TIPPING POINTS IN THE EARTH SYSTEM

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Climate sensitivity estimation using linear system fit: extending the Gregory method

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TiPES webinar 2020-06-24

UNIVERSITY OF COPENHAGEN

Met Office

Current project

- postdoc @ Utrecht University

(with Anna von der Heydt & Henk Dijkstra)

- Work on WP4 ‘**Climate Sensitivity**’:

If we increase the atmospheric CO_2 concentration,
how much warmer does the Earth get?

- **TODAY**: talk about endeavours since JAN 2020

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TIPES
TIPPING POINTS IN THE EARTH SYSTEM

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My background

2009-2013 BSc in Mathematics & Physics @ Leiden

2013-2015 MSc in Applied Mathematics @ Leiden

2015-2019 PhD in Applied Mathematics @ Leiden

'Lines in the Sand:

behaviour of self-organised vegetation

patterns in dryland ecosystems'

→Pattern formation

→Dynamical system theory

→Combination with ecology

Equilibrium Climate Sensitivity (ECS)

Experiment using climate models:

Increase CO_2 concentration

What is the increase in temperature ΔT_* in the new equilibrium?

- Equilibrating climate models takes very, very long

  (especially for e.g. very high-resolution simulations)

- Need for techniques to estimate equilibrium state/temperature

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Basic Idea of Gregory method (1)

Warming is due to net positive radiative imbalance

$$R = R_{SW,\downarrow} - R_{SW,\uparrow} - R_{LW,\uparrow}$$

incoming sunlight | reflected sunlight | Planck radiation

When $\Delta R = R - R_0 = 0$ no more warming:

→ equilibrium warming $\Delta T_* = T_* - T_0$

[Gregory et al (2004)]

Basic Idea of Gregory method (2)

Assuming all feedbacks are directly temperature dependent:

$$\Delta R = R(T) - R_0$$

Close to equilibrium T_*, Taylor expansion gives approximation

$$\Delta R(T) = R'(T_*)\,[T - T_*]$$

Rewriting $T = T_0 + \Delta T$ gives:

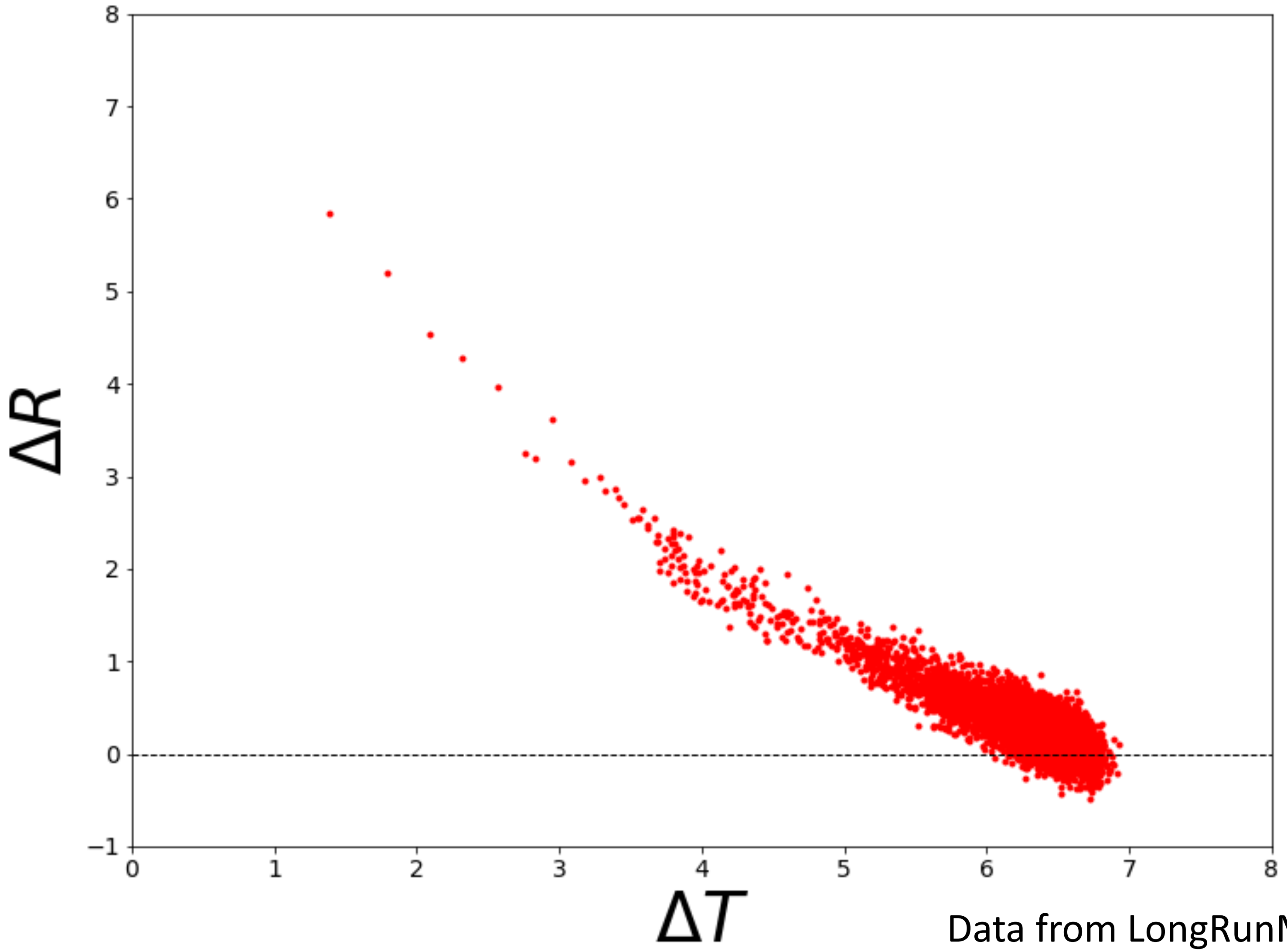
$$\Delta R(\Delta T) = R'(T_*)\Delta T - R'(T_*)\Delta T_*$$

Linear regression on data:

$$\Delta R = a\,\Delta T + f \;\rightarrow\; \Delta T_*^{est} = -\,a^{-1}\,f$$

[Gregory et al (2004)]

Gregory Plot for CESM 1.0.4



Data from LongRunMIP; [Rugenstein et al (2019)]

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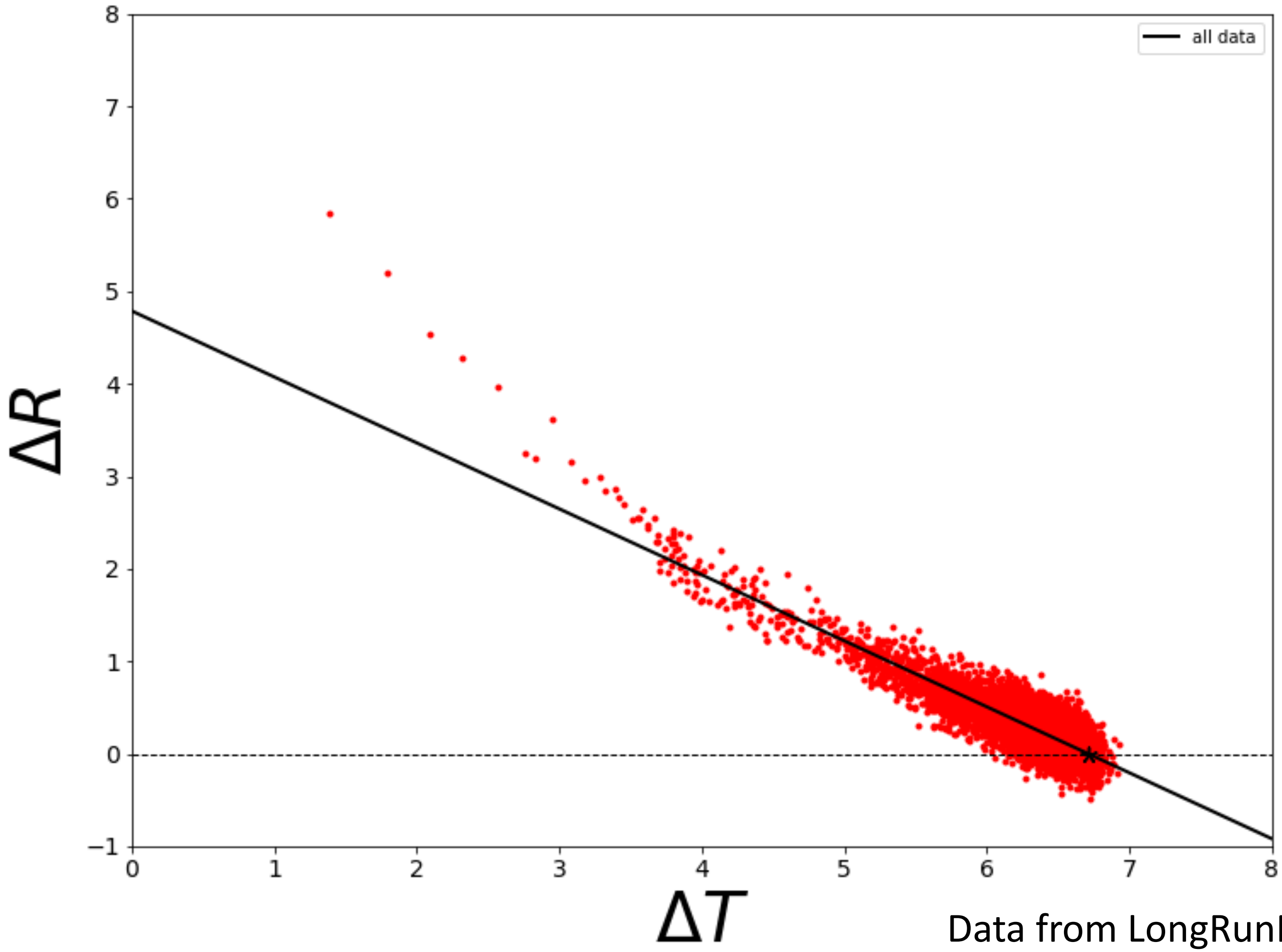

