

A thousand years of feedbacks

The last millennium as a testbed

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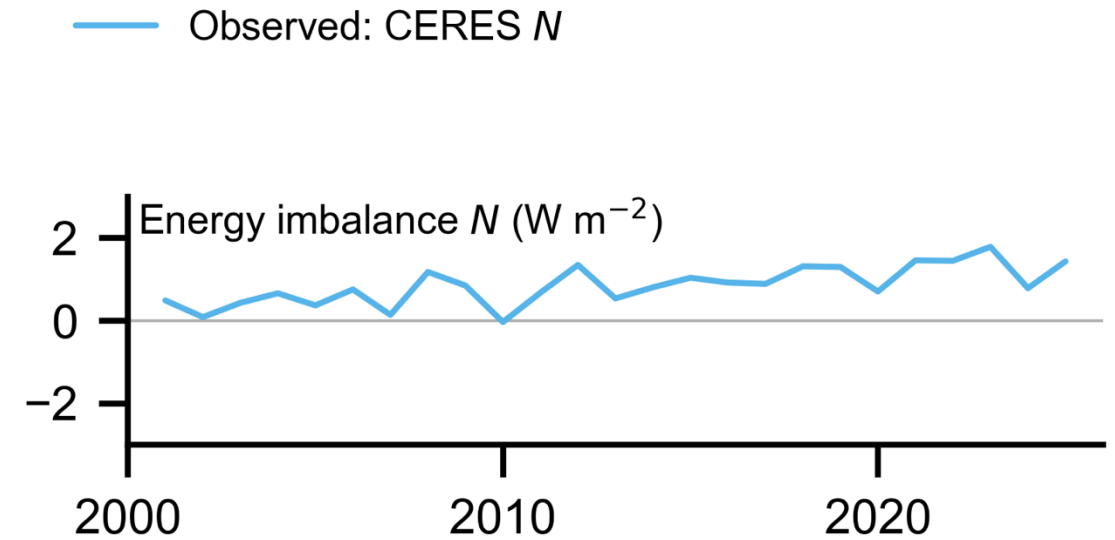
University of Washington

