Extreme sensitivity and climate tipping points

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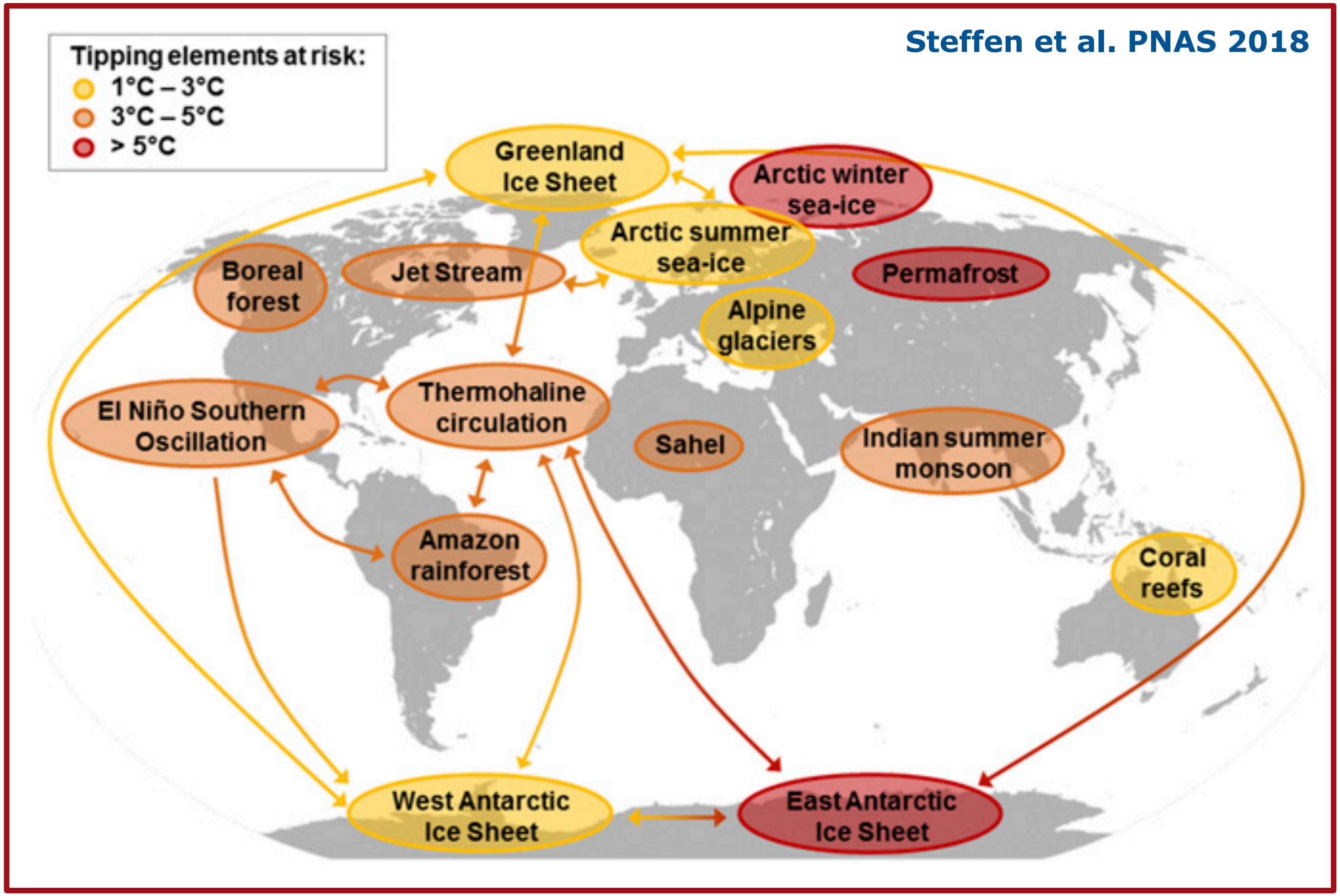
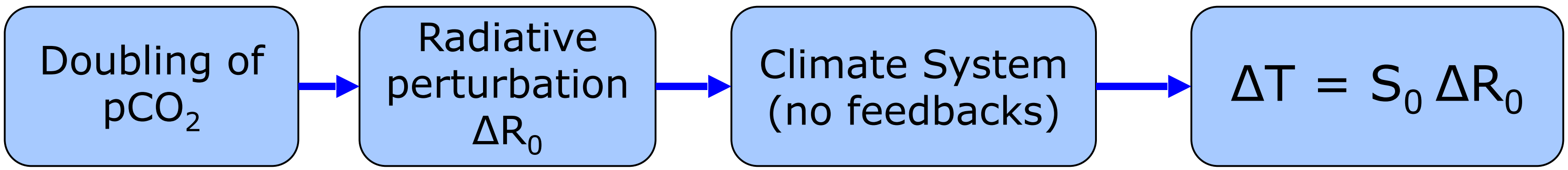
Tipping elements in the climate system



Need a comprehensive framework to quantify the Climate Response!

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)

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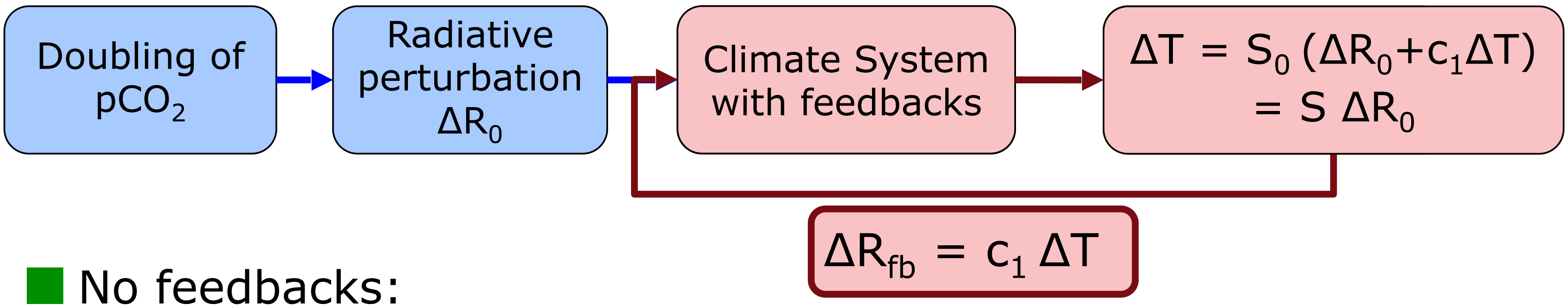