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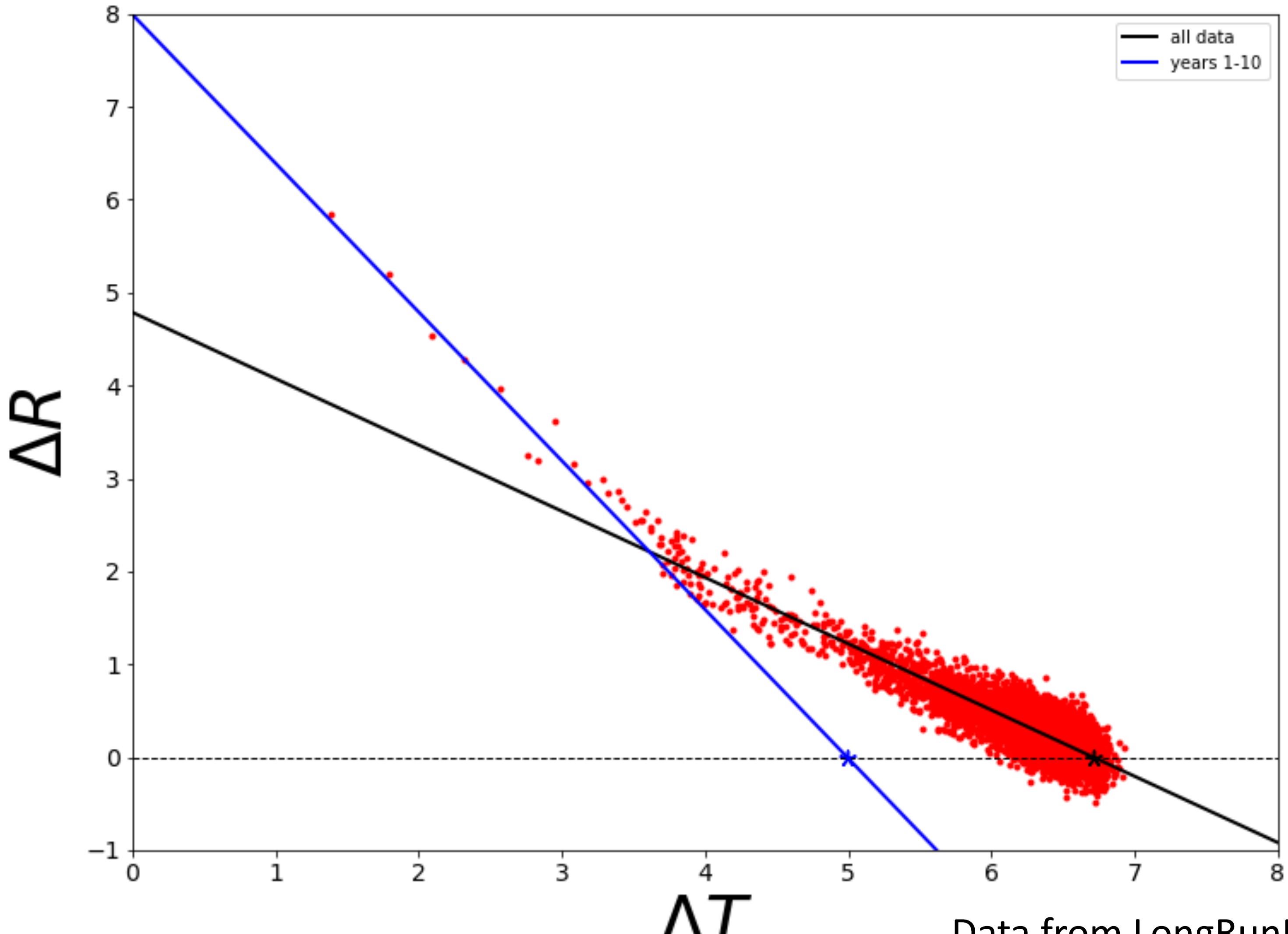

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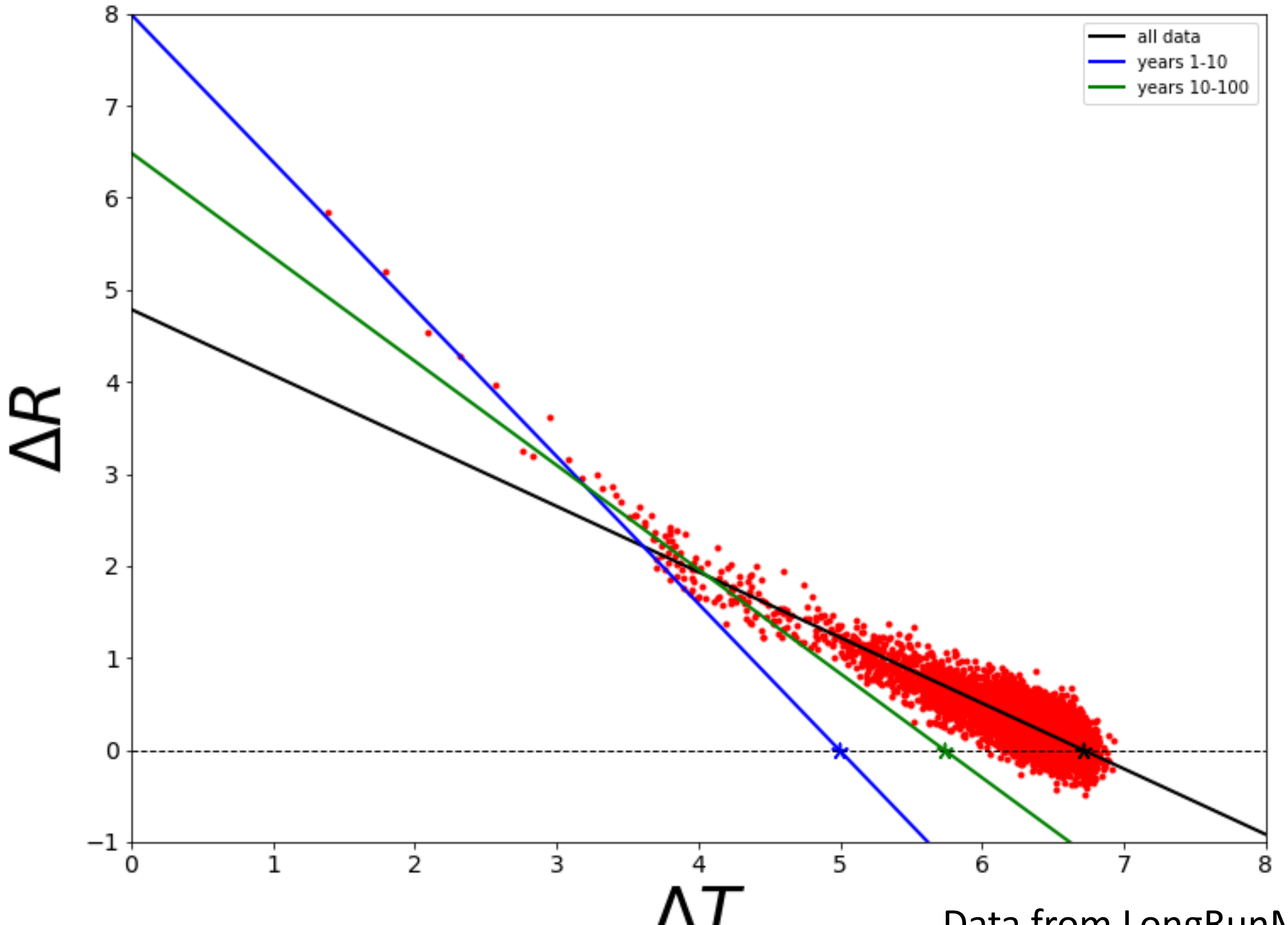

