Utrecht University

Department of Physics

IMAU

Institute for Marine and Atmospheric research Utrecht

Uncertainty quantification of climate sensitivity: State-dependence, extreme values and the probability of tipping

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TiPES

TIPPING POINTS IN THE EARTH SYSTEM

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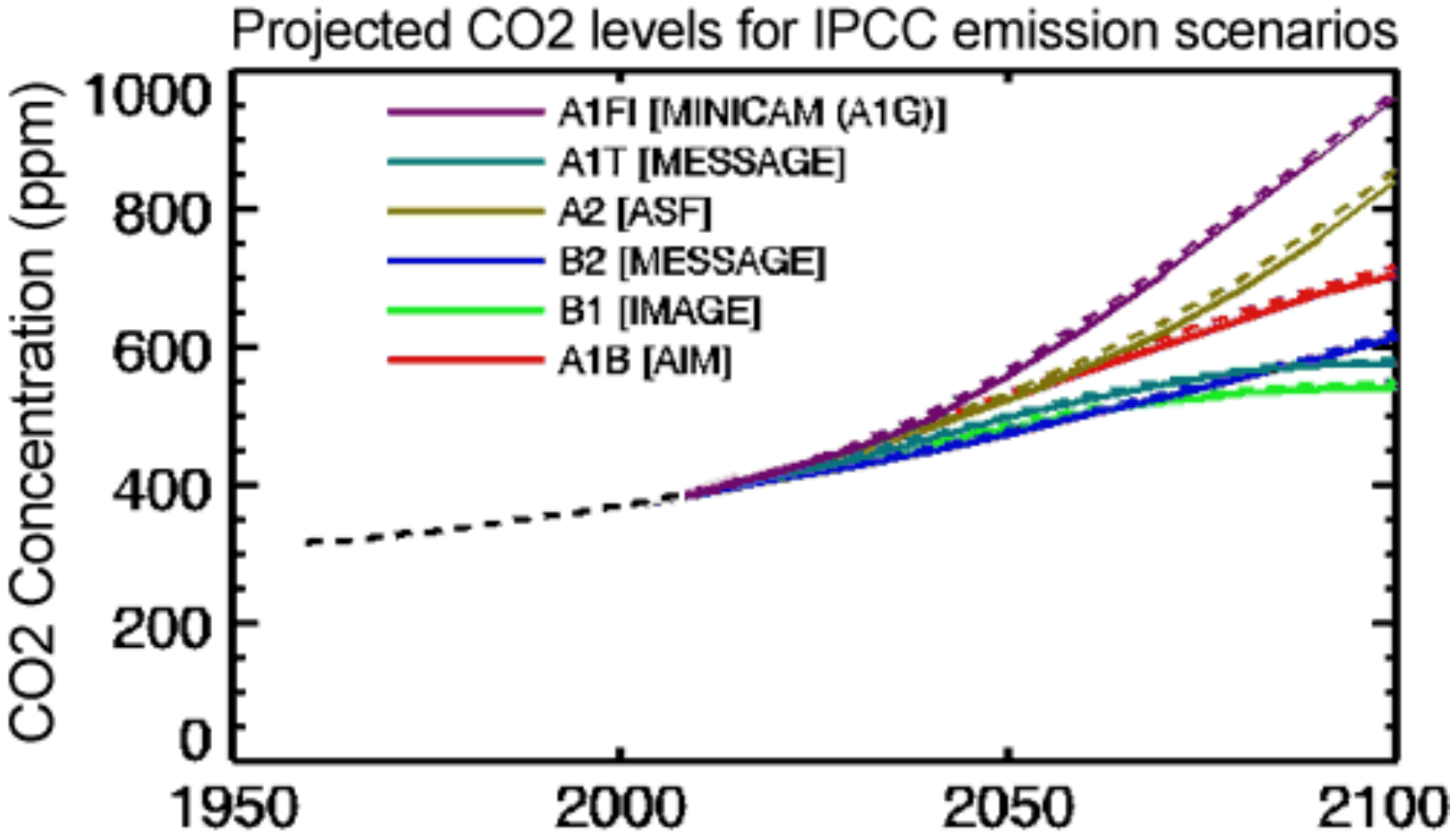
NESSC

NETHERLANDS EARTH SYSTEM SCIENCE CENTRE

Climate forcing…



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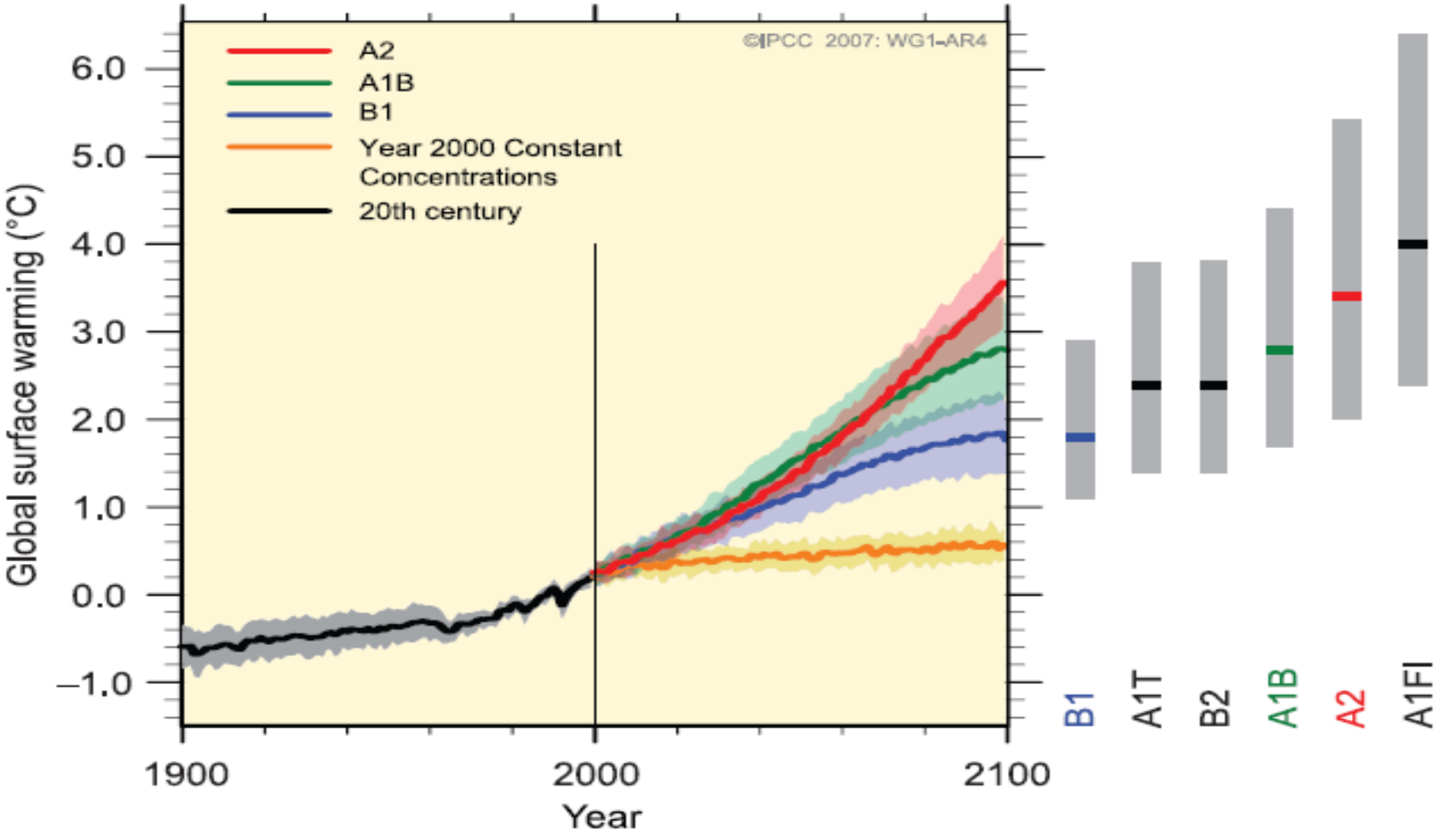
… Models' Response

Shaded area includes results of > 20 climate models (GCMs)