October 21, 2026 / CFMIP Meeting



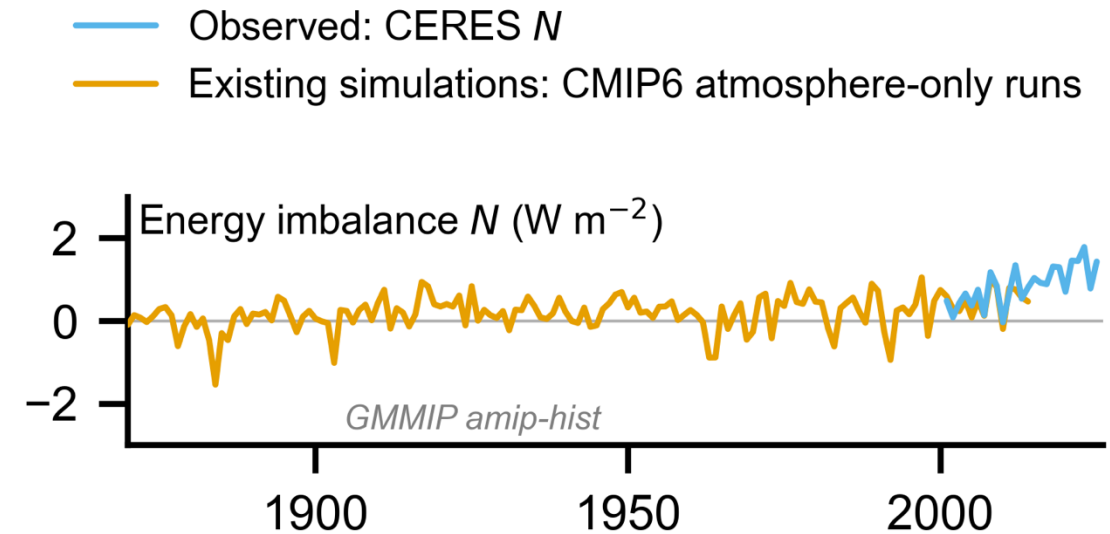
We have a limited record of N, F, and R

25-year satellite record of
top-of-atmosphere radiation



We have a limited record of N, F, and R

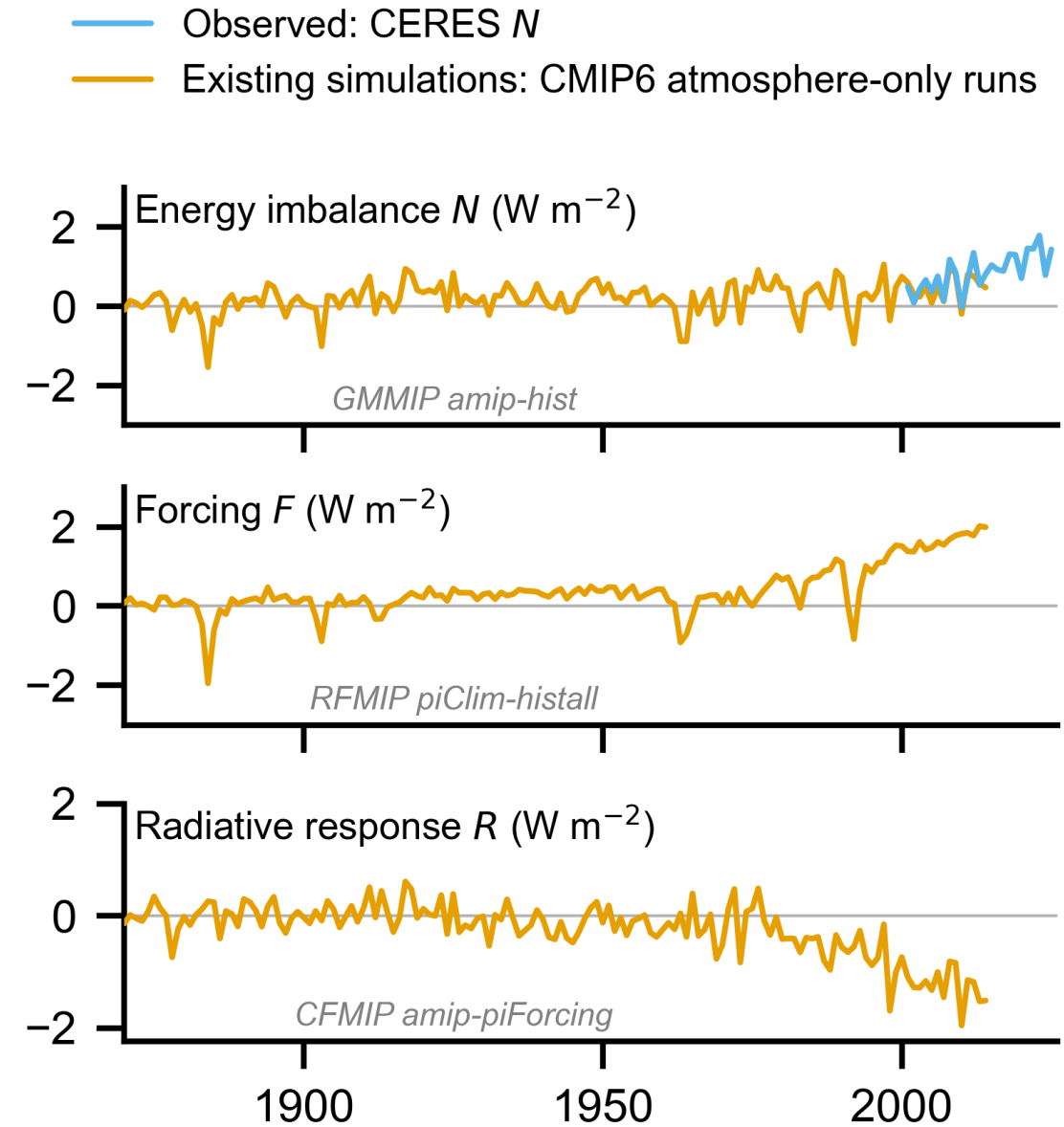
Atmosphere-only simulations
allow us to extend the record and
separate F from R