- No feedbacks:

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

- With feedbacks:

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

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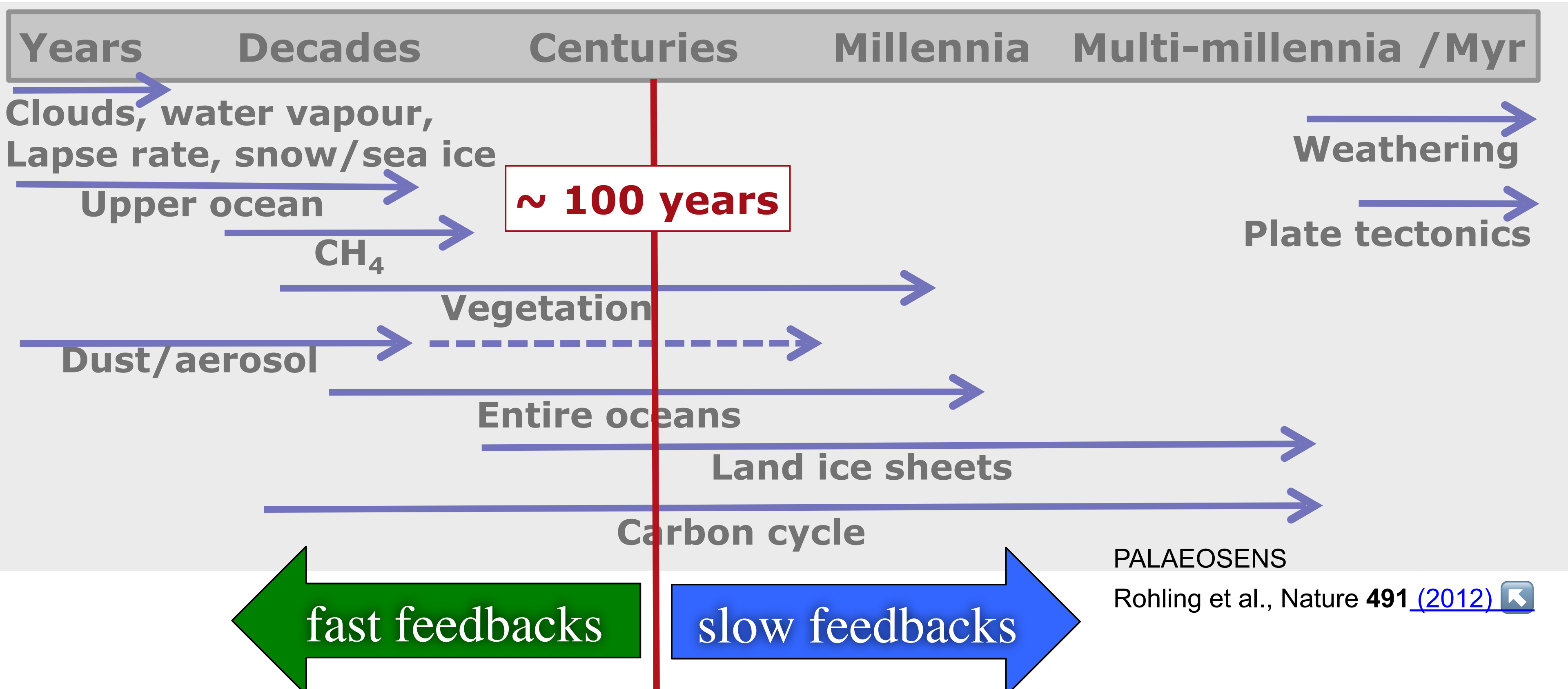
Quantifying climate sensitivity: problems

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

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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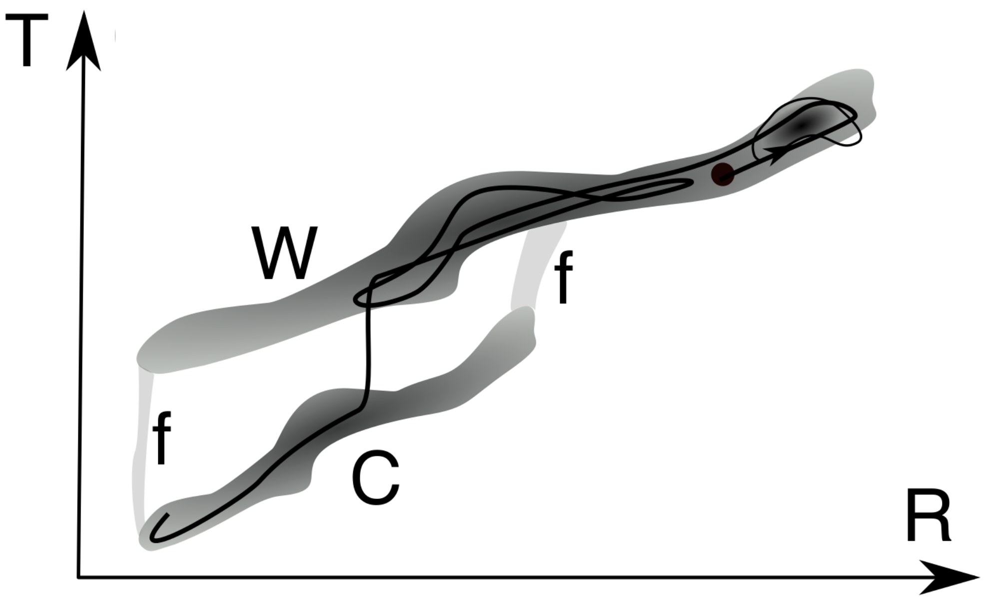
Palaeoclimate sensitivity S: trajectory on a 'climate attractor'