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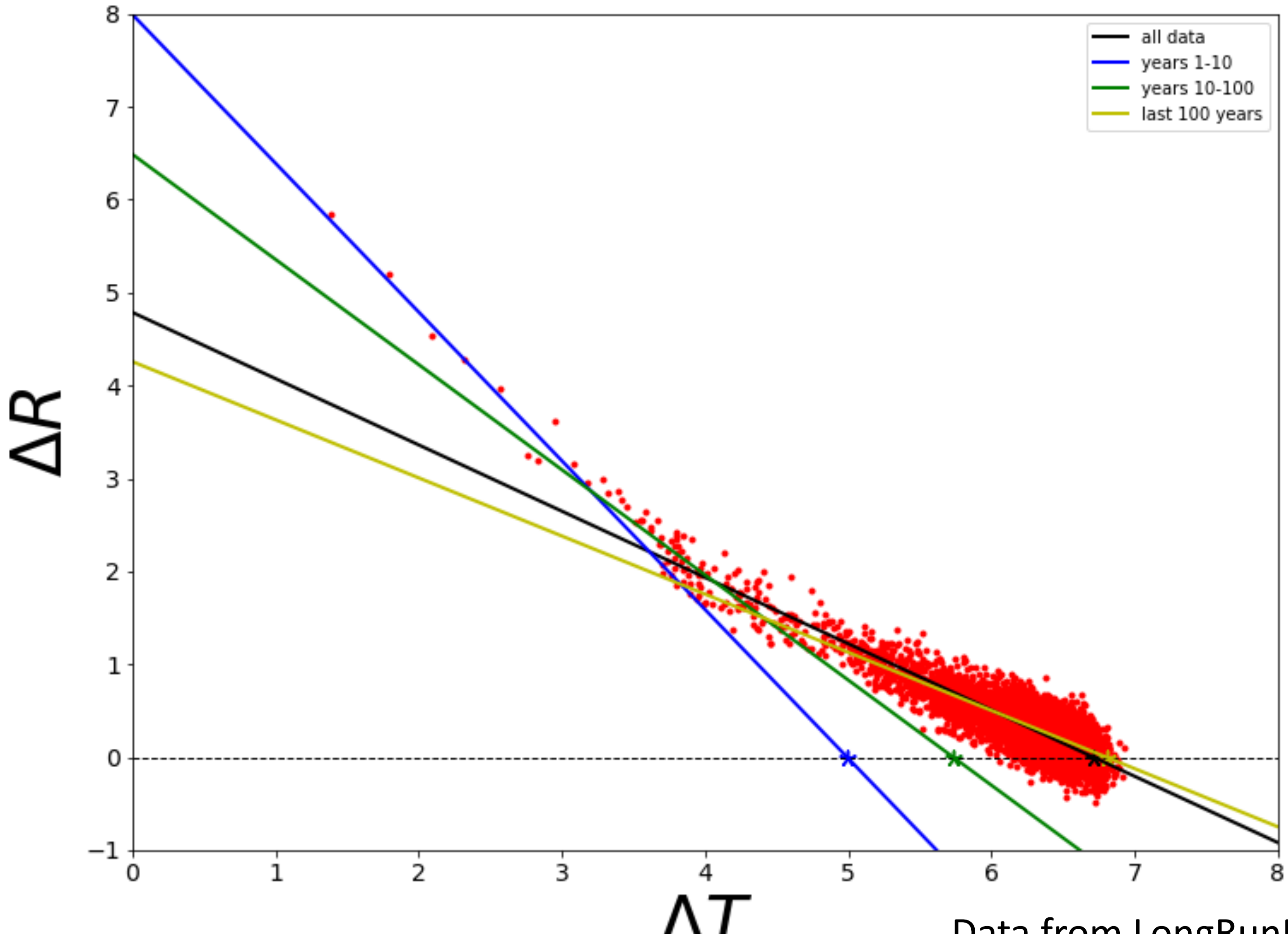

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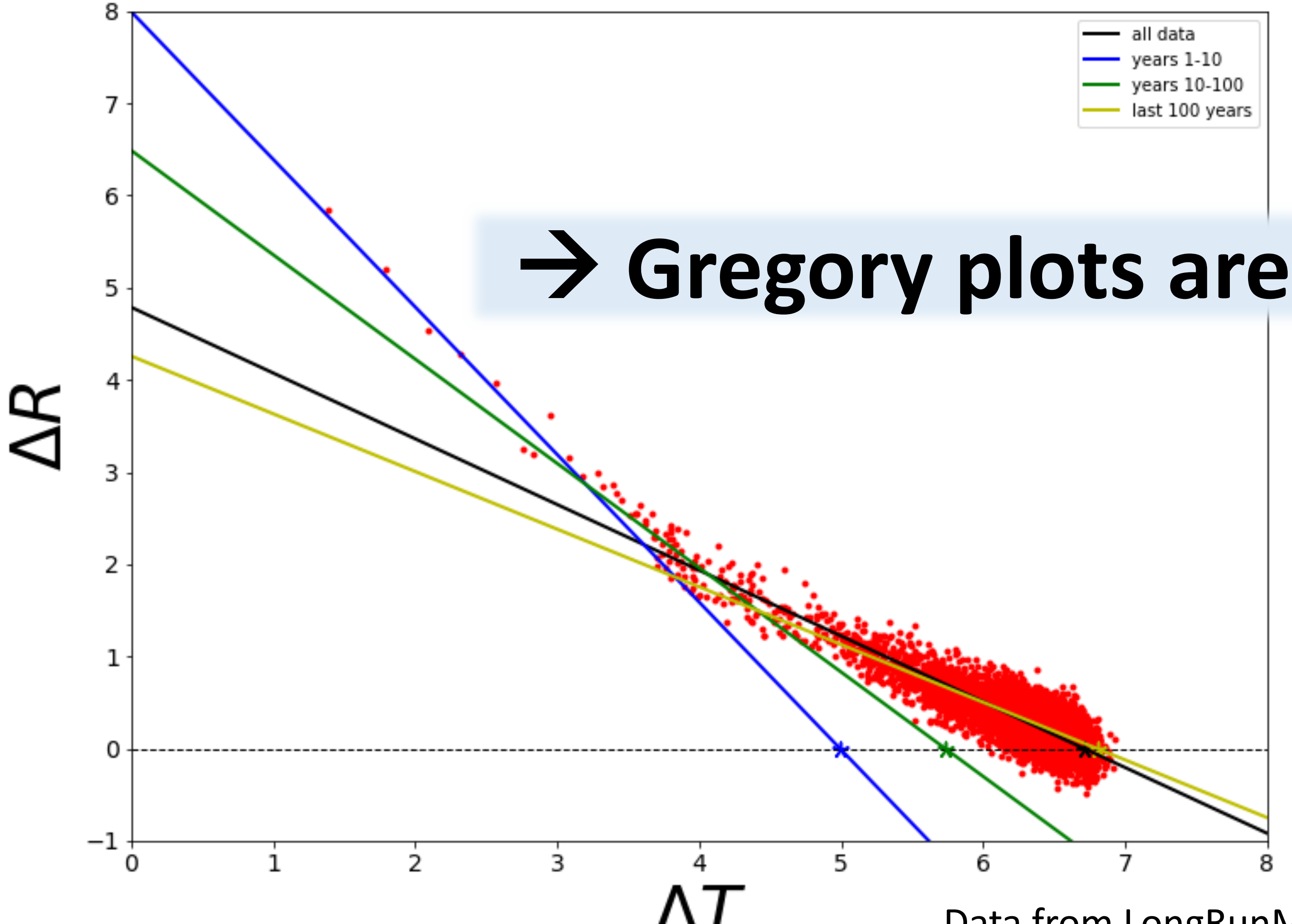

→ Gregory plots are non-linear!