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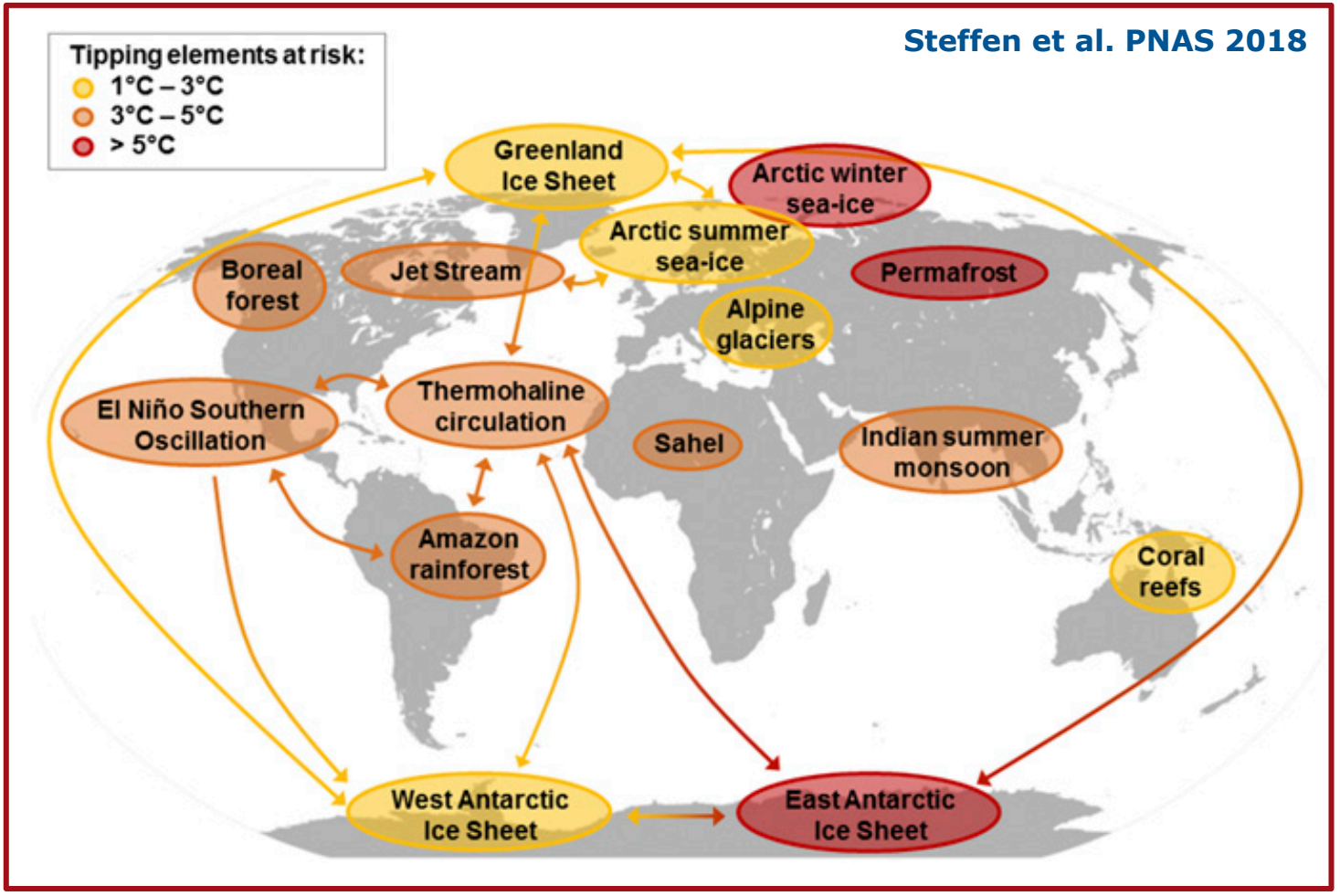
Tipping elements in the climate system



Need a comprehensive framework to quantify the Climate Response!

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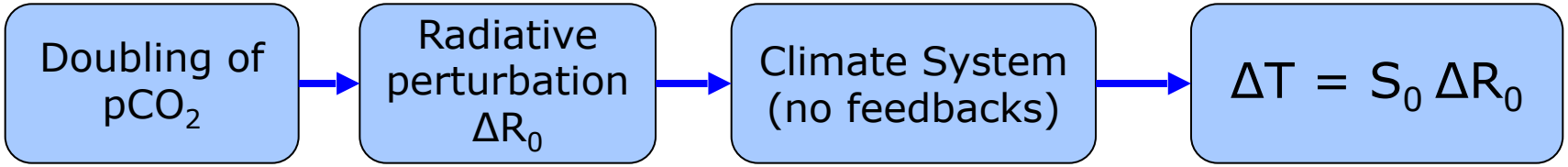
What is climate sensitivity?

- Equilibrium change in global mean surface temperature after a doubling of the atmospheric CO_2 concentration.



- No feedbacks:

  Planck response $S_0 = 0.3$ K/(W/m^2)

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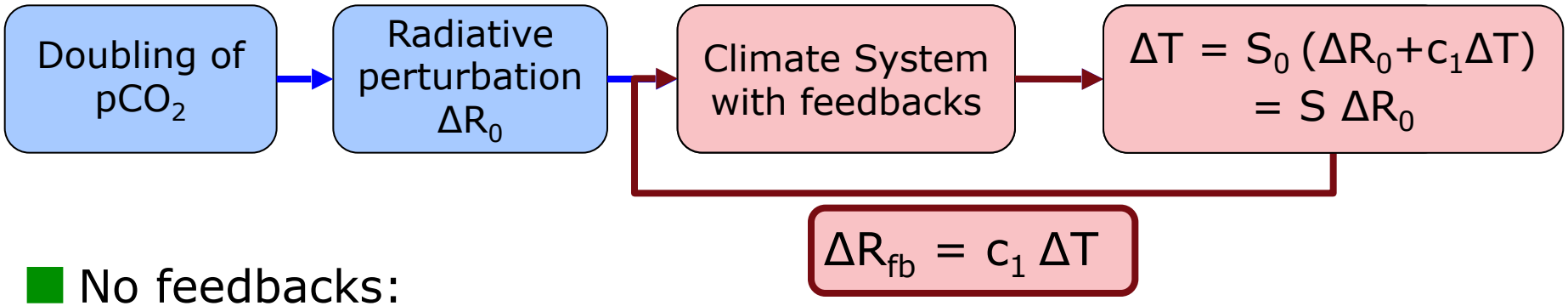
What is climate sensitivity?

- Equilibrium change in global mean surface temperature after a doubling of the atmospheric CO_2 concentration.



- No feedbacks:

  Planck response $S_0 = 0.3$ K/(W/m²)

- With feedbacks:

$$S = \Delta T / \Delta R_0$$

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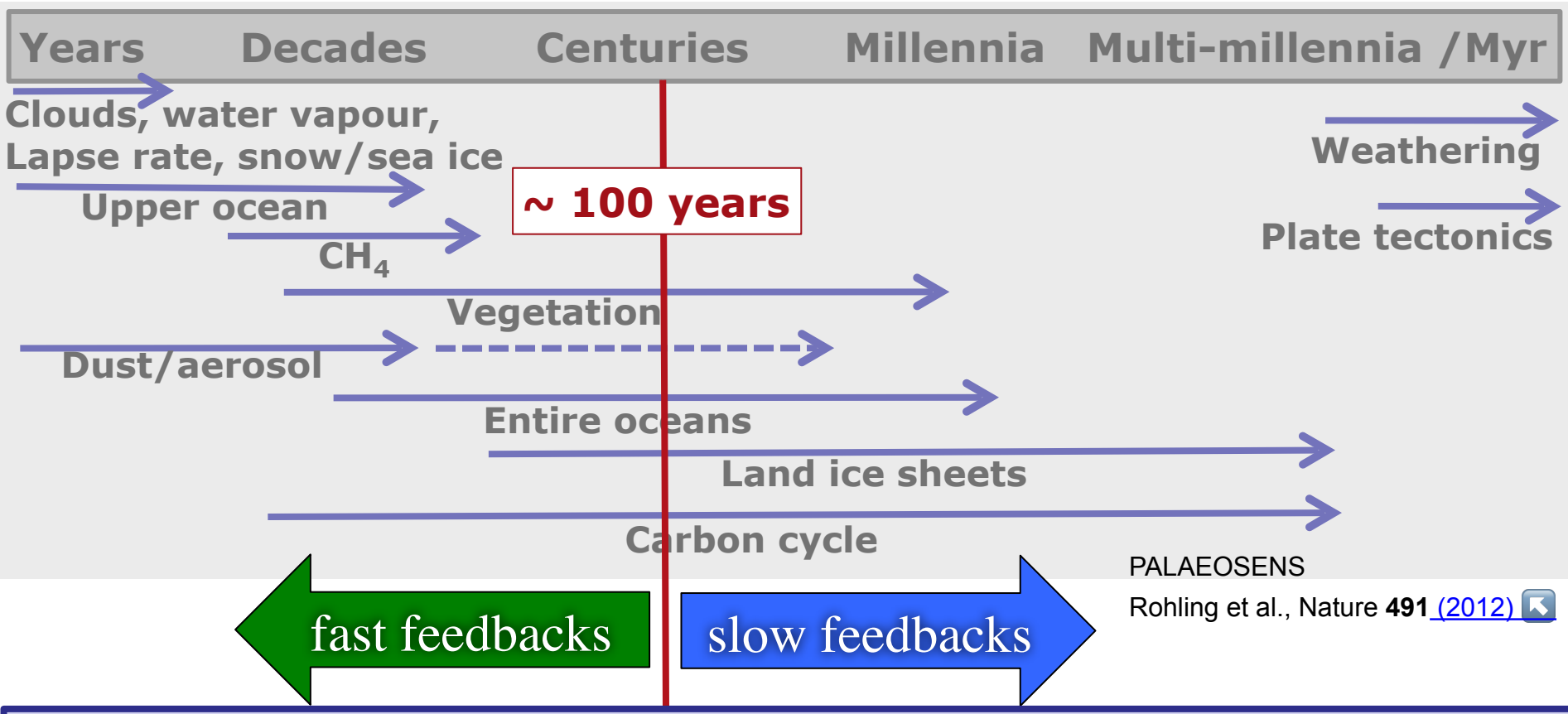
Quantifying climate sensitivity: problems

- Timescales and equilibrium
  - ★ Slow and fast feedback processes.
  - ★ Timescale separation.