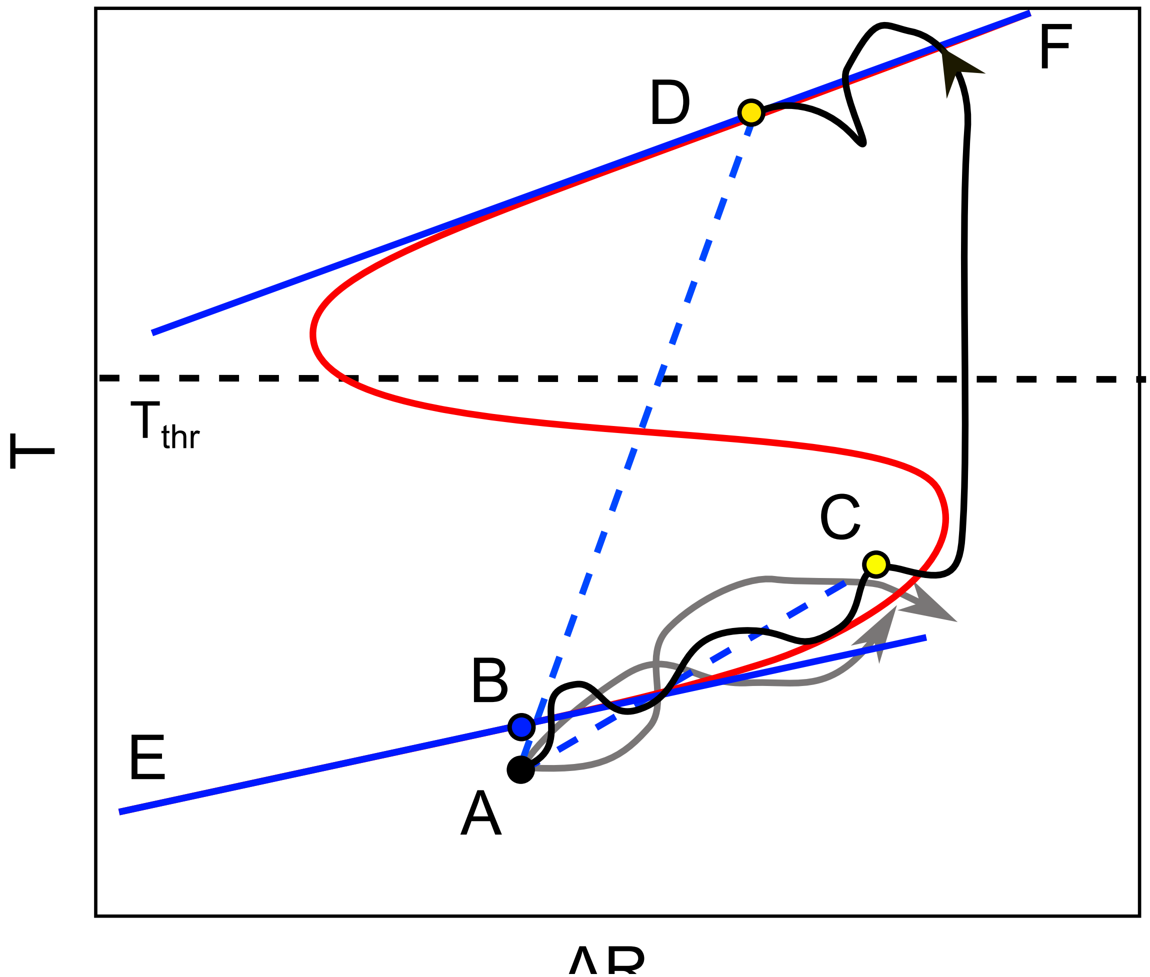
$$c_T \frac{dT}{dt} = R_{\text{forcing}} + R_{\text{slow}} + R_{\text{fast}} - R_{\text{OLW}}$$

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



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

The 'climate attractor'



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

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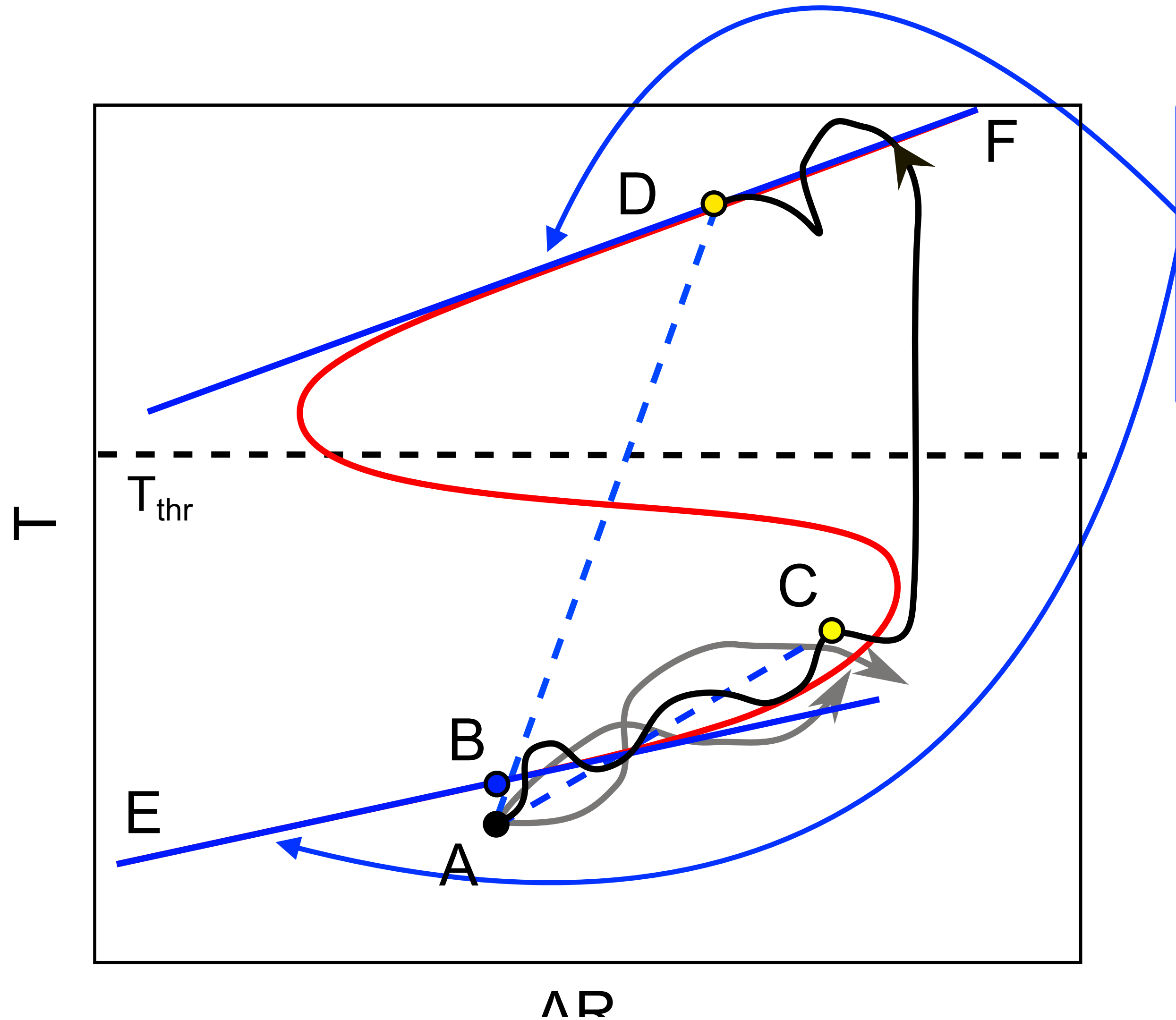
The 'climate attractor'