Data from LongRunMIP; [Rugenstein et al (2019)]

Step back: dynamical system point of view (1)

Nonlinearity in Gregory plot (`state-dependency'):

→ Feedbacks are not constant (& not instantaneous)

$$\cancel{R = R(T)} \rightarrow R = R(T, \alpha)$$

Feedbacks

Let y denote (complete) system state

Dynamical system: $y' = f(y)$

Linearize around equilibrium state y_*: $y' = Df(y_*)[y - y_*]$

Thus, linear system of form

$$\Delta y' = A\,\Delta y + F \rightarrow \Delta y_* = A^{-1} F$$

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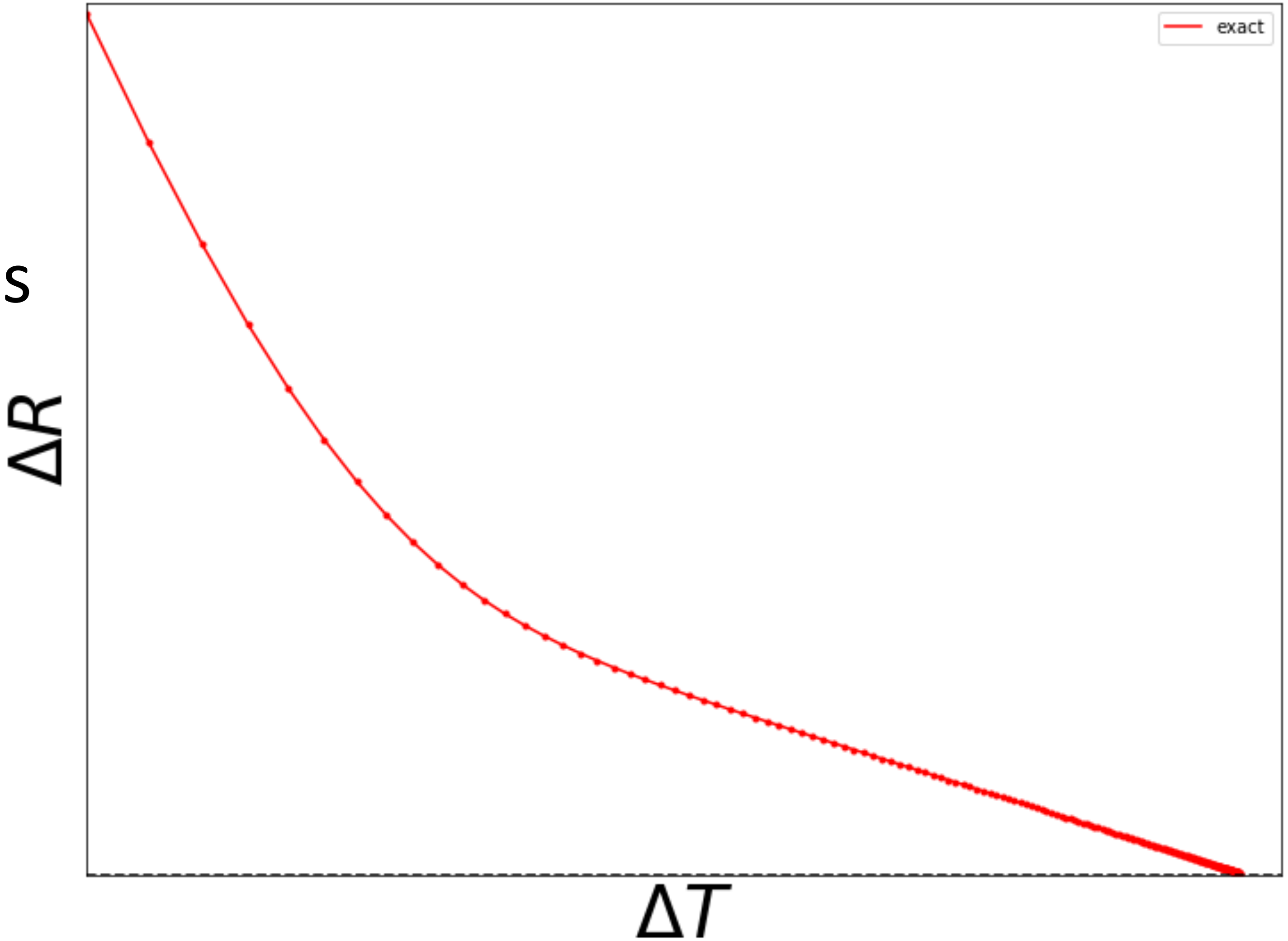
Step back: dynamical system point of view (2)

$$\Delta y' = A\,\Delta y + F$$

Solutions sum of exponentials

$$\Delta y(t) - \Delta y_* = \sum_{j=1}^{n} c_j v_j e^{\lambda t}$$

(v_j eigenvectors, λ_j eigenvalues of A)



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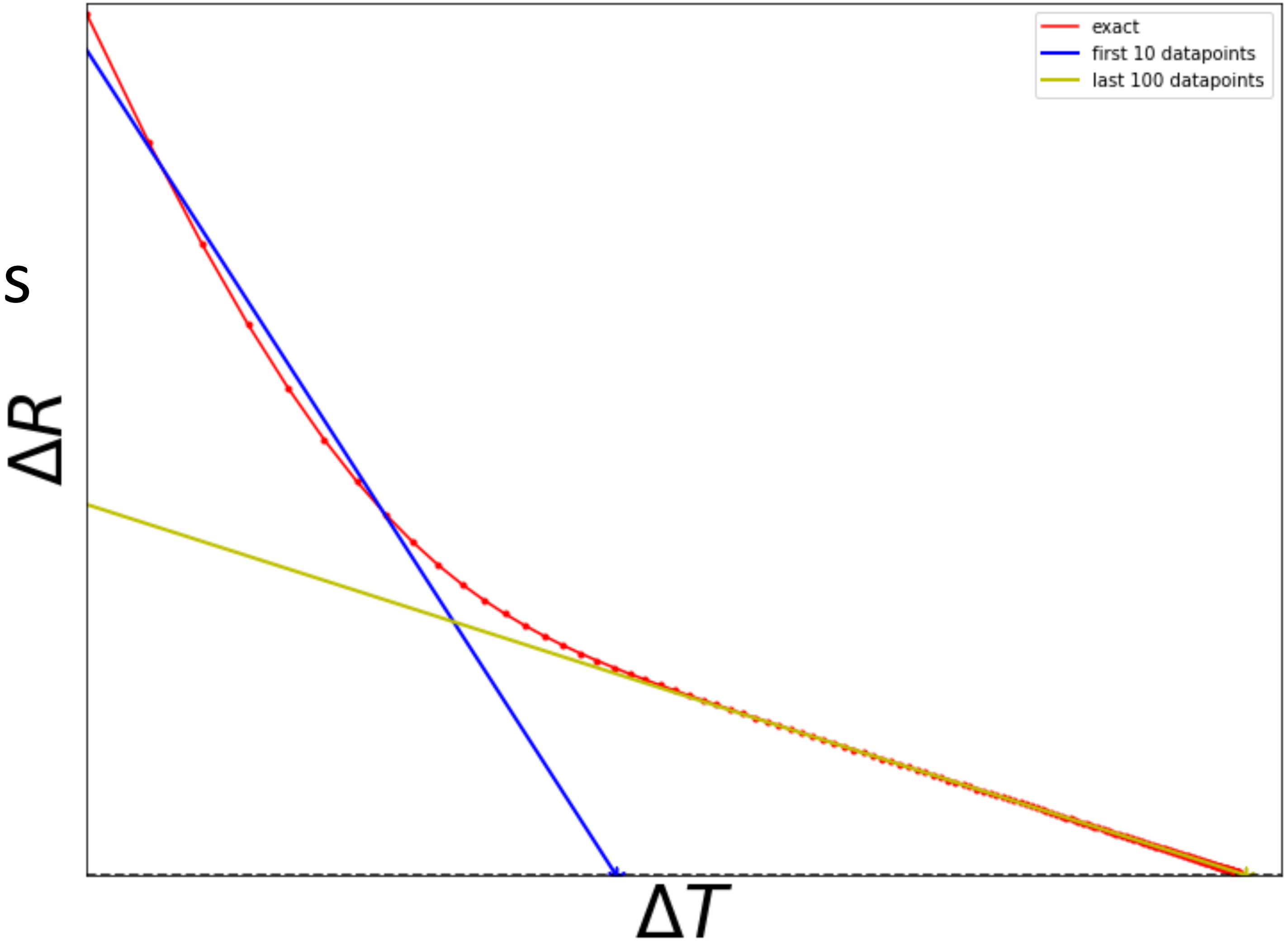

