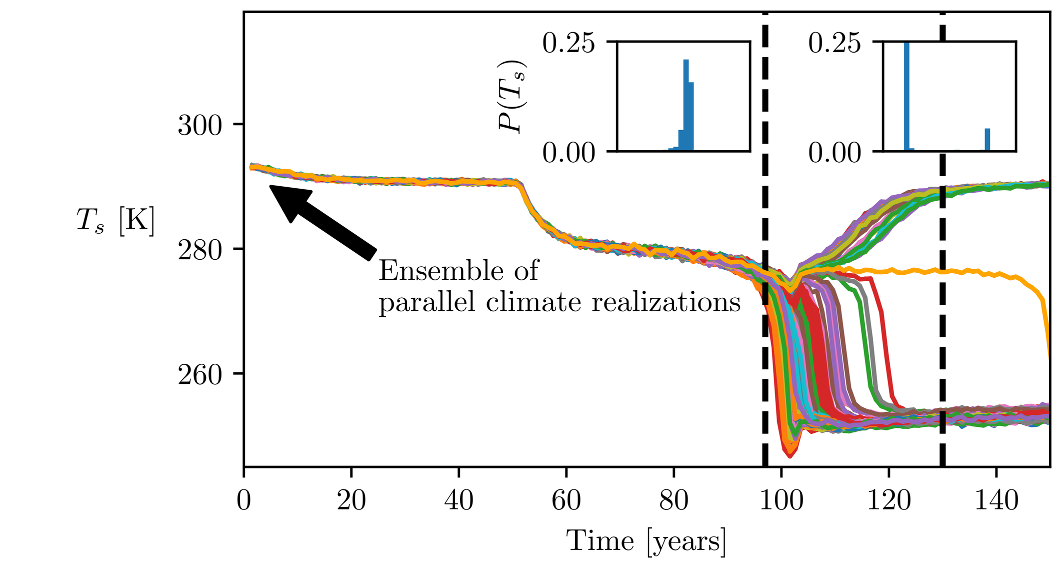


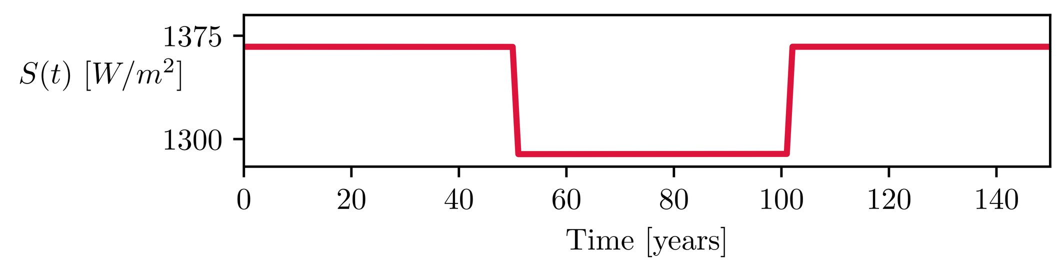


- Small difference in initial conditions ⇒ **completely different outcomes**
- Individual simulations are **not representative** of the transition
- There is no way to determine which attractor the system will end up on