- **Dependence on the background climate**
  - ★ **(Fast) feedback processes are not "constant".**

- **Tipping points in the climate system**
  - ★ New 'flavours' of climate sensitivity.
  - ★ Extremes in climate sensitivity vs probability of tipping.

Time scales & equilibrium



PALAEOSENS

Rohling et al., Nature **491** (2012)

Earth system sensitivity

$$S^p = S_{[CO_2]} = \frac{\Delta T}{\Delta R_{[CO_2]}}$$

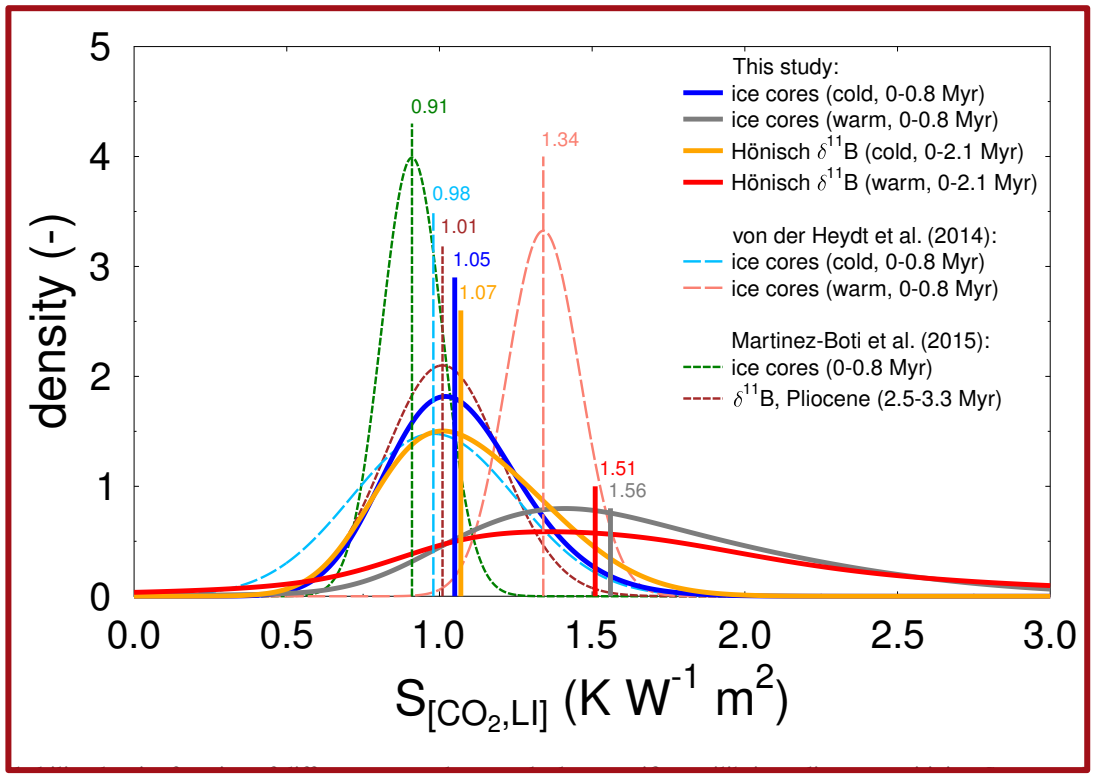
'Correct' for slow feedbacks, e.g.

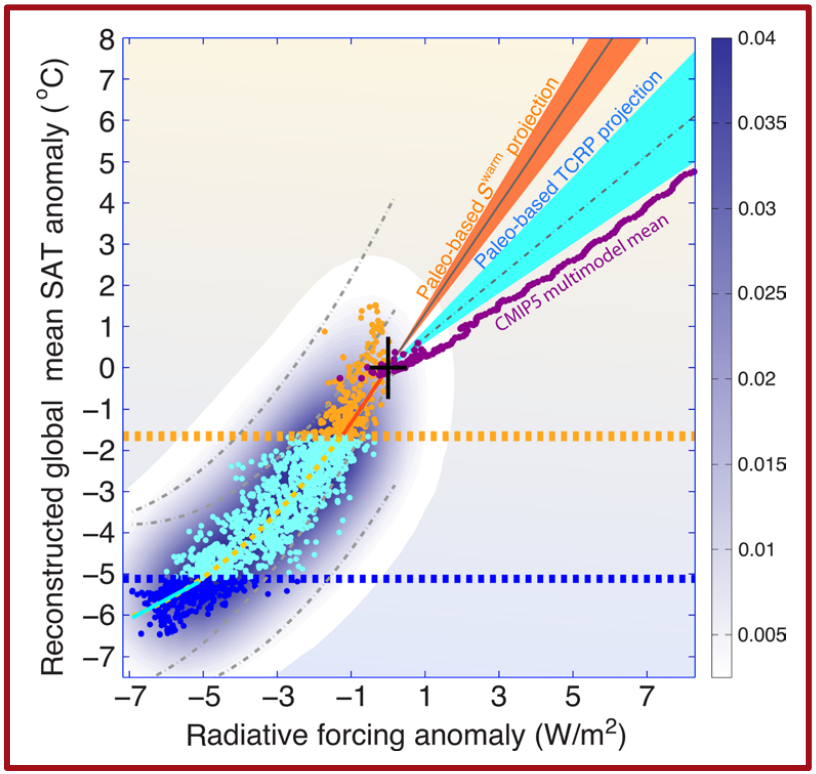
$$S_{[CO_2,LI]} = \frac{\Delta T}{\Delta R_{[CO_2]} + \Delta R_{[LI]}}$$

'Equilibrium' sensitivity S:

$$S_{forcing,slow} = \frac{\Delta T}{\Delta R_{forcing} + \Delta R_{slow}}$$

Last 800 kyr: State dependent feedbacks





Köhler, von der Heydt, et al. Clim. Past (2015)

von der Heydt et al. Curr. Clim. Change Rep. (2016)

Friedrich et al. Sci. Adv. (2016)

Eqilibrium climate sensitivity (ECS) is higher during interglacials than in cold periods.

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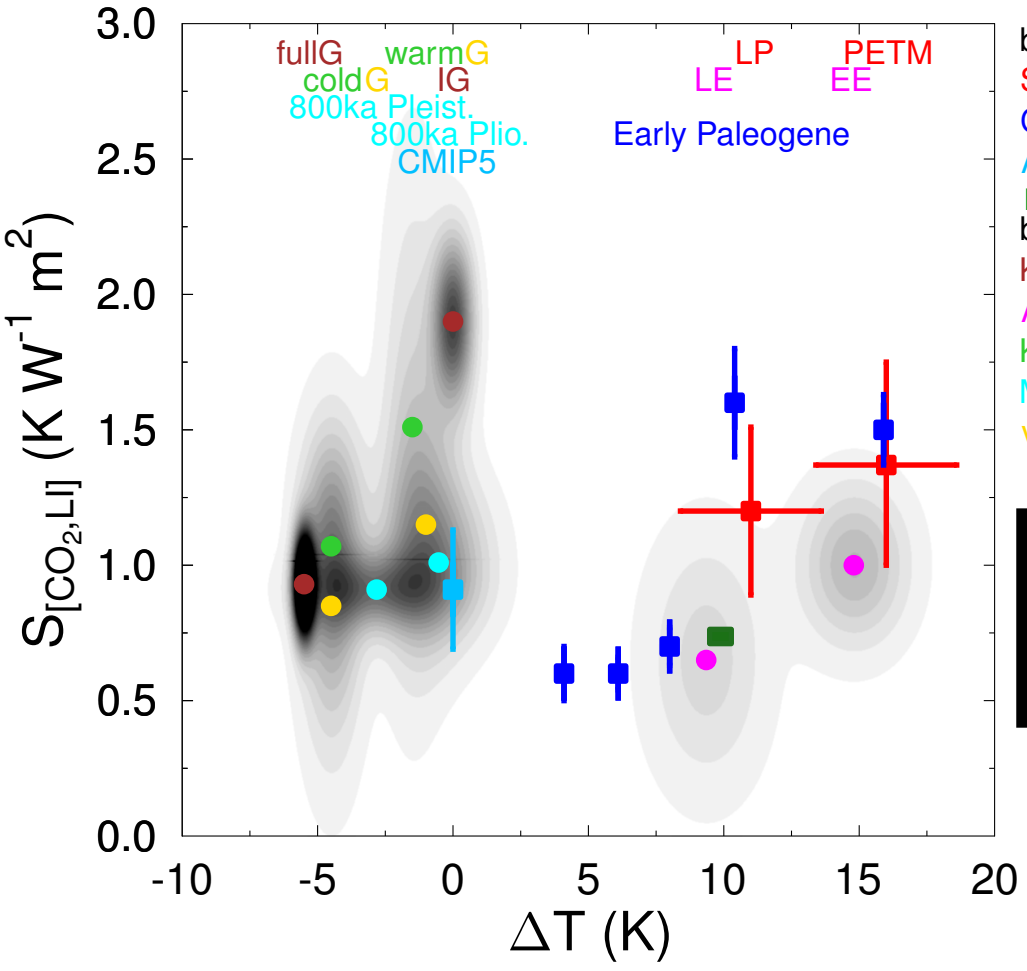
State dependent ECS from palaeoclimate data and models



based on climate models:
Shaffer 2016 (LP / PETM)
Caballero 2013 (Paleogene: 2-32×CO_2)
Andrews 2012 (CMIP5 multi-model mean)
Baatsen 2018 (LE)
based on simpler models and data:
Köhler 2016 (fullG / IG @2.1Ma)
Anagnoustou 2016 (LE / EE)
Köhler 2015 (coldG / warmG @2.1Ma)
Martinez-Boti 2015 (800ka Pleist. / Plio.)
vdHeydt 2014 (coldG / warmG @800ka)

PALAEOSENS 2012 N (all@65Ma)

IPCC 2013 (90%CF range)

von der Heydt et al. Curr. Clim. Change Rep. (2016)

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Distributions of climate sensitivity - origin of uncertainty?