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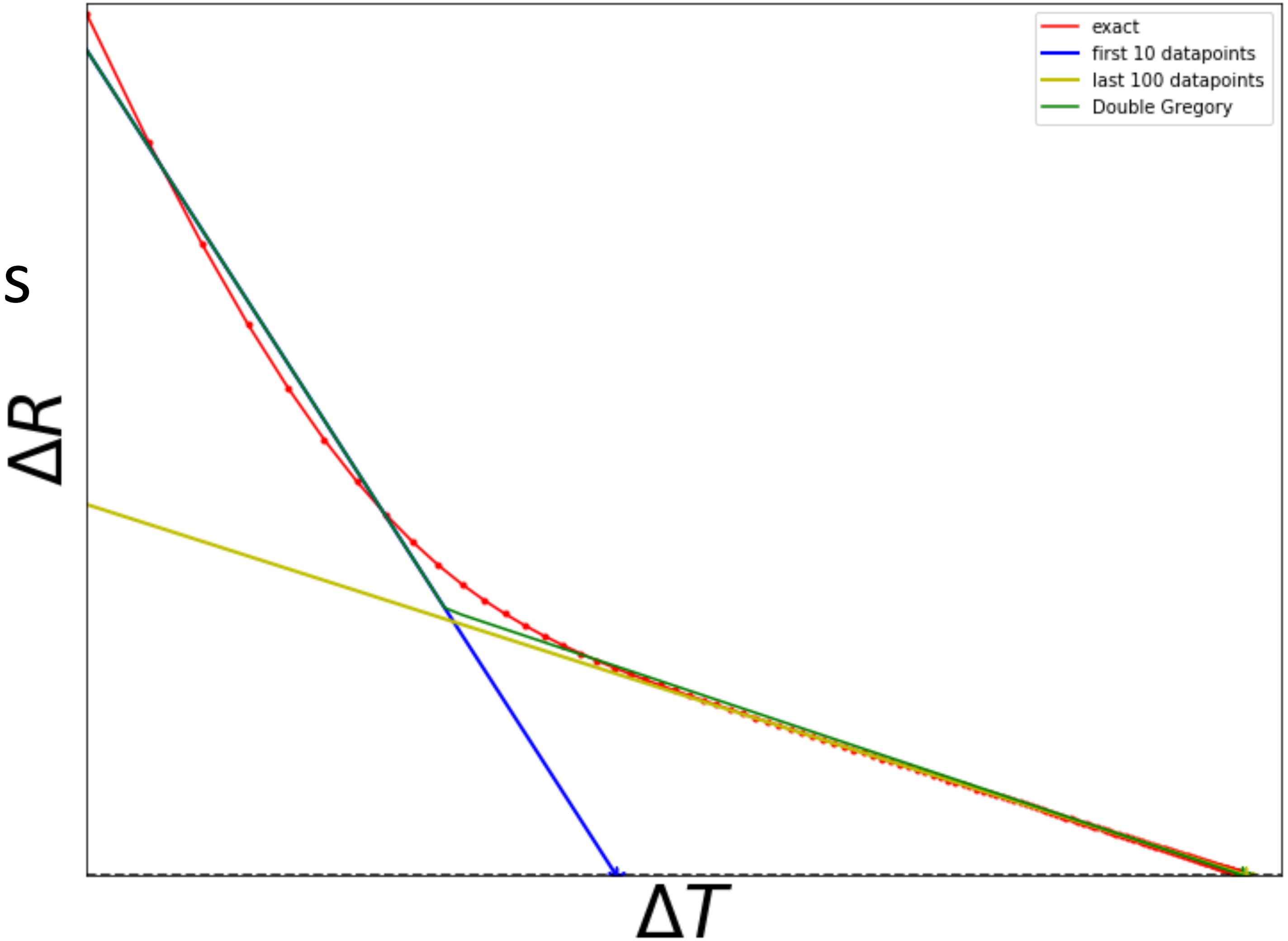

Idea:

Fit a linear system!

$$\Delta Y = A\,\Delta X + F \rightarrow \Delta X_*^{est} = A^{-1}\,F$$

ΔY:
m observables that tend to 0 in equilibrium

ΔX:
m observables that are estimated in equilibrium

Example:

$$\begin{bmatrix} \Delta \mathrm{R} \\ \Delta \alpha' \\ \Delta \varepsilon' \end{bmatrix} = \mathrm{A} \begin{bmatrix} \Delta \mathrm{T} \\ \Delta \alpha \\ \Delta \varepsilon \end{bmatrix} + F$$

α : effective top-of-atmosphere short-wave albedo

$$\alpha = {R_{SW,\uparrow}}/{R_{SW,\downarrow}}$$

ε : effective top-of-atmosphere long-wave emissivity

$$\varepsilon = {R_{LW,\uparrow}}/{T^4}$$

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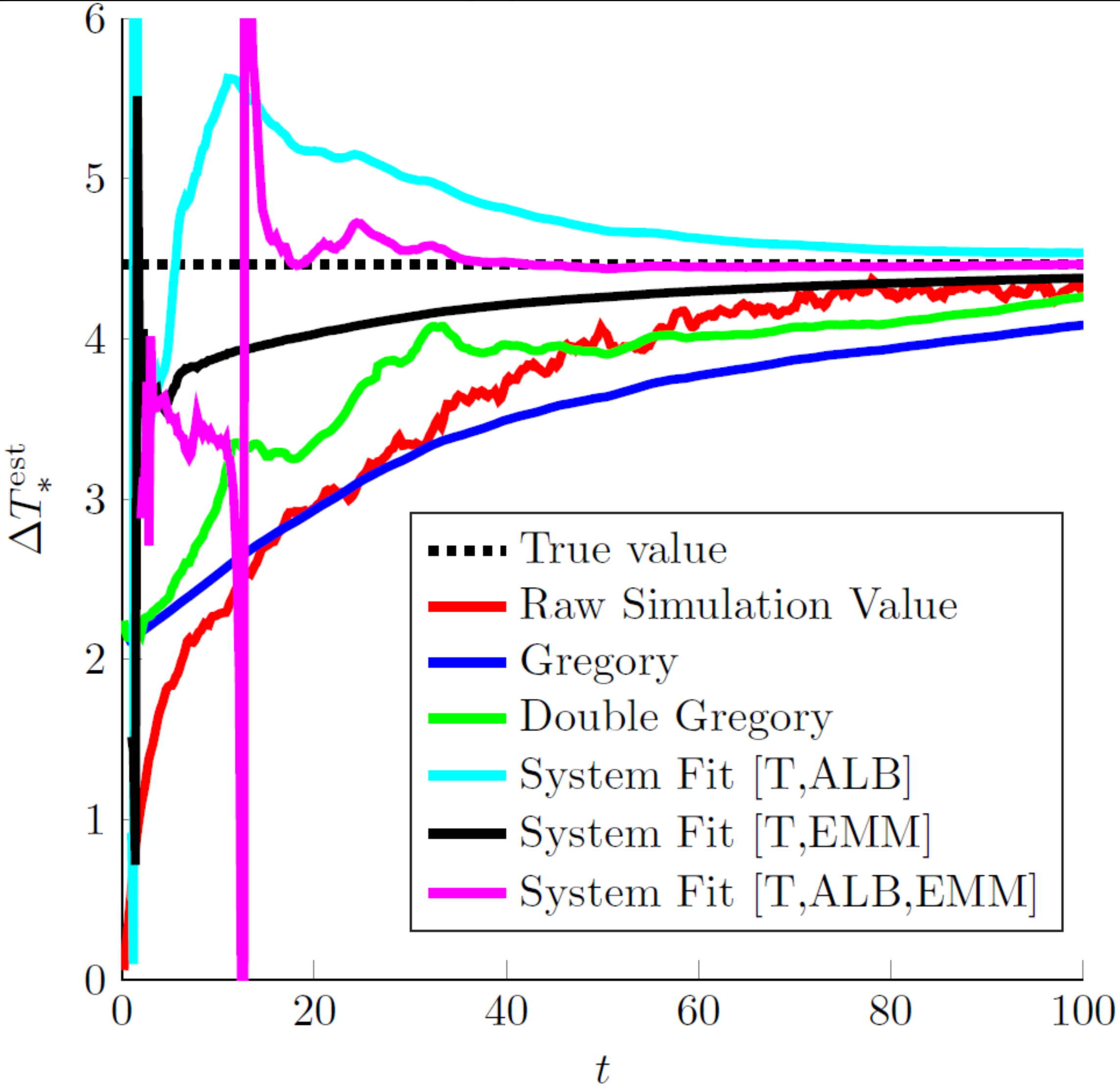
Toy model: global energy balance model