Instantaneous/Local slope sensitivity

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

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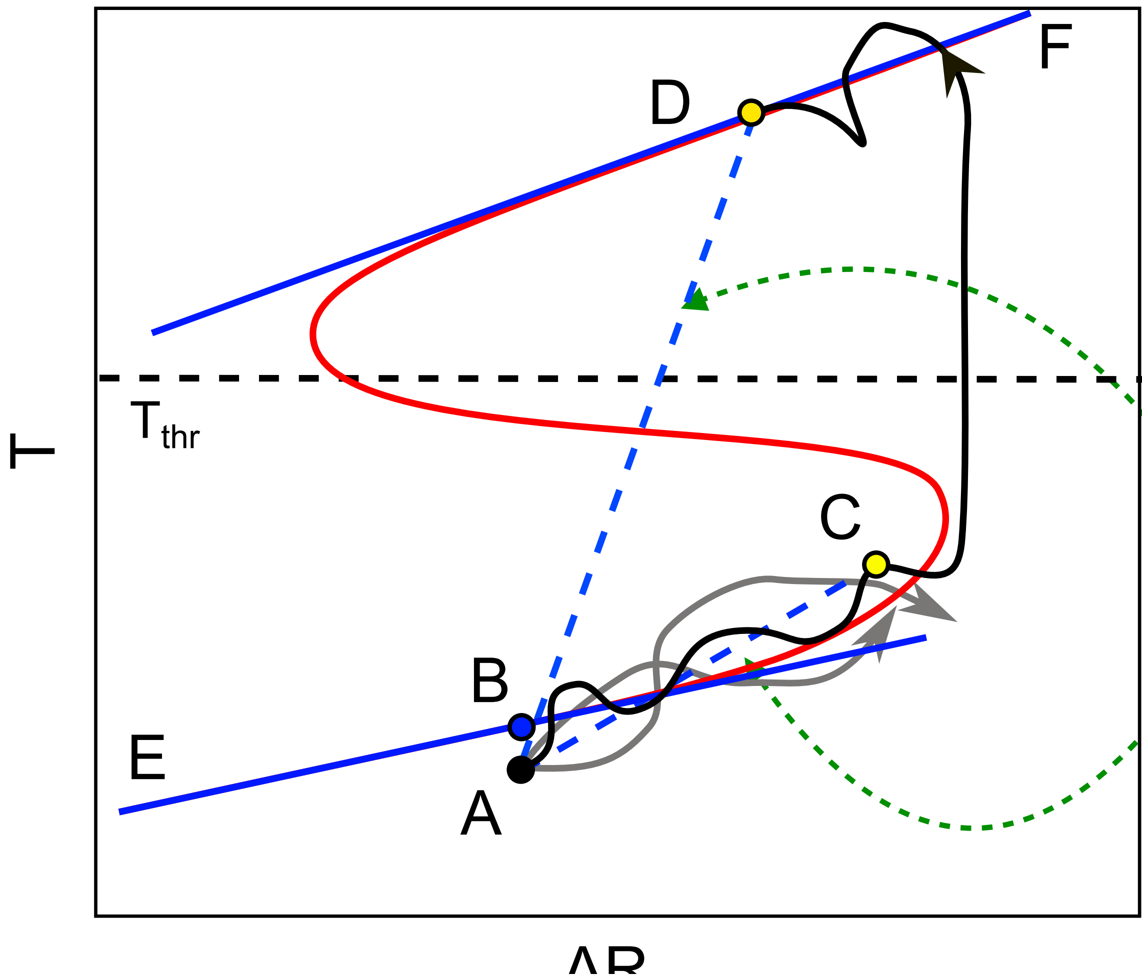

Instantaneous/Local slope sensitivity

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

Incremental sensitivity (fixed Δt)