- Uncertainty from observations, model, unaccounted processes
  - ★ Big uncertainties in quantification for radiative forcing.
  - ★ Palaeoclimate: Big uncertainty in climate reconstruction.

- **Climate dynamics:**
  - ★ feedback processes change with background climate!
  - ★ Very high climate sensitivity:
    - nonlinearities in the climate system - evidence for tipping?

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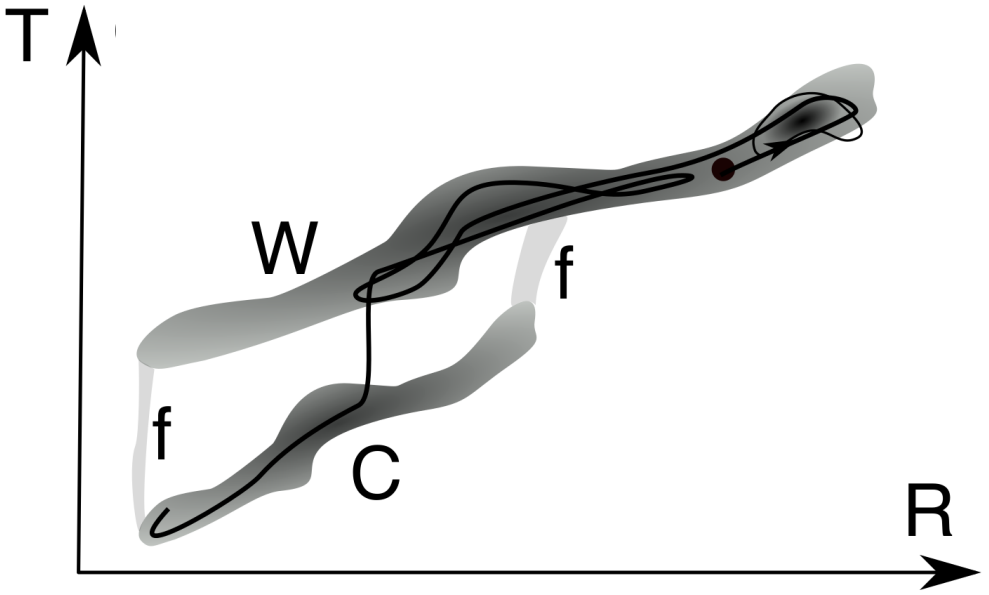
Palaeoclimate sensitivity S: trajectory on a 'climate attractor'

$$c_T \frac{dT}{dt} = R_{\text{forcing}} + R_{\text{slow}} + R_{\text{fast}} - R_{\text{OLW}}$$

$$S_{\text{forcing,slow}} = \frac{\Delta T}{\Delta R_{\text{forcing}} + \Delta R_{\text{slow}}} \approx \frac{dT}{d(R_{\text{forcing}} + R_{\text{slow}})}$$



von der Heydt & Ashwin, Dyn. Stat. Clim. Syst. **1** dzx001 (2016)

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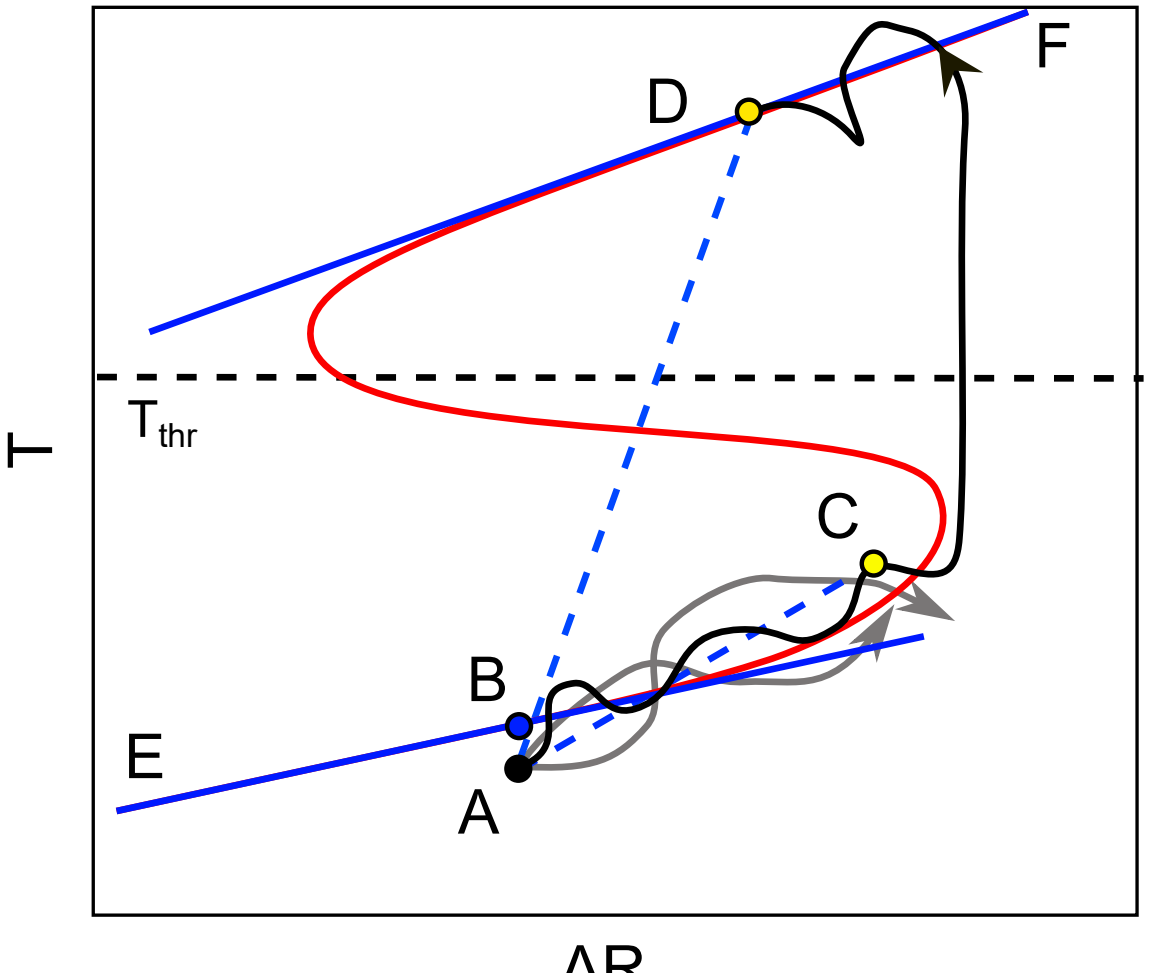
The 'climate attractor'



Ashwin & von der Heydt, J. Stat. Phys. (2019)

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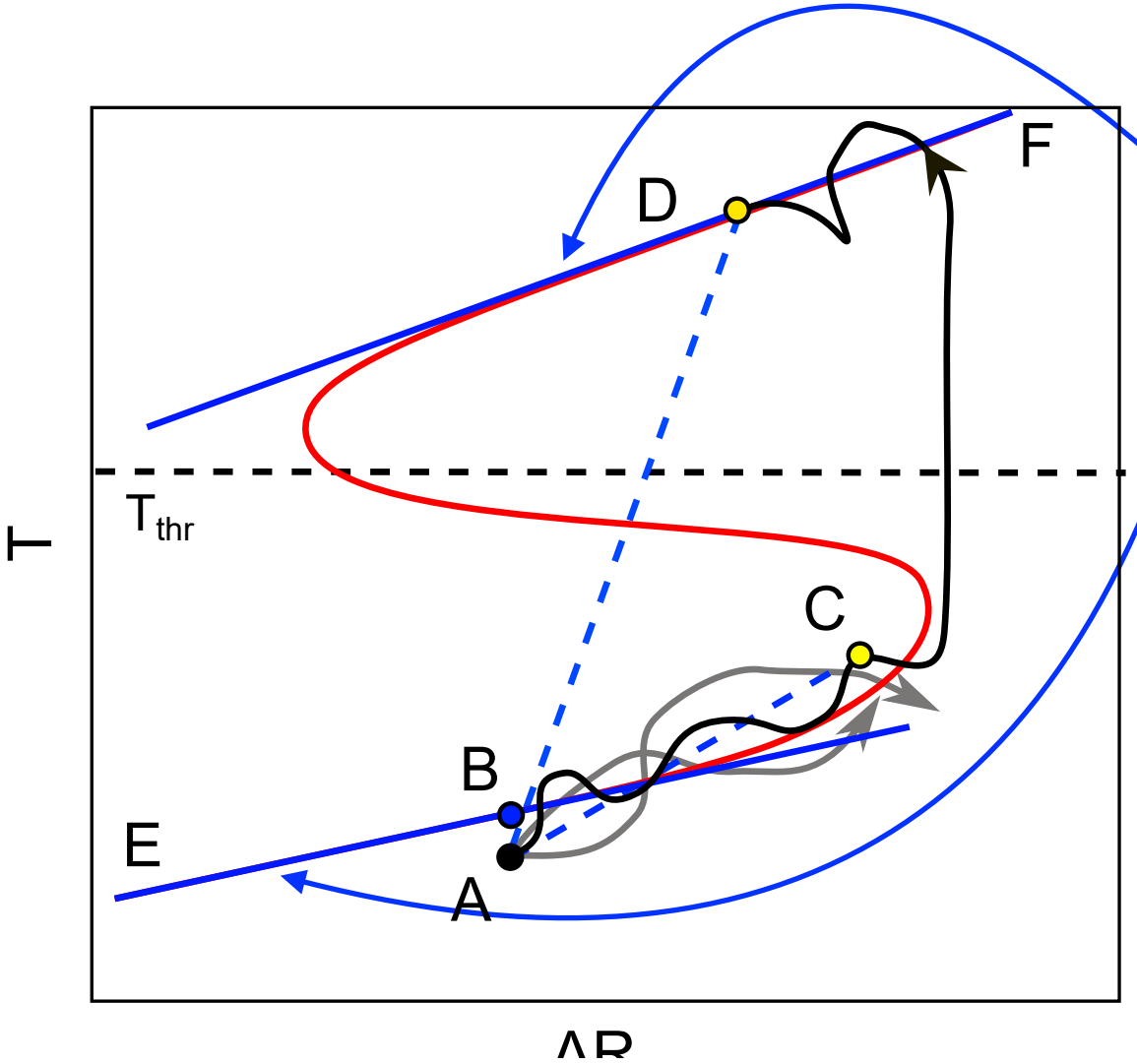