Testing on LongRunMIP data

- Models run to ‘equilibrium’ (practice: runs of at least 1000 years)
- Work with ‘abrupt-4xCO2’ forcing experiments

Experiment

- Run estimation technique with data up to time t
- Compare with ‘equilibrium value’
- Determine effectiveness of techniques for time frame

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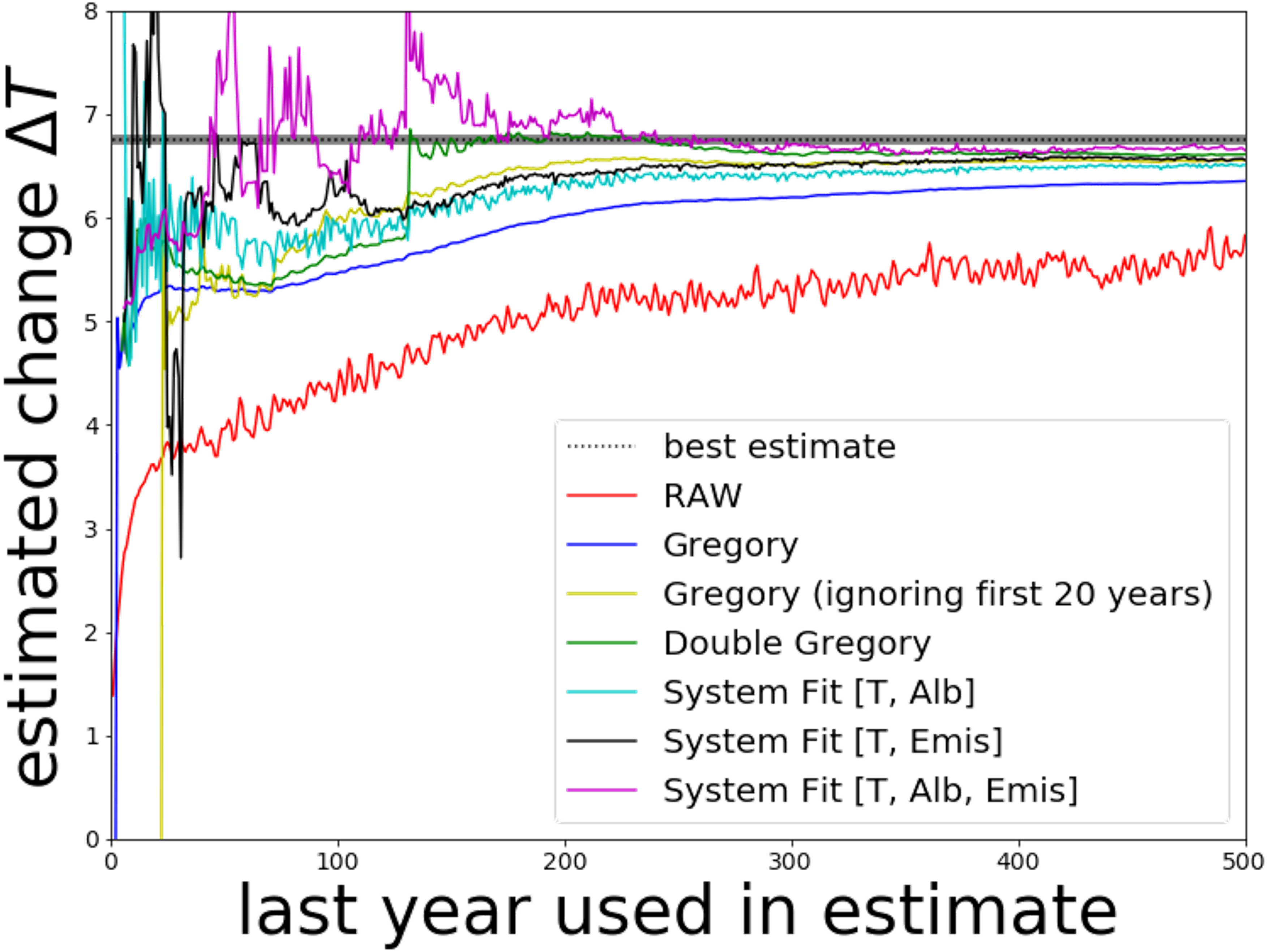
CESM 1.0.4



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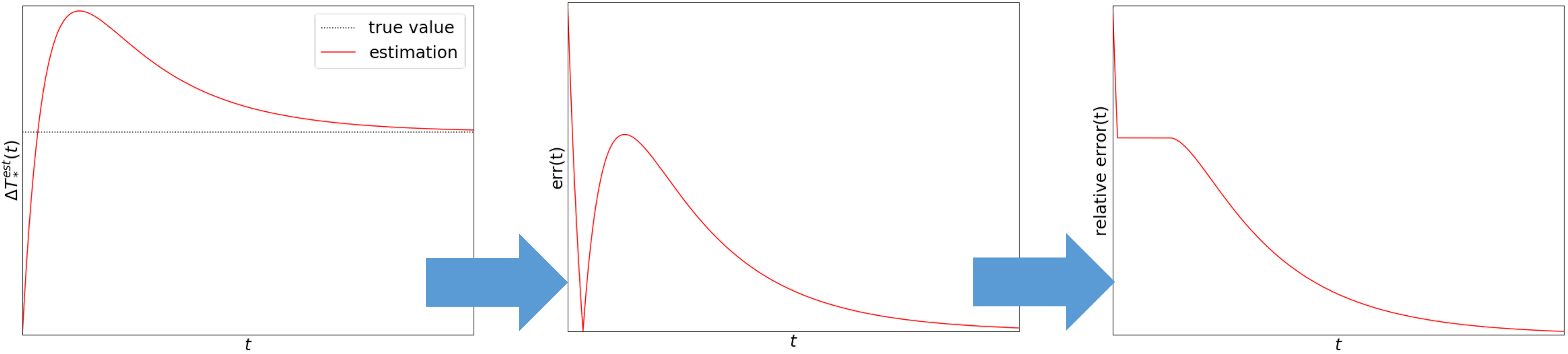
Measure for effectiveness

- Denote `equilibrium' warming by ΔT_*
- Measure for maximum of relative error one ought to expect

$$\text{relative error}\,(t) := \max_{s\geq t}\left|\frac{\Delta T_*^{est}(s)-\Delta T_*}{\Delta T_*^{est}(s)}\right|$$