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

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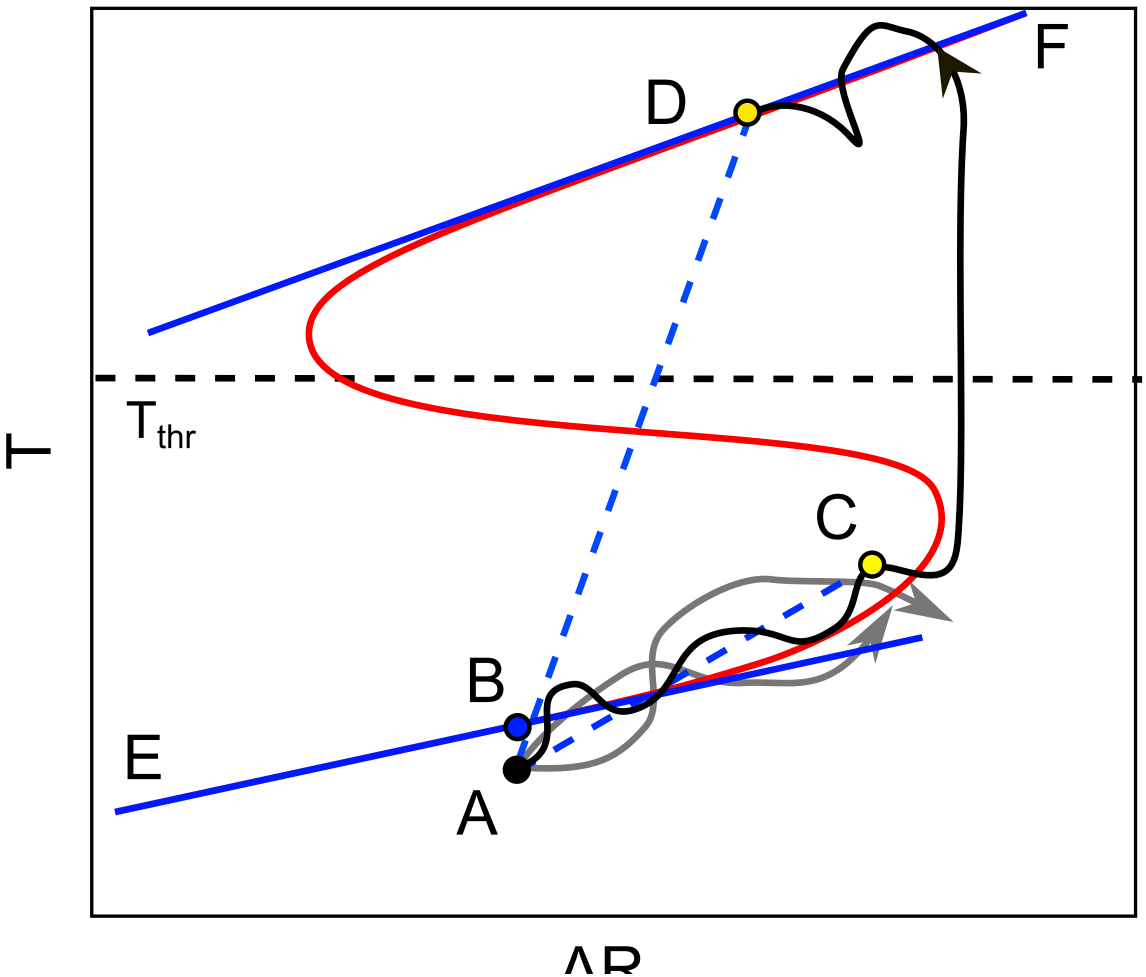
The ‘climate attractor’



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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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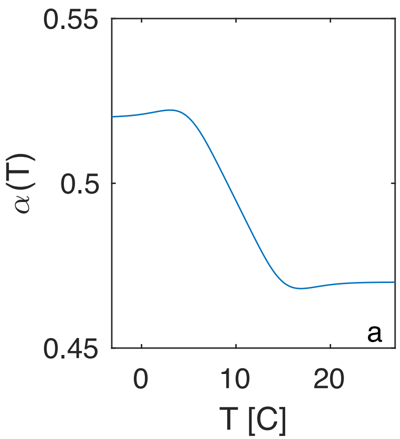
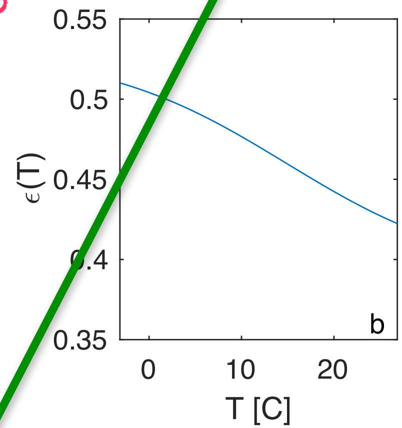
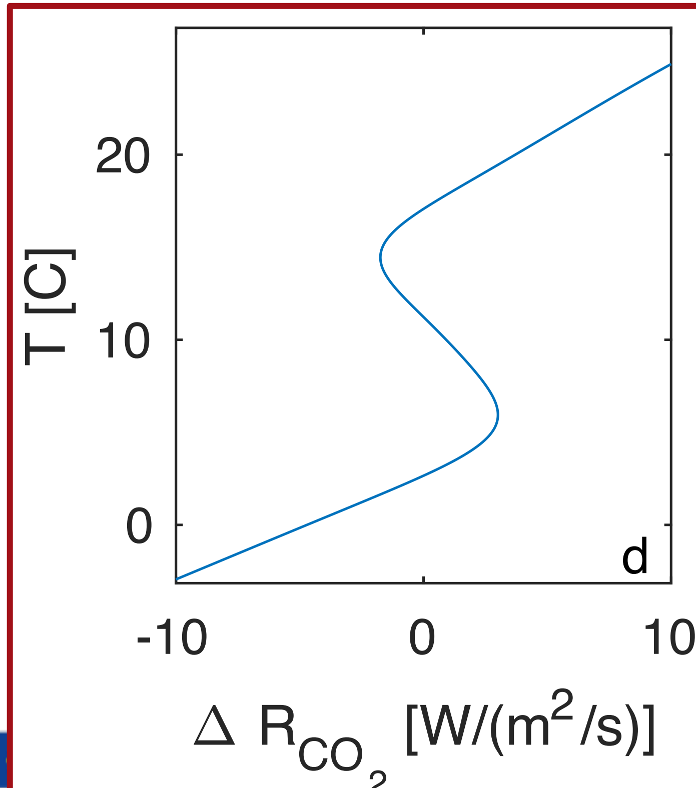
Energy Balance model

$$C_T\, dT = \Big[Q_0\big(1-\alpha(T)\big) + \underbrace{A \ln\left(\frac{C}{C_0}\right)}_{\Delta R_{CO_2}} - \varepsilon(T)\,\sigma T^4\Big]\,dt + \underbrace{\eta_T\, \omega_T}_{\text{noise}}$$