Instantaneous/Local slope sensitivity

$$S = \left[\frac{d}{dT}\Delta R_{[CO_2]}\right]^{-1}$$

Ashwin & von der Heydt, J. Stat. Phys. (2019)

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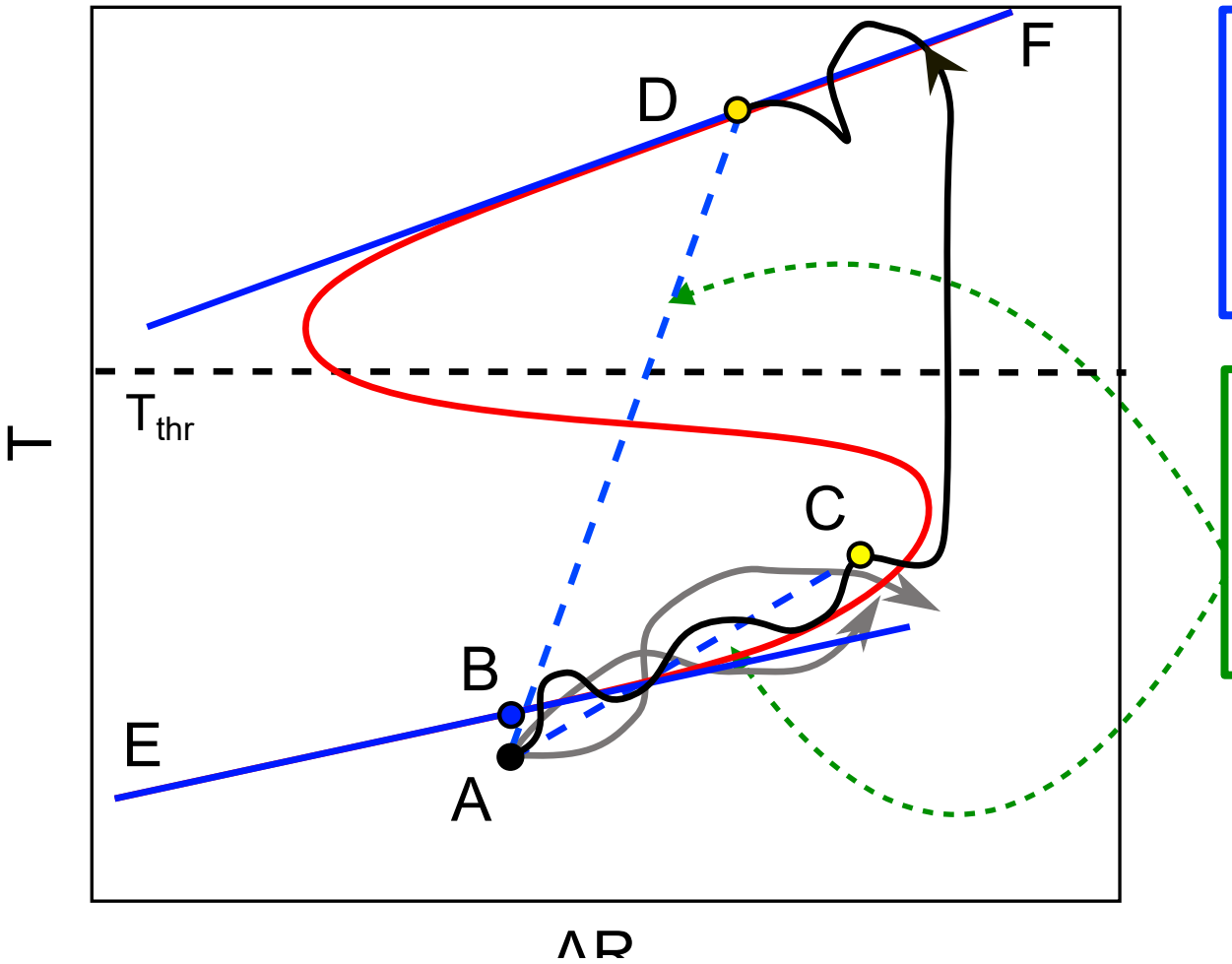

Instantaneous/Local slope sensitivity

$$S = \left[\frac{d}{dT}\Delta R_{[CO_2]}\right]^{-1}$$

Incremental sensitivity (fixed Δt)

$$S_0^{\Delta t}(x) = \frac{T(\varphi_{\Delta t}(x)) - T_0}{R(\varphi_{\Delta t}(x)) - R_0}$$

Ashwin & von der Heydt, J. Stat. Phys. (2019)

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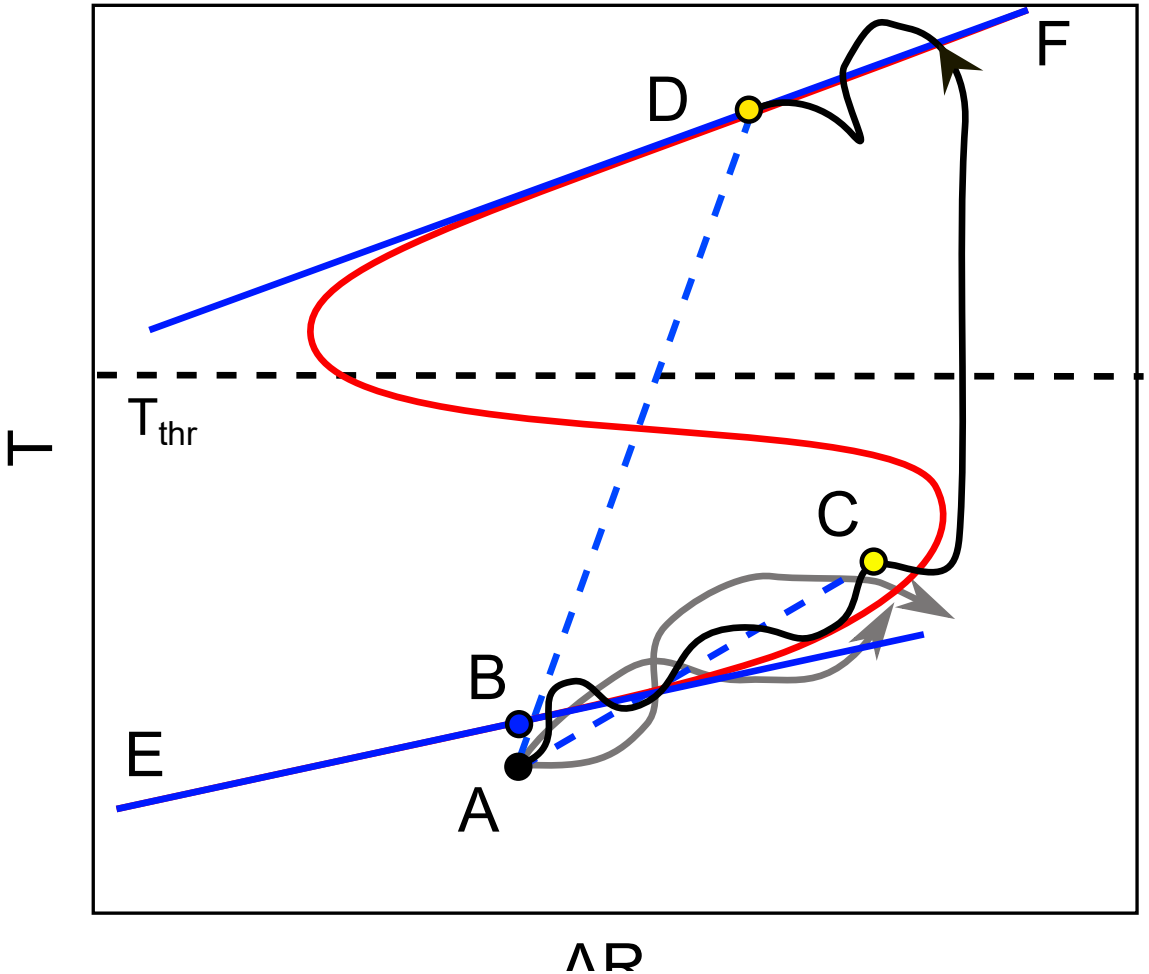
The 'climate attractor'