$$N = F + R$$

We have a limited record of N, F, and R

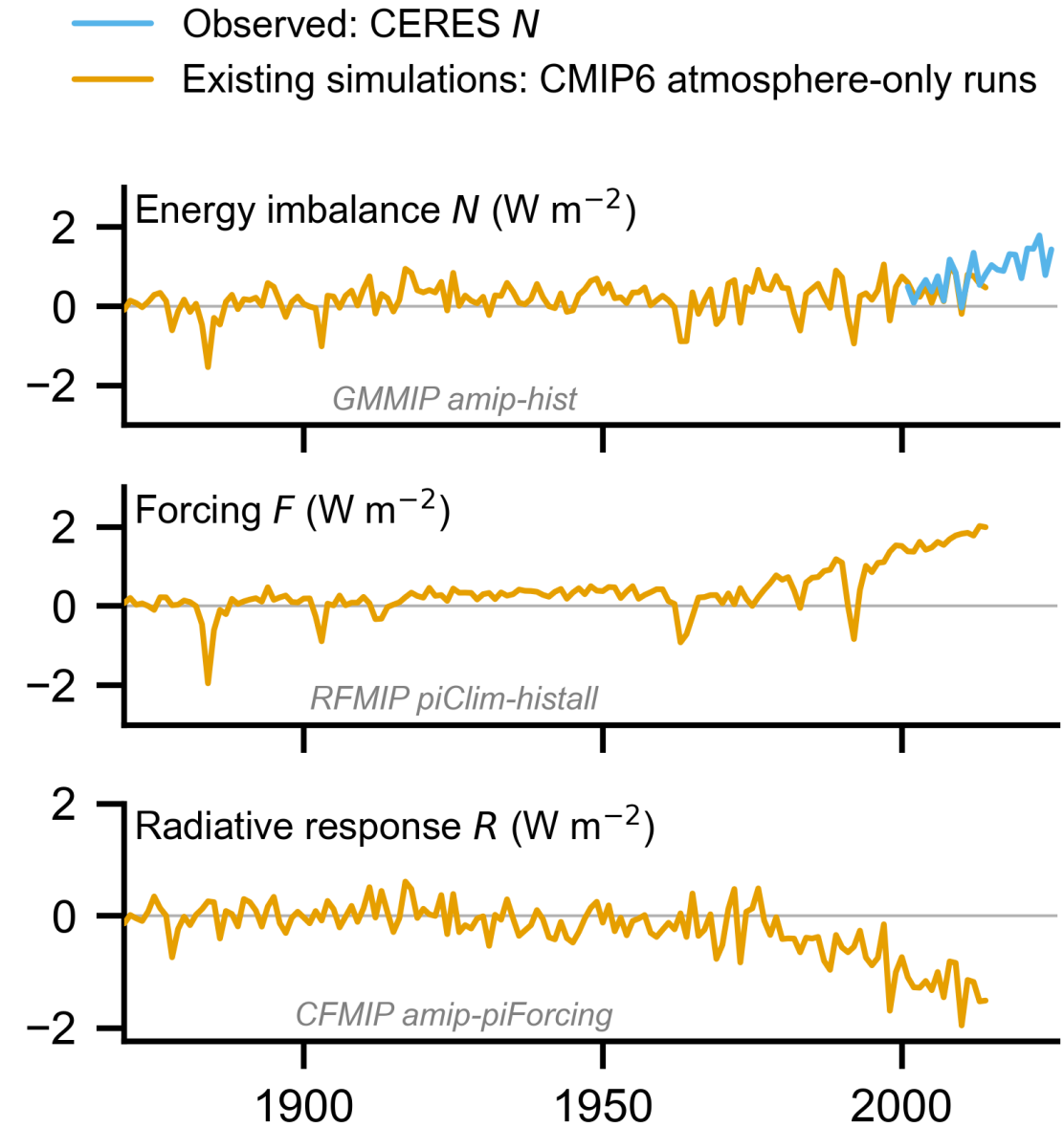
Atmosphere-only simulations
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We have a limited record of N, F, and R

What we have learned about the historical period:

- Radiative sensitivity differs by region
- Clouds respond to the warming pattern
- Feedbacks vary in time