albedo: $\alpha(T)$ — emissivity: $\varepsilon(T)$







wandering CO_2 = additional noise

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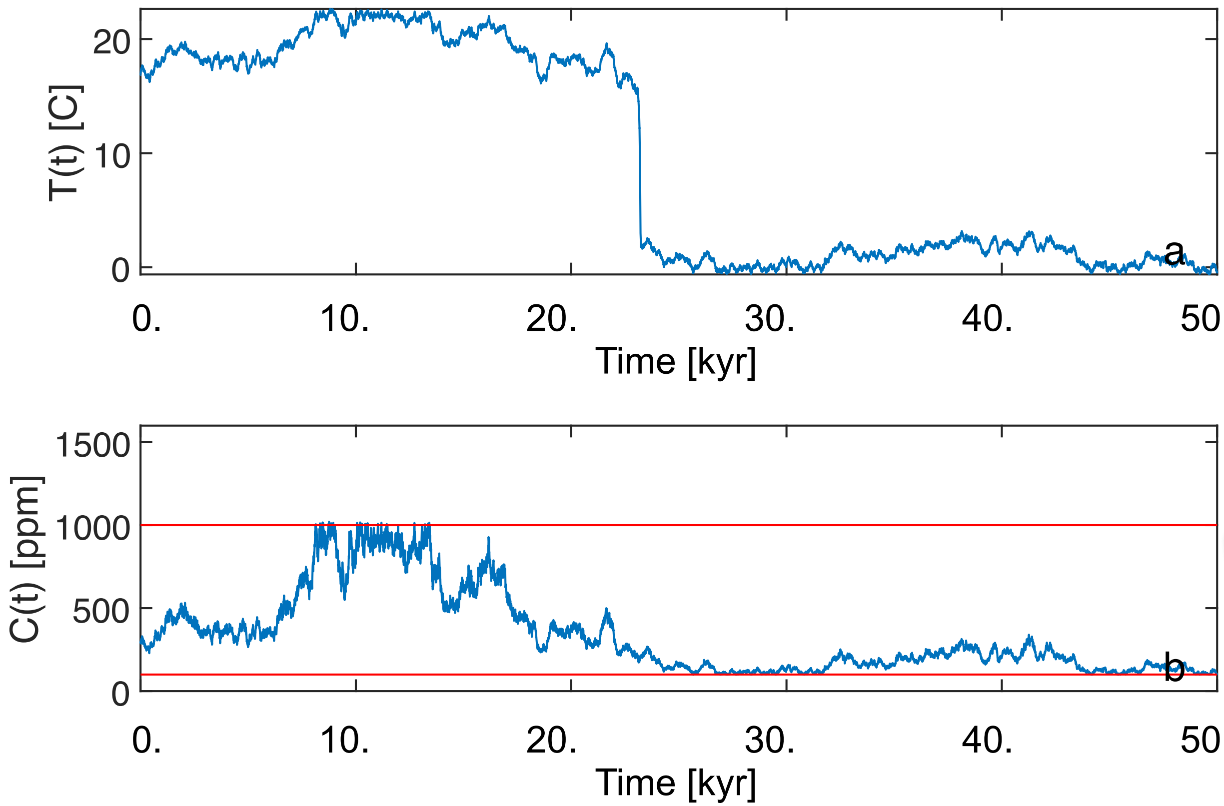
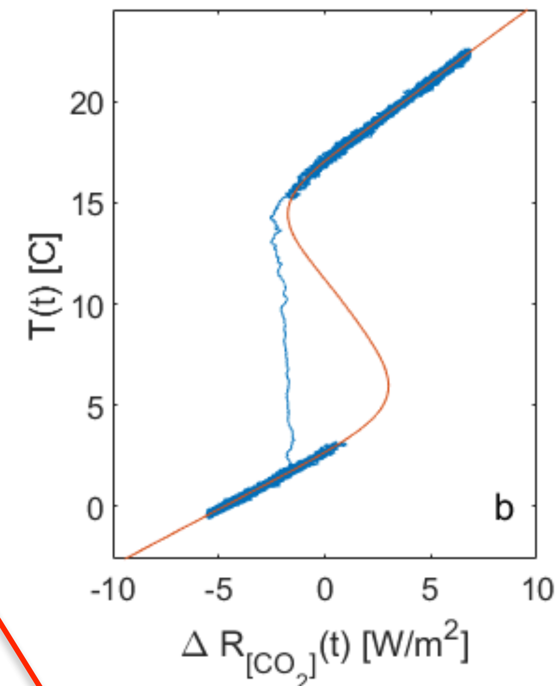
Energy Balance model with noise

Typical time series under ‘wandering’ CO_2



Climate ‘attractor’



limits of wandering CO_2

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Instantaneous sensitivity

$$S = 1/\lambda$$

$$\lambda = \frac{d}{dT}\Delta R_{[CO_2]} = [\epsilon'(T)T + 4\epsilon]\sigma T^3 + Q_0\alpha'(T)$$

- Different S on each branch: state-dependence
- Near saddle-nodes: runaway climate

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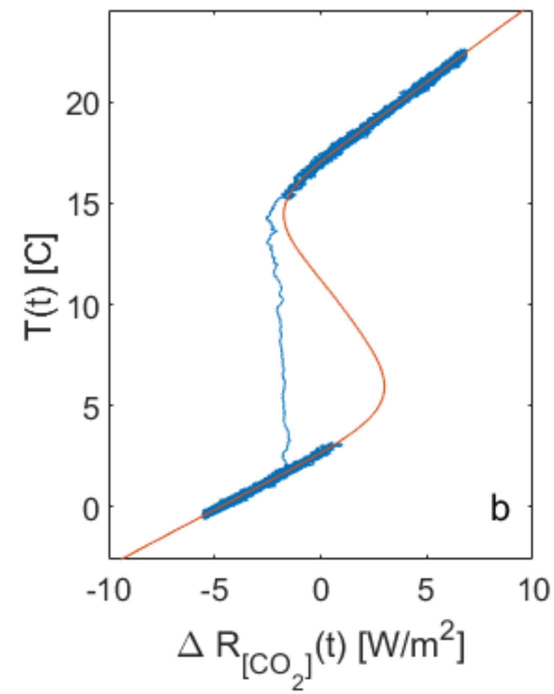