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Two-point sensitivity (all Δt)

$$S_{0,1}^{\infty} = \frac{T_1 - T_0}{R_1 - R_0}.$$

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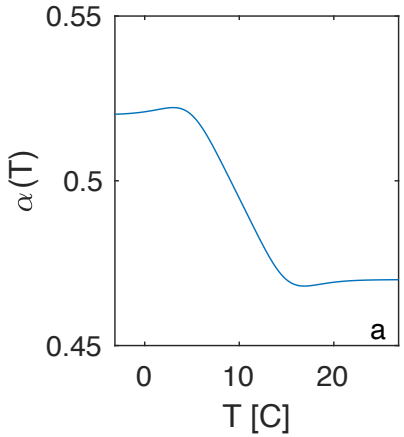
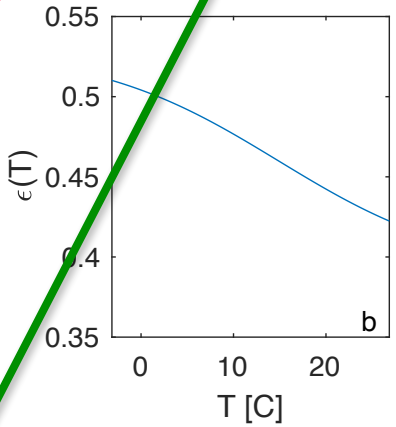
Energy Balance model

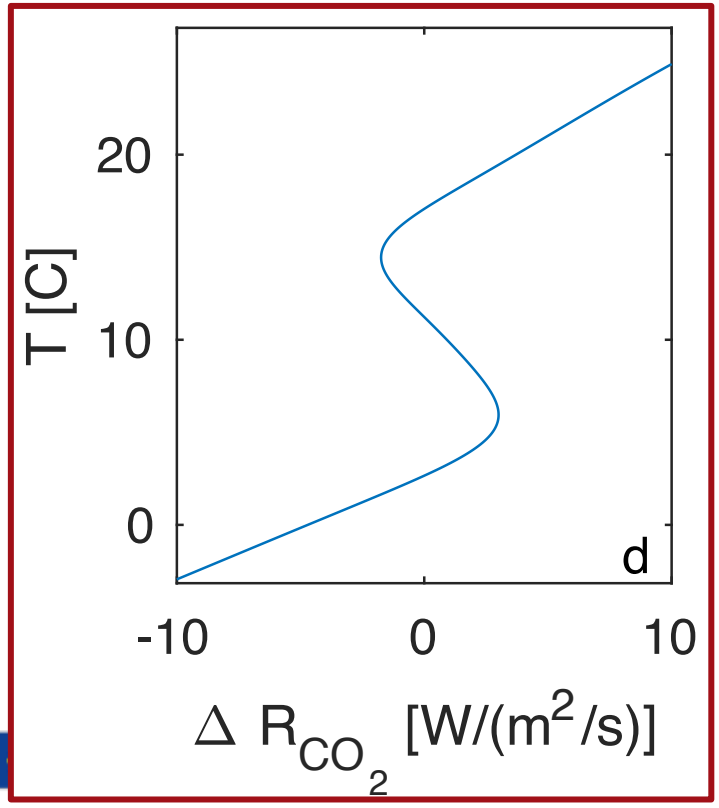
$$C_T dT = \left[Q_0 (1 - \alpha(T)) + A \ln\left(\frac{C}{C_0}\right) - \varepsilon(T) \sigma T^4 \right] dt + \eta_T \omega_T$$

ΔR_{CO_2} (over the $\ln$ term) · noise (over $\eta_T \omega_T$) · albedo (over $\alpha(T)$) · emissivity (over $\varepsilon(T)$)



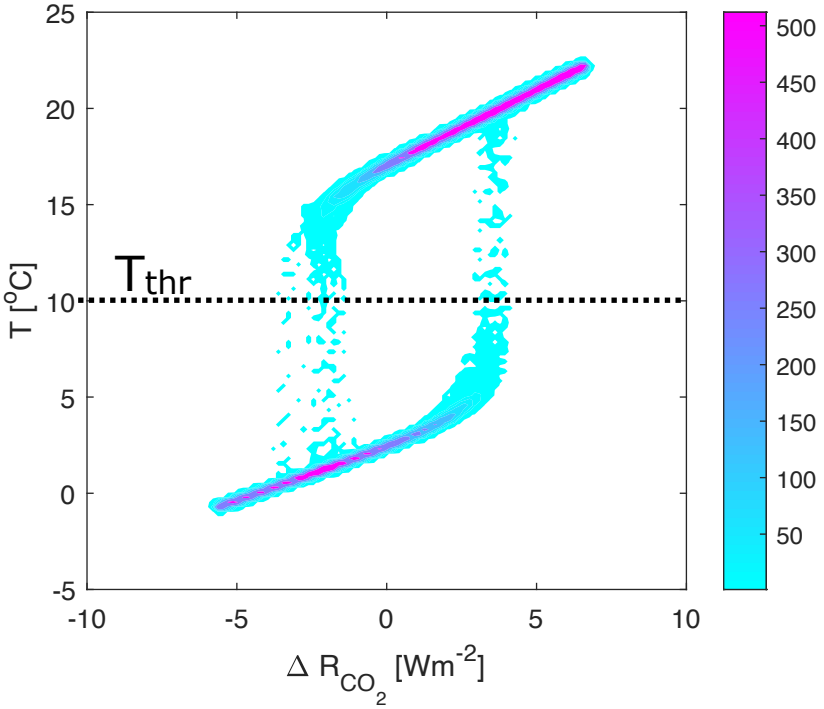


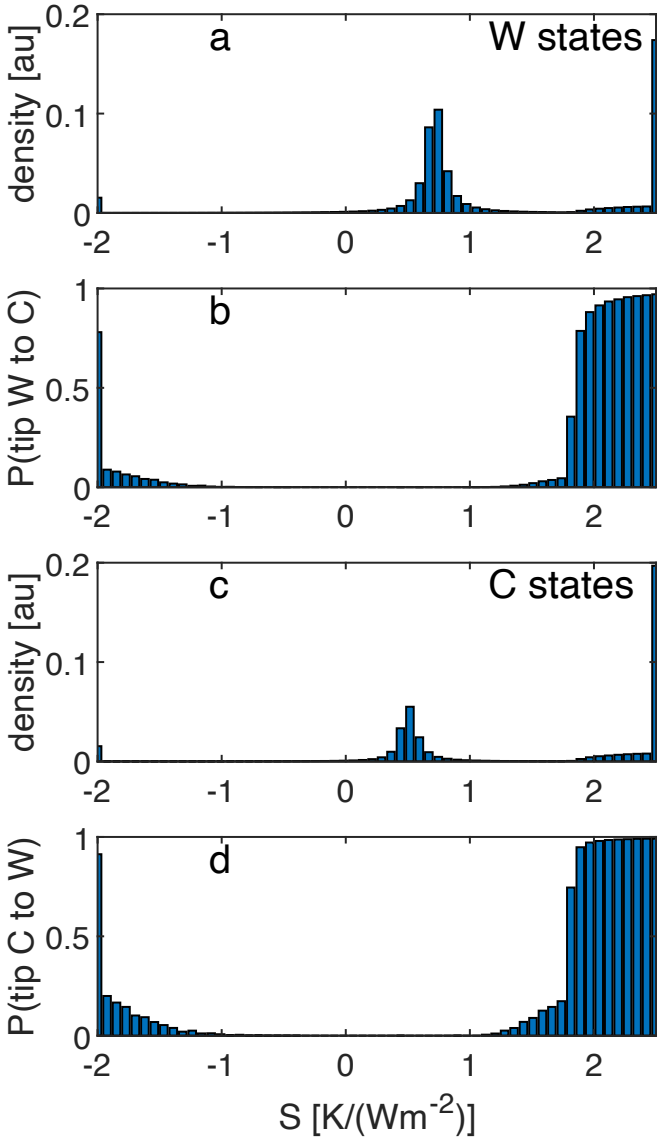
wandering CO_2 = additional noise



Ashwin & von der Heydt, J. Stat. Phys. (2019)