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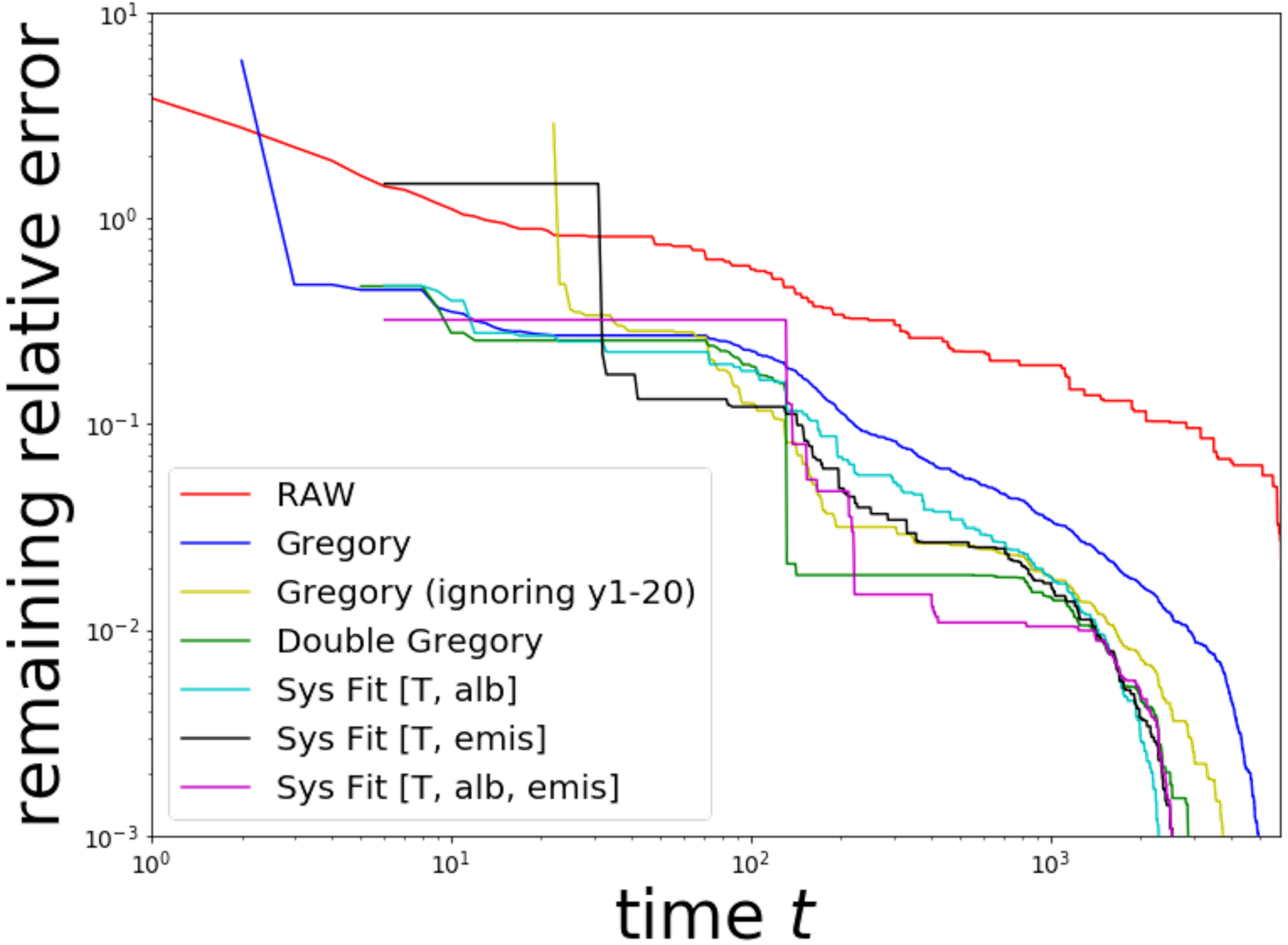

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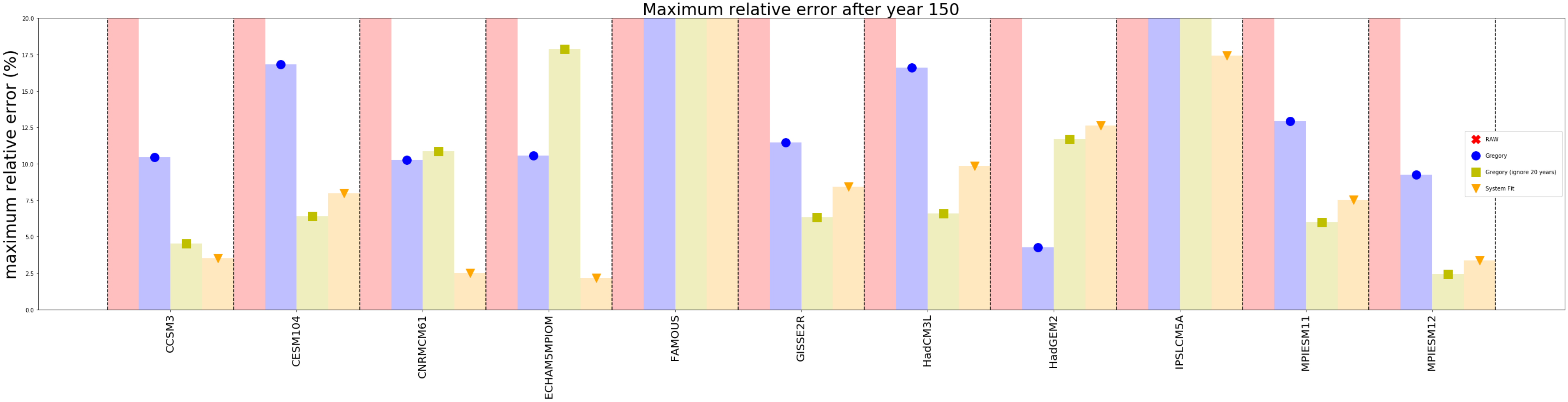
Results for all models



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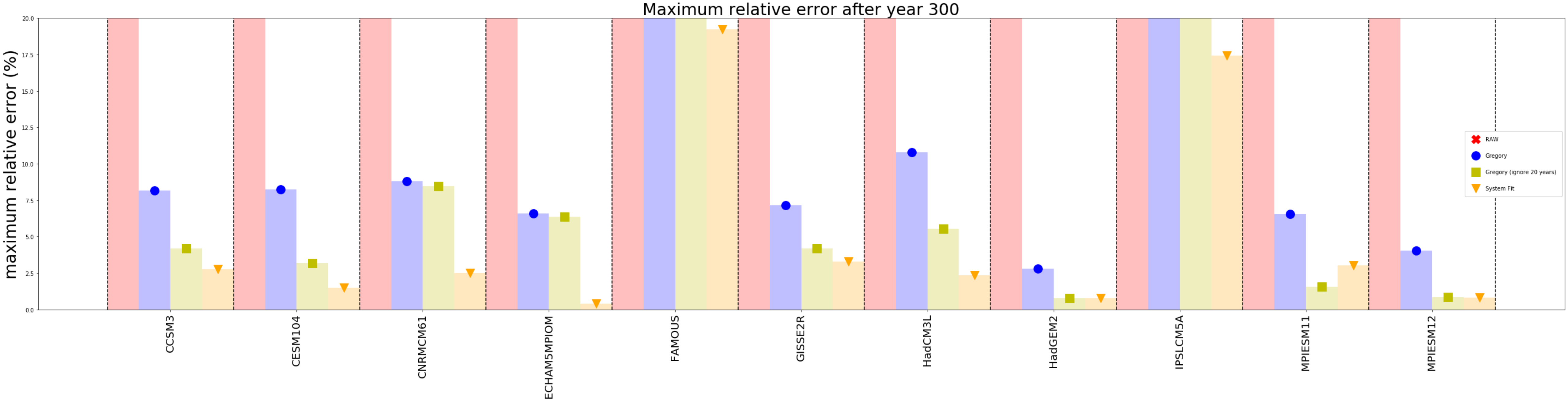