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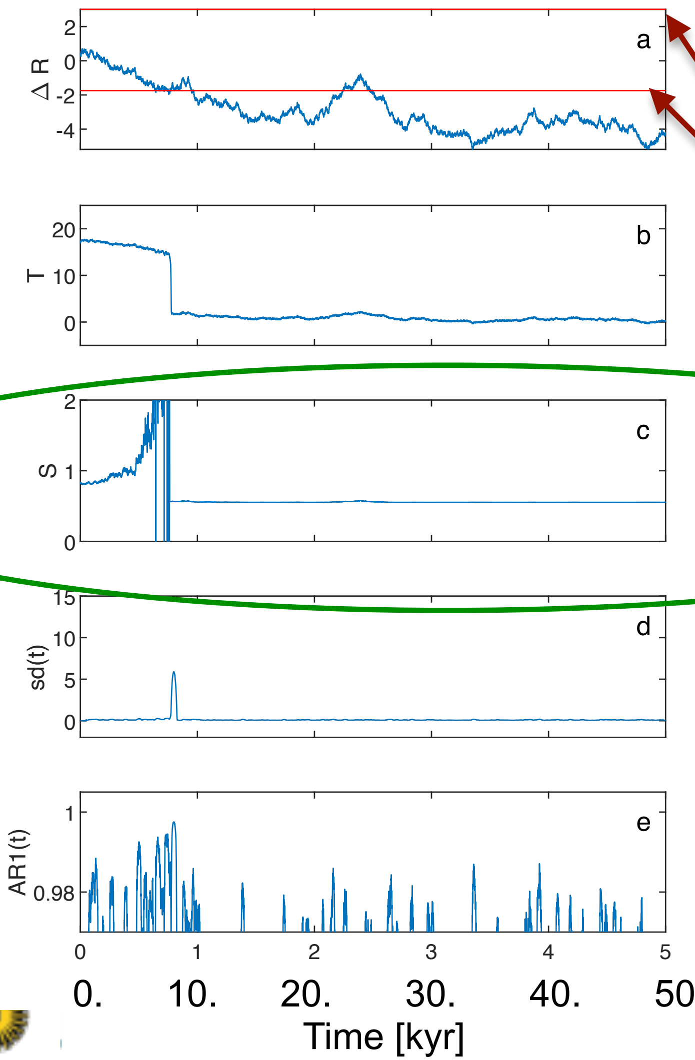
Instantaneous sensitivity and early warning

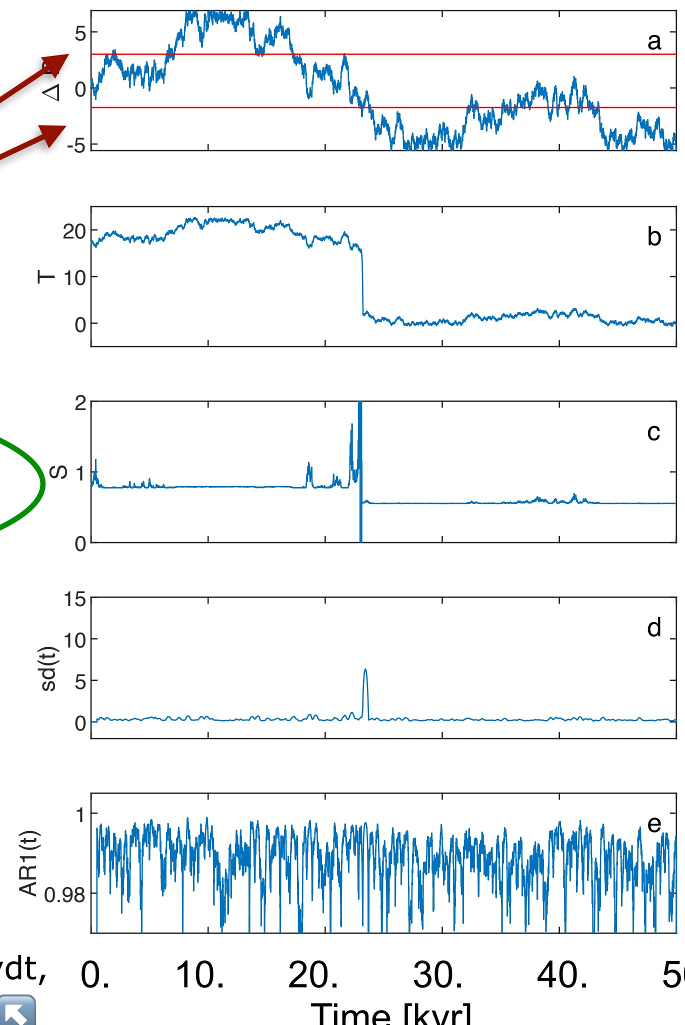
$$S = 1/\lambda$$

$$\lambda = \frac{d}{dT}\Delta R_{[CO_2]} = [\epsilon'(T)T + 4\epsilon]\sigma T^3 + Q_0\alpha'(T)$$

slow evolution of CO_2 (~ T)



fast evolution of CO_2



Saddle node points

Early warning of regime shift?