Ensemble of climate realizations

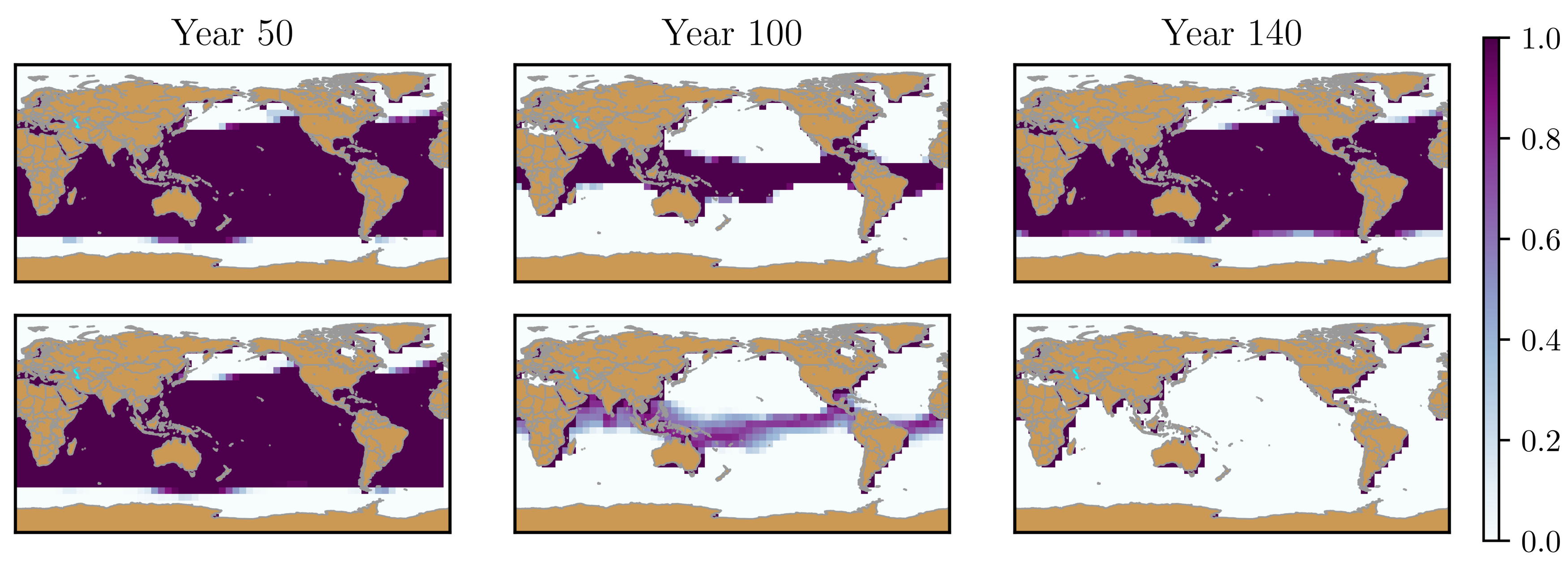
- Instead, follow an **ensemble** of parallel climate realizations [4]
- The 125 ensemble members converge to the **snapshot attractor** (or pullback attractor [5])
- Statistical quantities can be computed: **average, standard deviation**, with respect to its natural measure





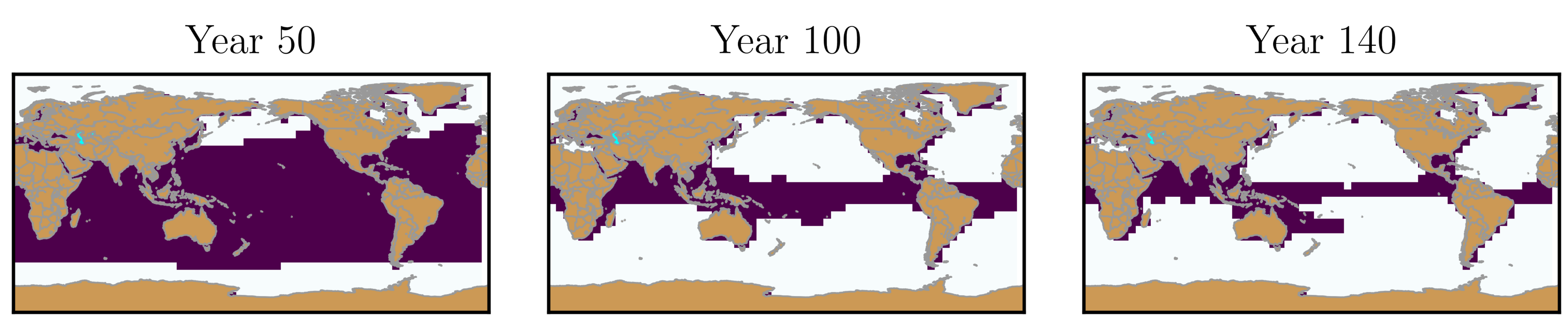
- The transition to Snowball Earth is **probabilistic**, no prediction is possible based on a single simulation
- The **snapshot attractor** splits into two, resulting in two types of typical behavior
- Before the splitting, the **standard deviation** of the ensemble grows: **precursor**
- The **orange curve** runs near the **time dependent** edge state

Typical sea ice cover ending in the two snapshot attractors



- The expected behavior (average) is computed over the two snapshot attractors
- **Local probability of sea ice formation**

Sea ice cover in the edge state



- Narrow band of **unfrozen sea** remaining at the Equator

Summary

- Individual trajectories are not meaningful
- Constructing the snapshot attractor with ensemble methods
- The snapshot attractor splits, which is preceded by increased standard deviation
- All three equilibria (two attractors and the edge state) are found

Additional material on

The project was also supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences (T.H.), and by the National Research, Development and Innovation Office – NKFIH under grants PD-121305 (T.H.), PD-124272 (M.H.), FK-124256 and K-125171 (T.H., M.H.)