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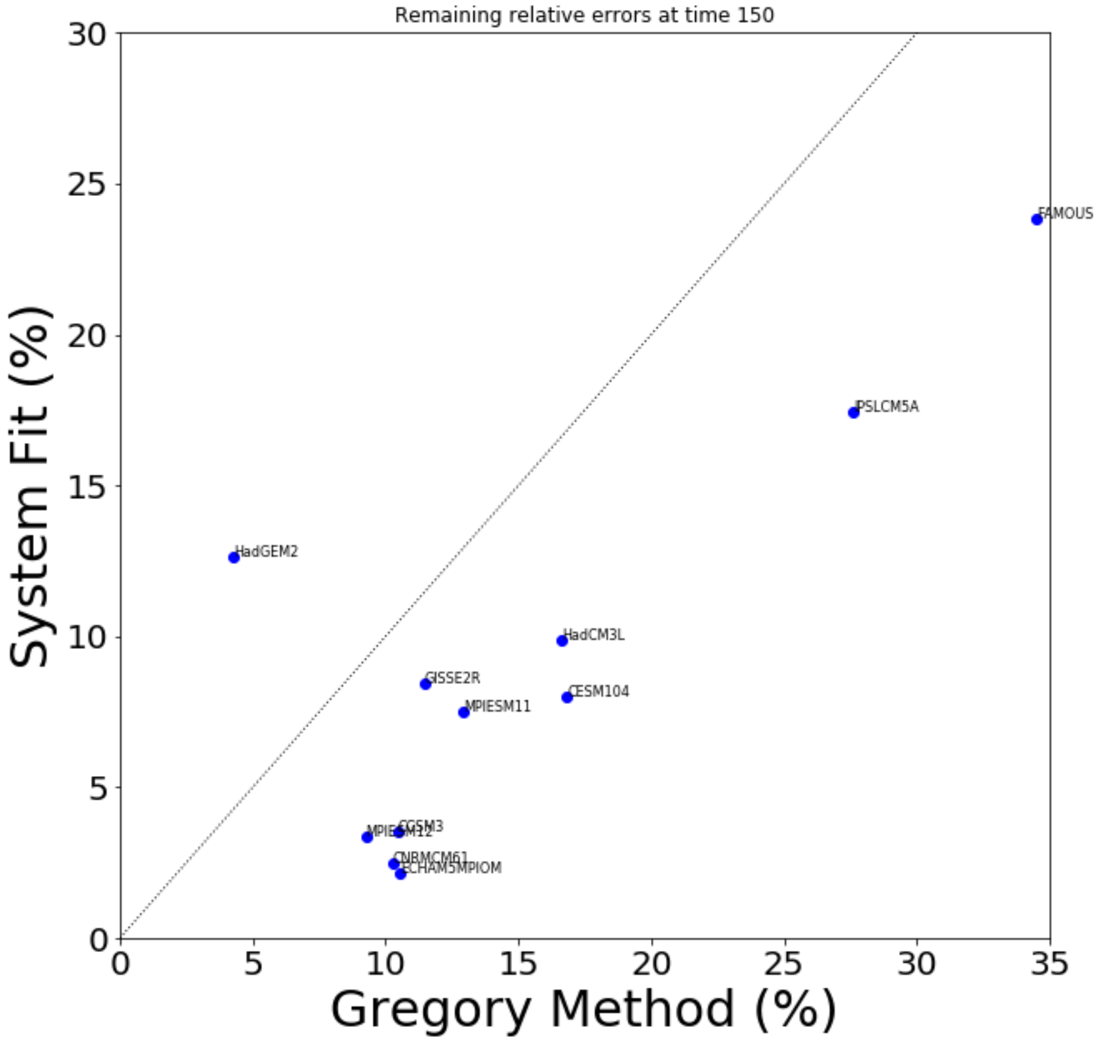
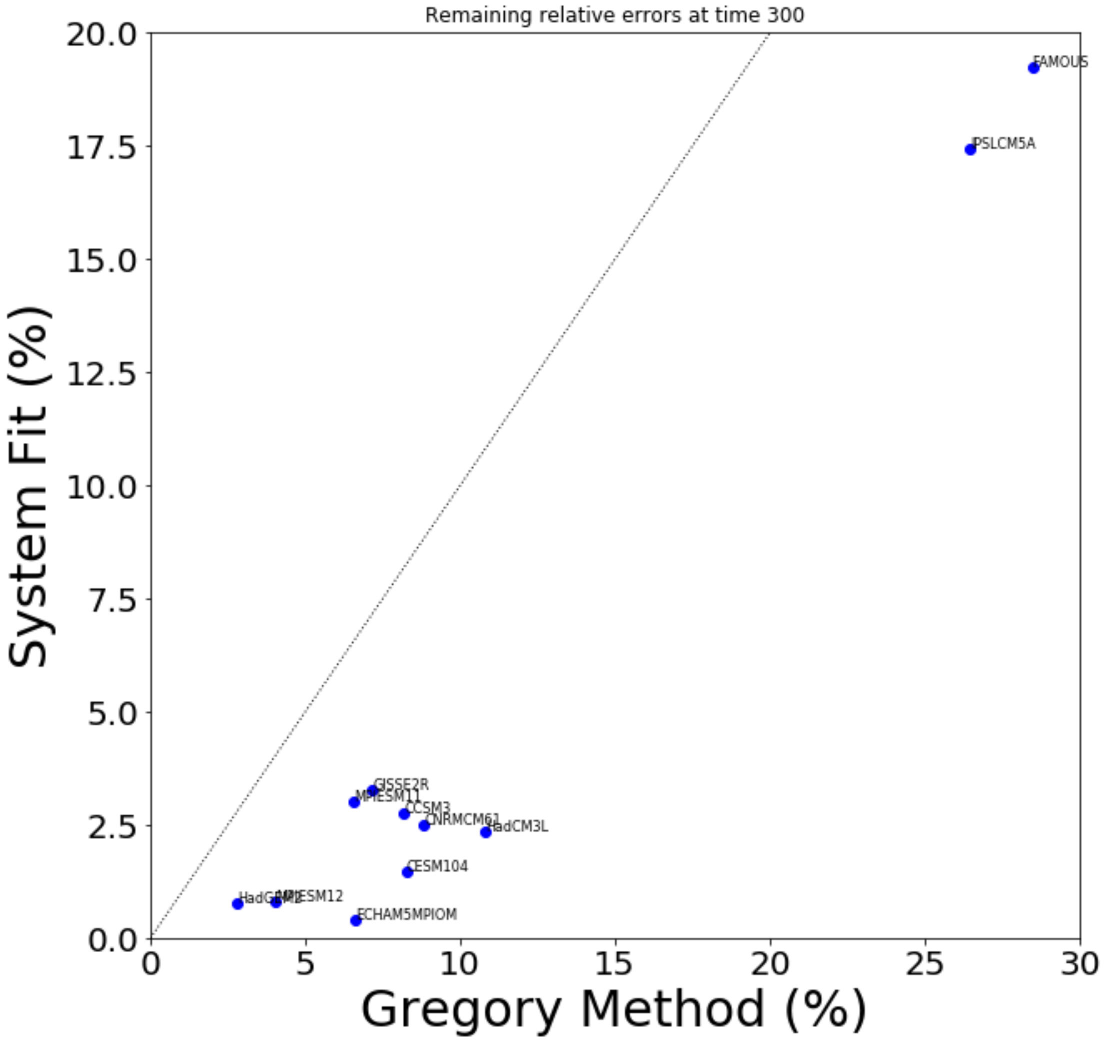
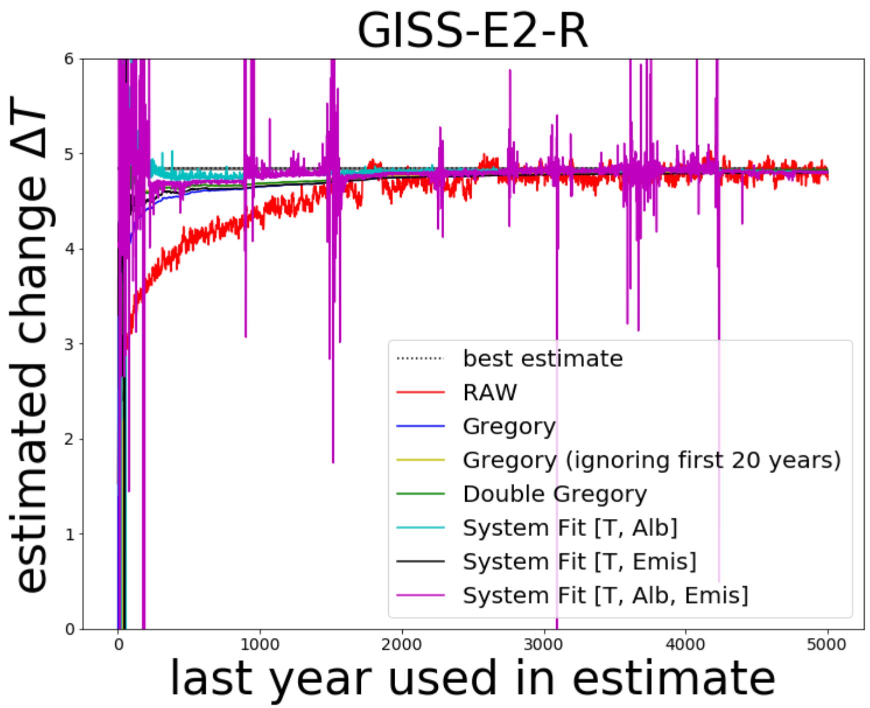




General observations so far (to be continued)

- Hard to find true increment ΔT_*
- Model-dependent & time-dependent which technique works best
  →However: almost always a system fit technique works best
- Some techniques rubbish on some models
  →Possibly due to model dynamics?



Possible extensions and use cases

- Can also predict other climate change indicators
  - Here: (effective top-of-atmosphere) albedo and/or emissivity
  - Other things might also be possible
- Can help to design experiments for e.g. high-resolution models
  - How long should we run those?
  - What kind of experiments/forcings/perturbations are best?

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