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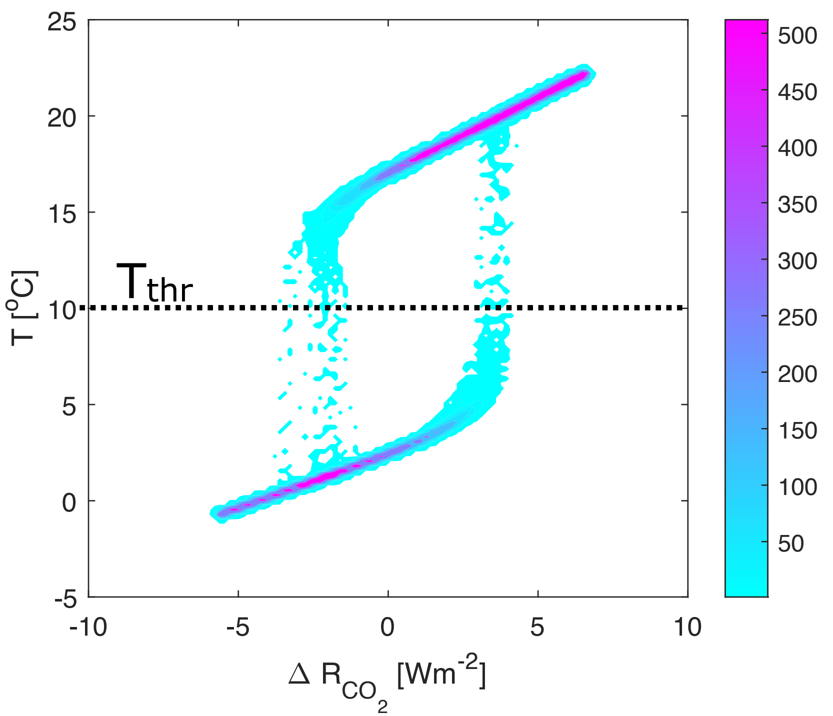
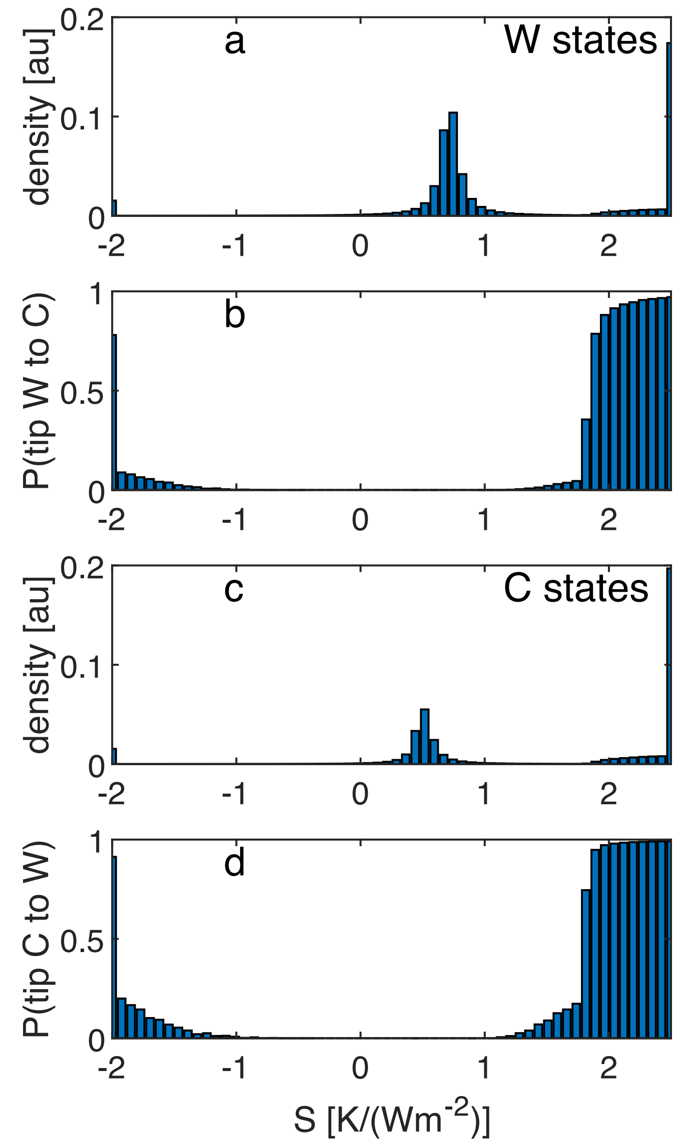
Two-point sensitivity





Conditional, incremental sensitivity for all delays up to 20kyr

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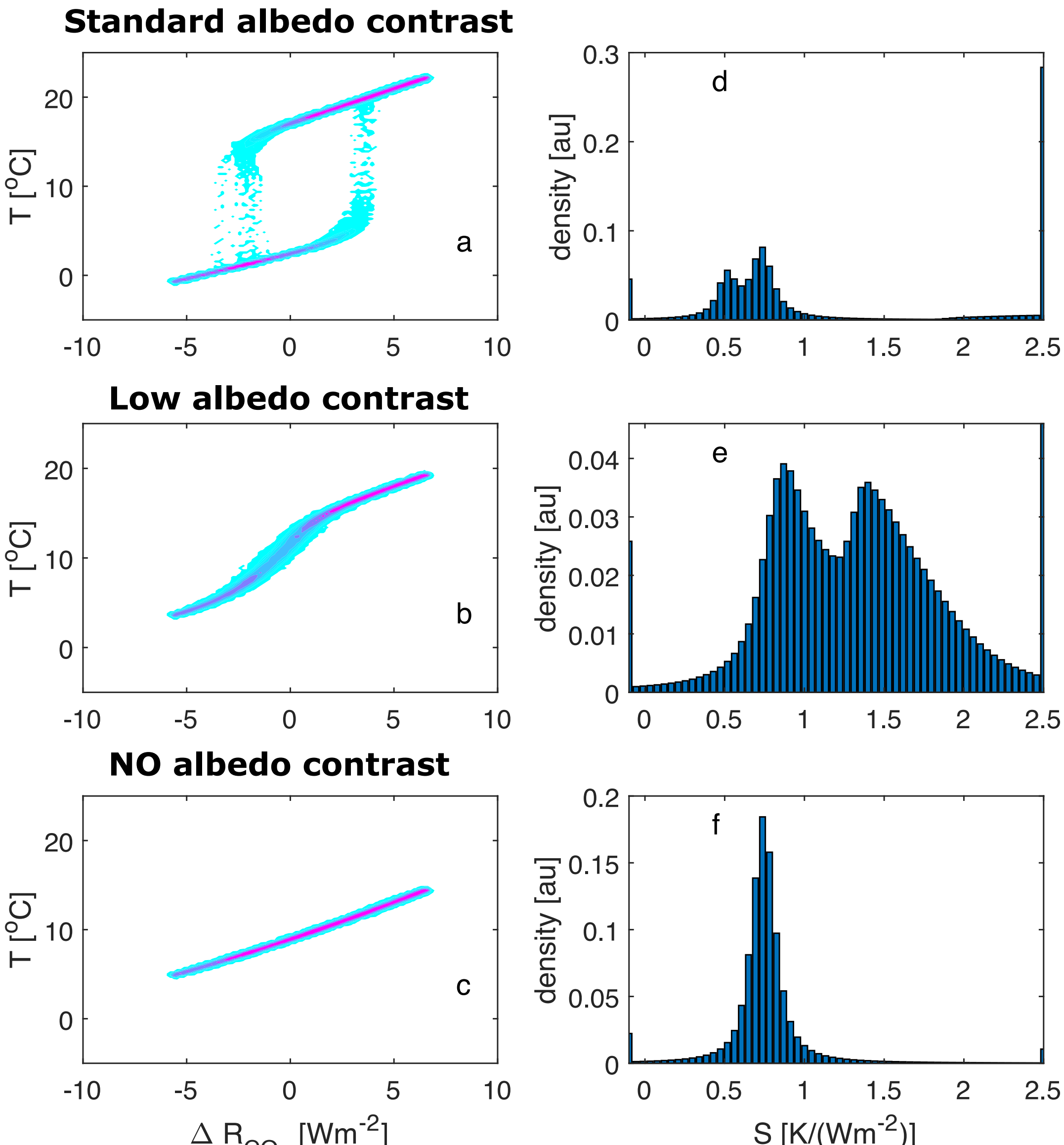
Skewed PDFs of two-point sensitivity



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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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.