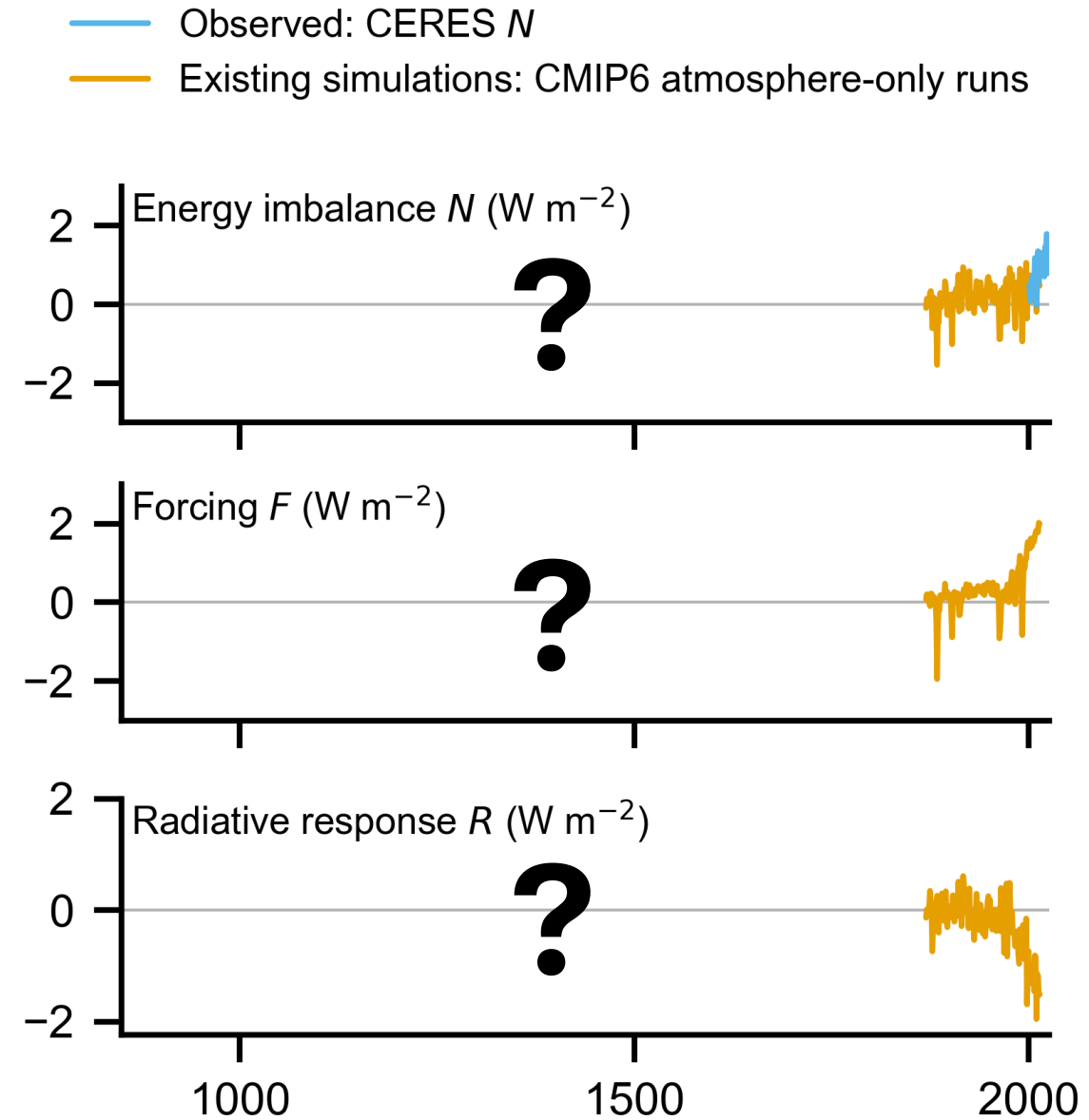


We have a limited record of N, F, and R

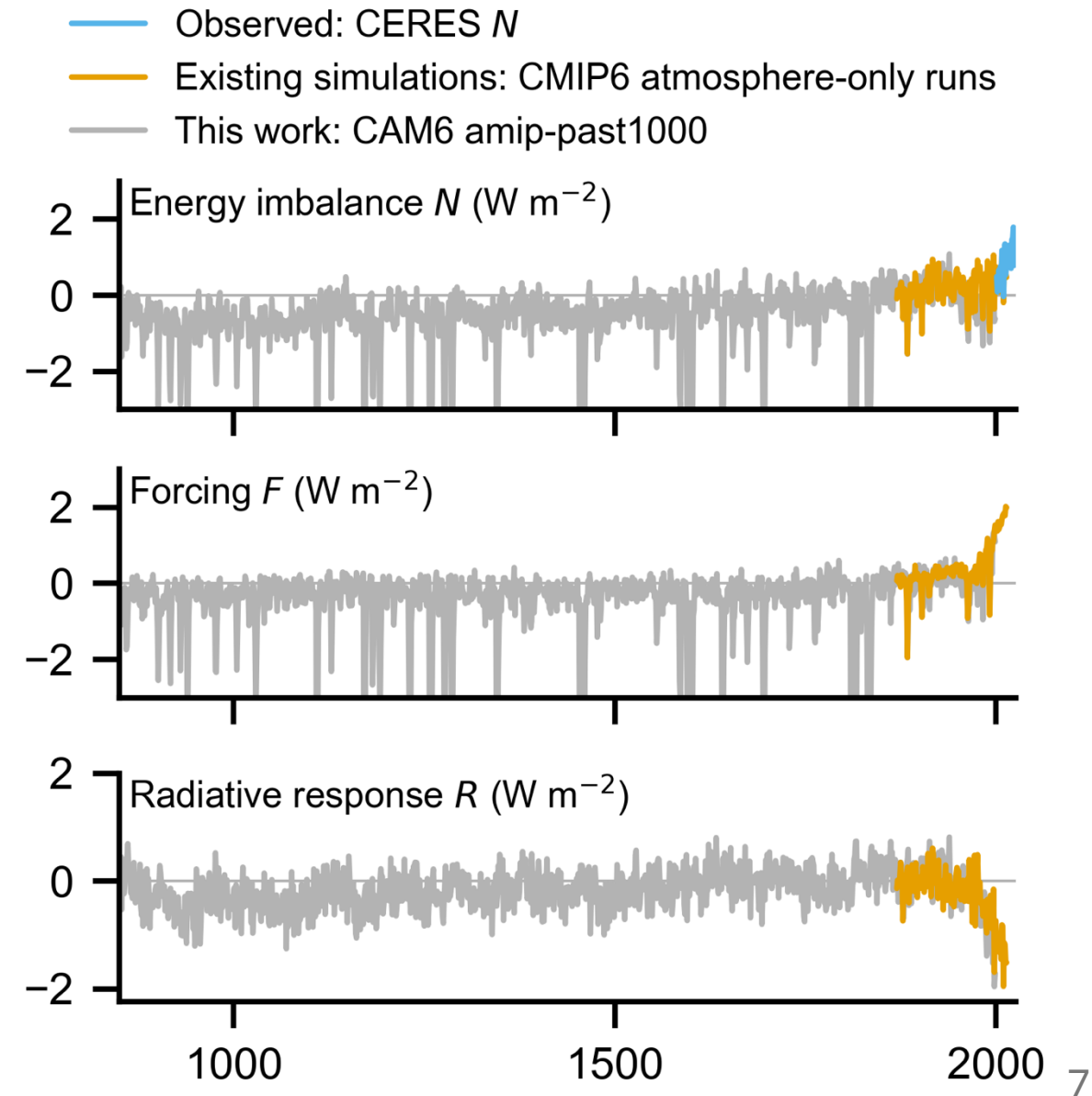
What we have learned
about the historical period:

- Radiative sensitivity differs by region
- Clouds respond to the warming pattern
- Feedbacks vary in time

What about the last millennium?
(850–1850)