Two-point sensitivity

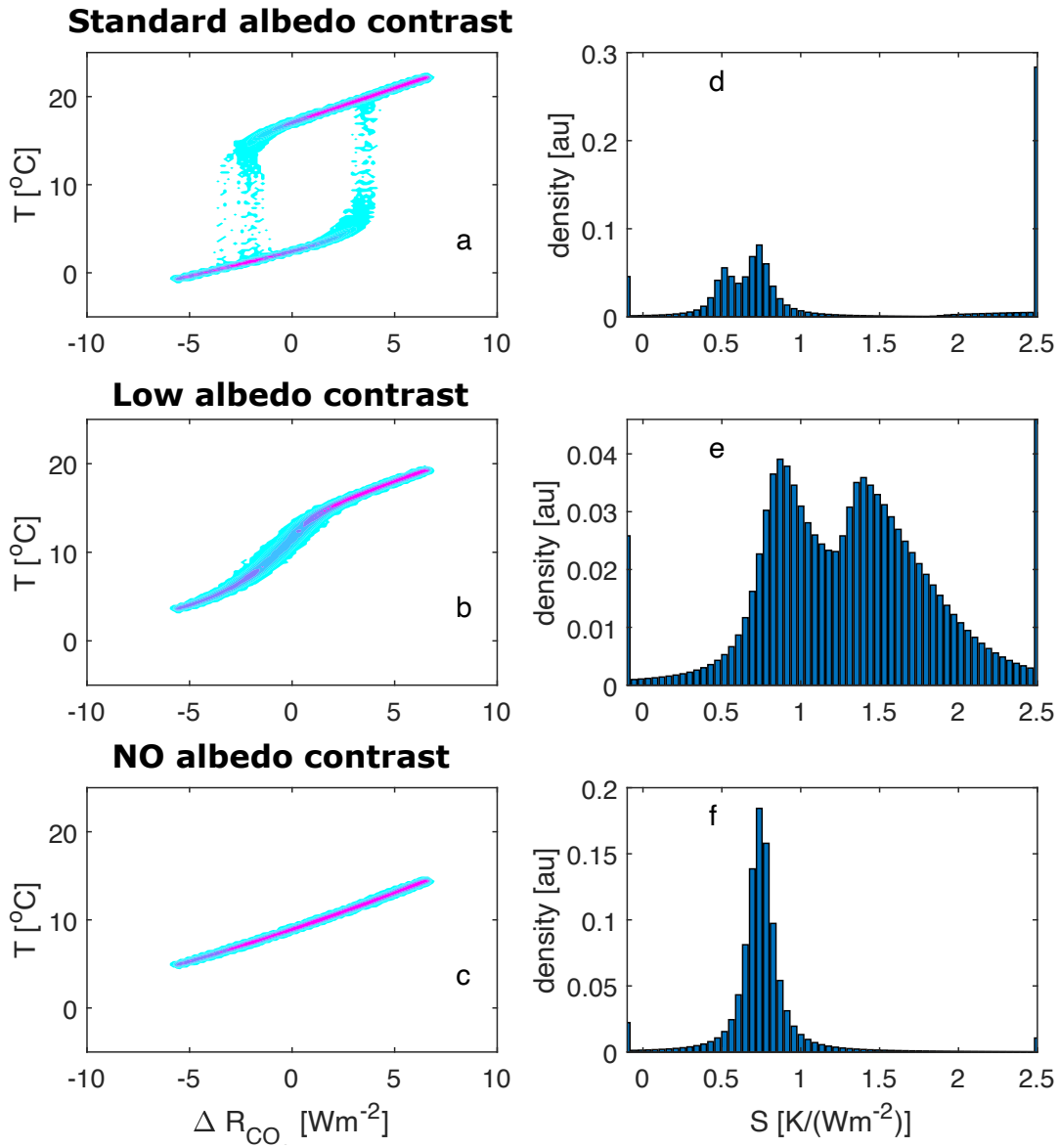




Conditional, incremental sensitivity for all delays up to 20kyr

Ashwin & von der Heydt, J. Stat. Phys. (2019)

Skewed PDFs of two-point sensitivity



Tipping and state-dependence of feedbacks

non-constant feedback factors

Only state-dependence of feedbacks

non-constant feedback factors

No state-dependence of feedbacks

constant feedback factors
~ Gaussian PDF

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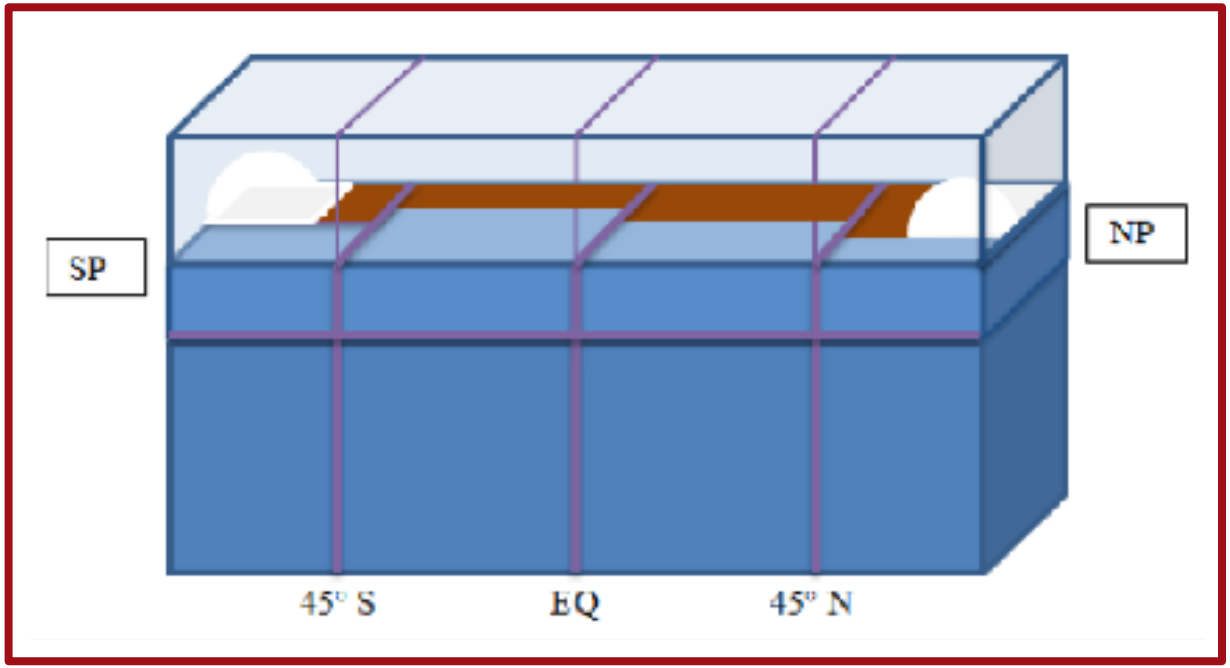
Conceptual climate model

Simple Earth System model: Gildor & Tziperman 2000, 2001, 2002



- ★ Atmosphere,
- ★ Ocean,
- ★ Sea ice,
- ★ Land ice,
- ★ Ocean biogeochemistry & dynamic atmospheric pCO_2,
- ★ Milankovitch forcing: insolation per box & NH land ice ablation.

von der Heydt & Ashwin, Dyn. Stat. Clim. Syst. **1** dzx001 (2016)

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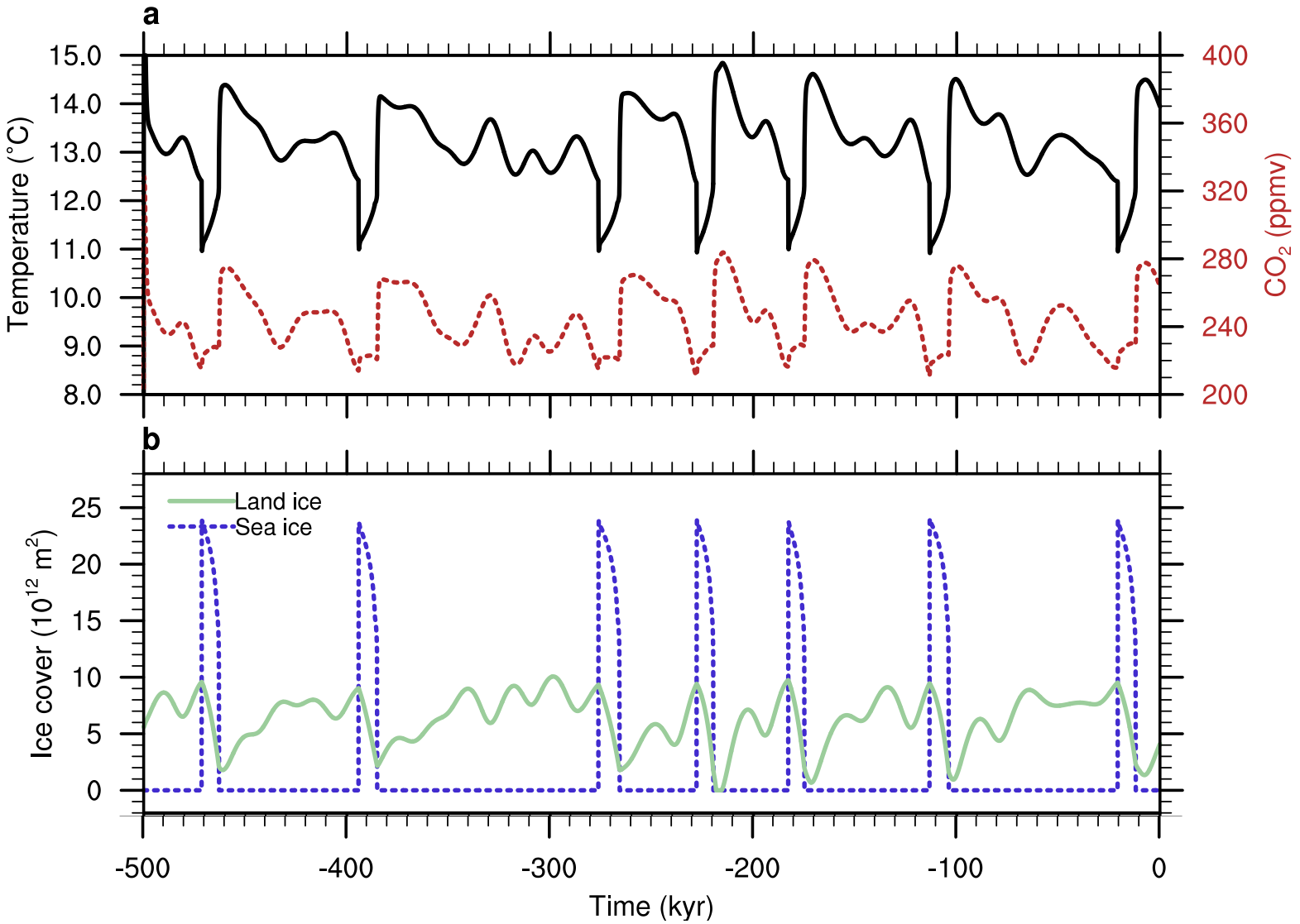
Model glacial-interglacial cycles