The last millennium as a testbed

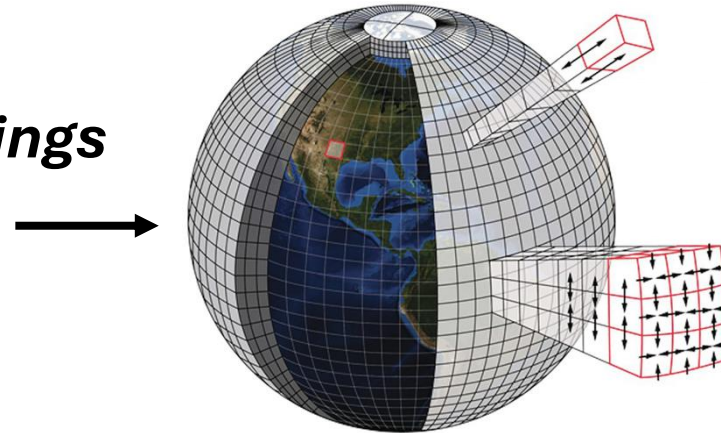


Atmosphere-only simulation over the last millennium

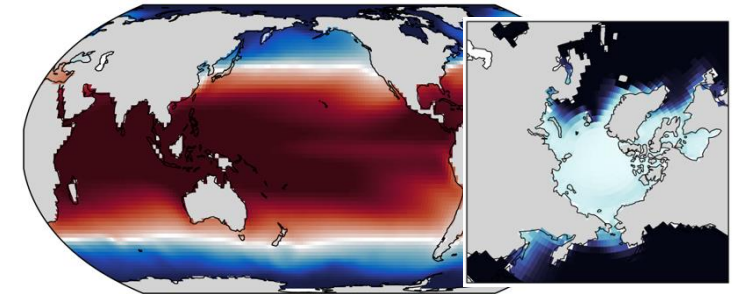
CMIP6 past1000 forcings

- Volcanic aerosols
- Solar
- Greenhouse gases
- ...

(Jungclaus et al., 2017)



CESM2/CAM6



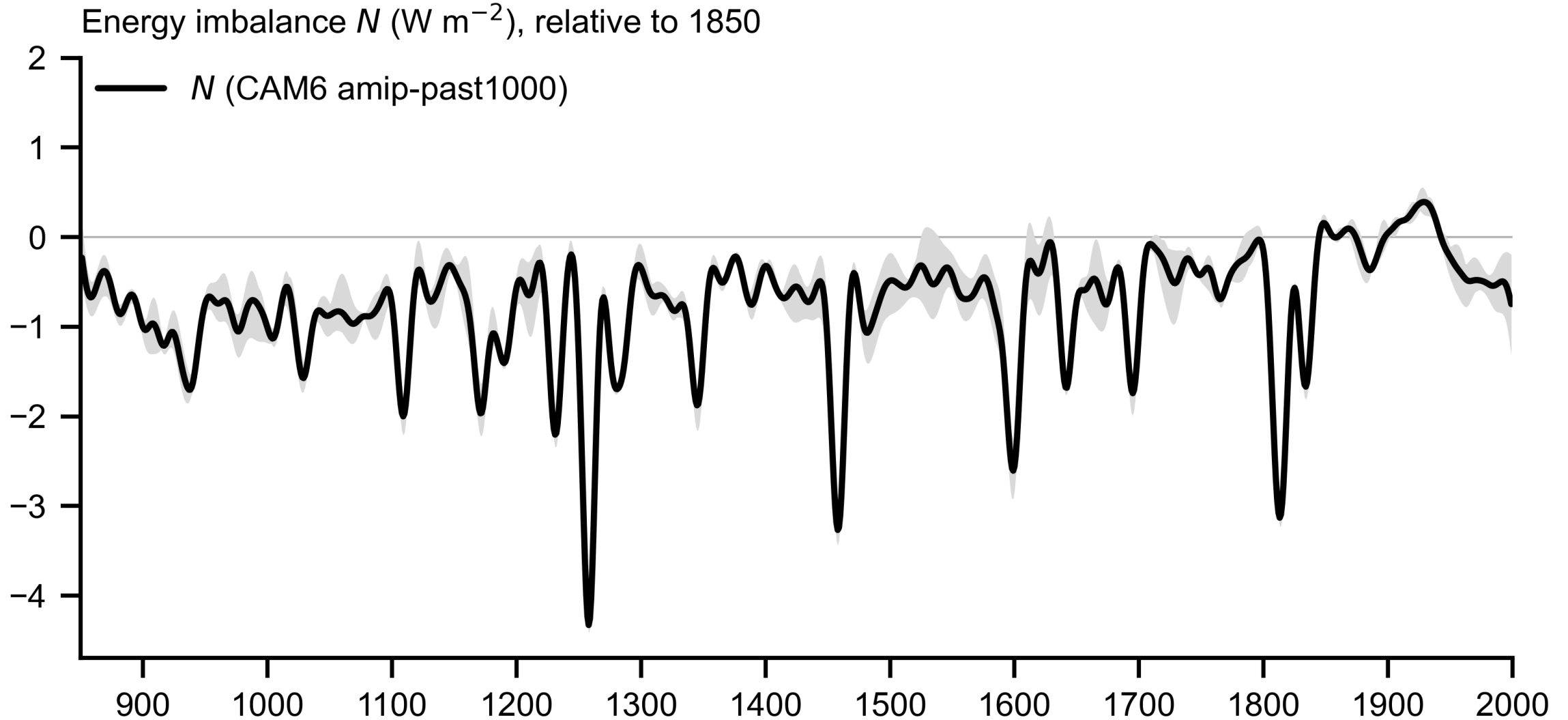
SST + sea ice
from proxy reconstruction
(Stiller & Hakim, 2026)