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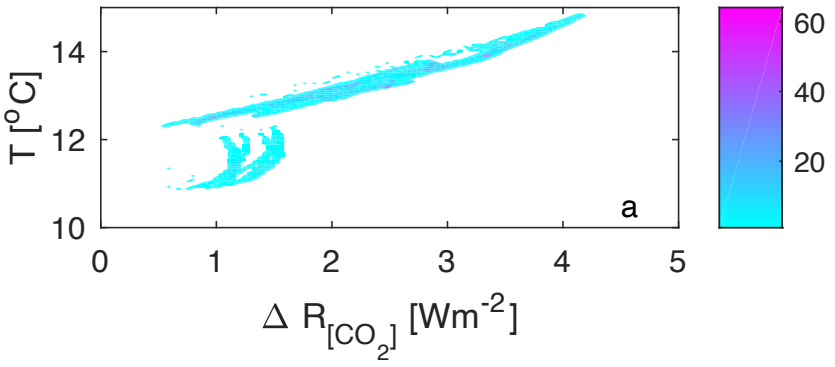
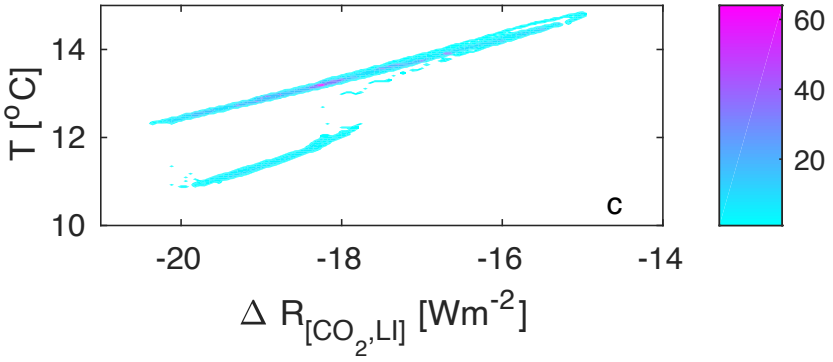
State dependent CS glacial cycles (conceptual climate model)



Earth System Sensitivity

'forcing' = only CO_2



Equilibrium Climate Sensitivity

'forcing' = CO_2 + Land Ice

ESS corrected for slow feedbacks

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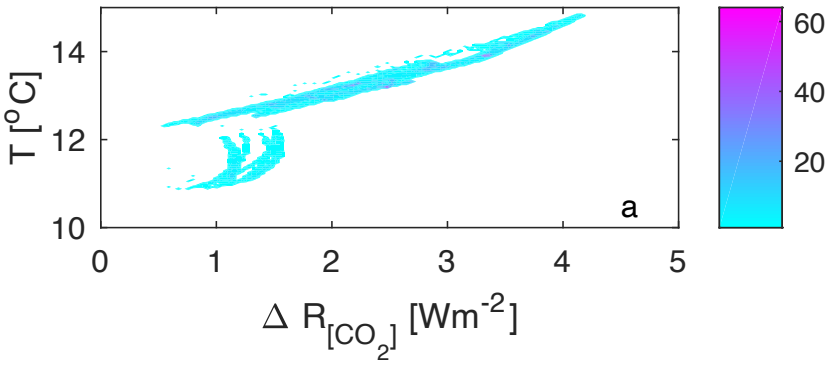

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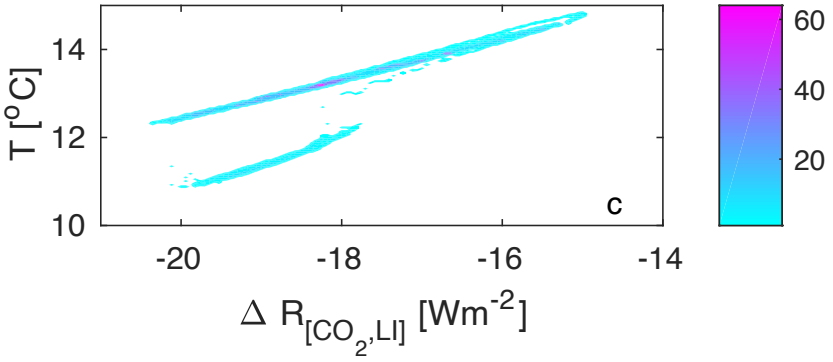

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Ashwin & von der Heydt, J. Stat. Phys. (2019)

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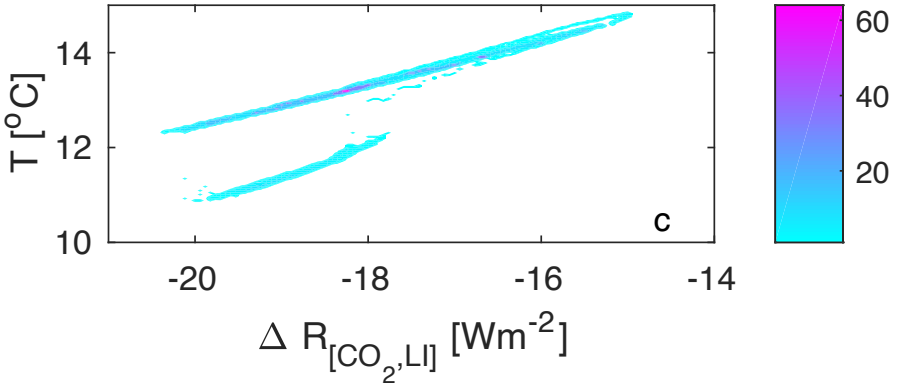
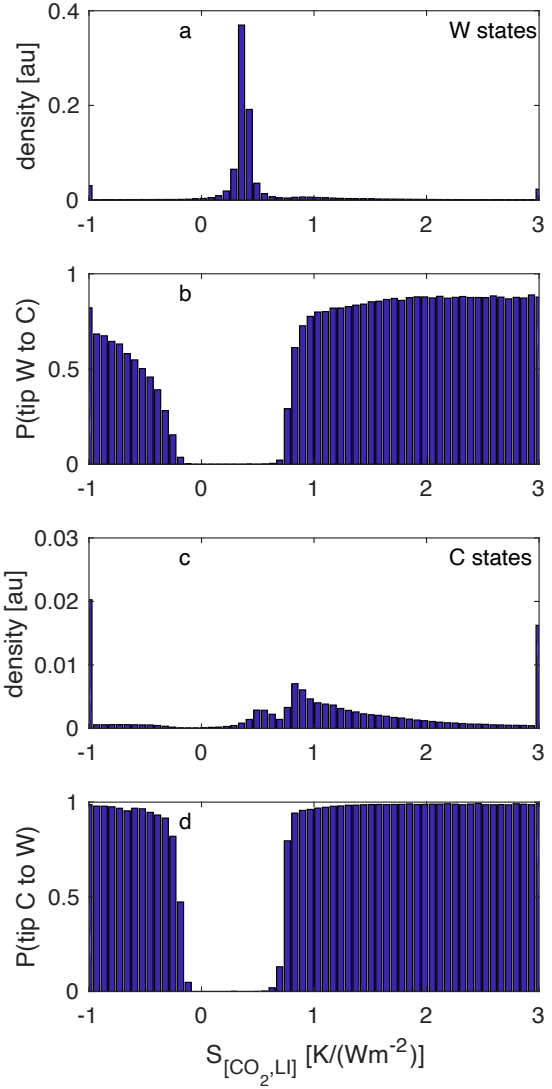
Two-point sensitivity & probability of tipping (conceptual climate model)





As in energy balance model:

High values of $S_{[CO2,LI]}$ correspond to high probability of regime (cold/ warm) transition

Ashwin & von der Heydt, J. Stat. Phys. (2019)

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Conclusions

- Climate sensitivity depends on the background climate state:
  - ★ non-constant fast feedback processes,
  - ★ multiple equilibrium or oscillatory states ('tipping').
- 'Flavours' of (palaeo)climate sensitivity on the 'climate attractor:
  - ★ instantaneous S: available from underlying model ('nearest equilibrium'),
  - ★ incremental S: fixed delay Δt,
  - ★ two-point S: all delays, two points on attractor.
- Nonlinearities lead to skewed PDFs of measured climate sensitivity
  - ★ Extremes of climate sensitivity seem to relate to high probability of tipping.