Two paired ensembles

	Gives us...	Forcing	SST/SIC
amip-past1000	N, F	Transient	Transient
amip-piForcing-past1000	R	Fixed (1850)	Transient

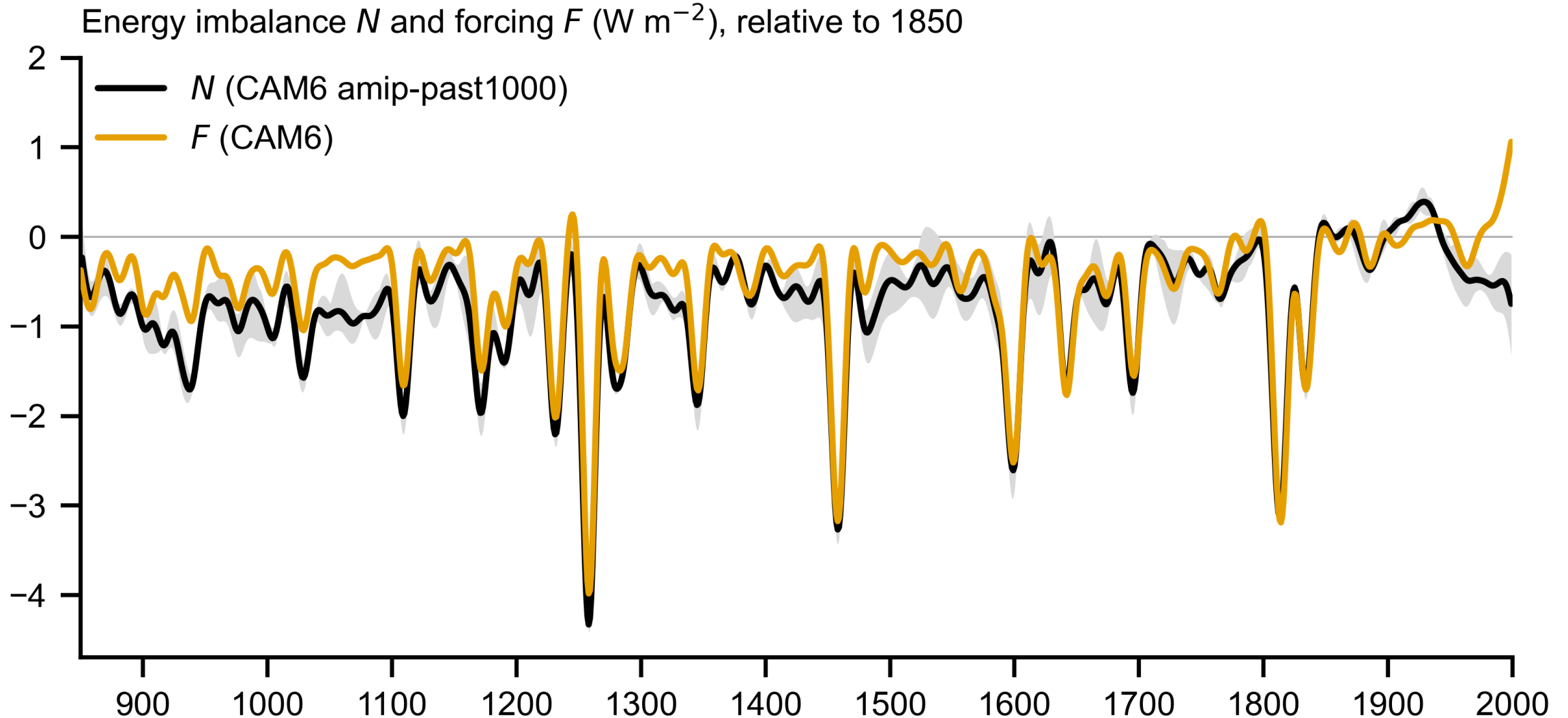
↑
3 members
=
3 plausible realizations
(pattern uncertainty)

Energy is lost throughout the last millennium



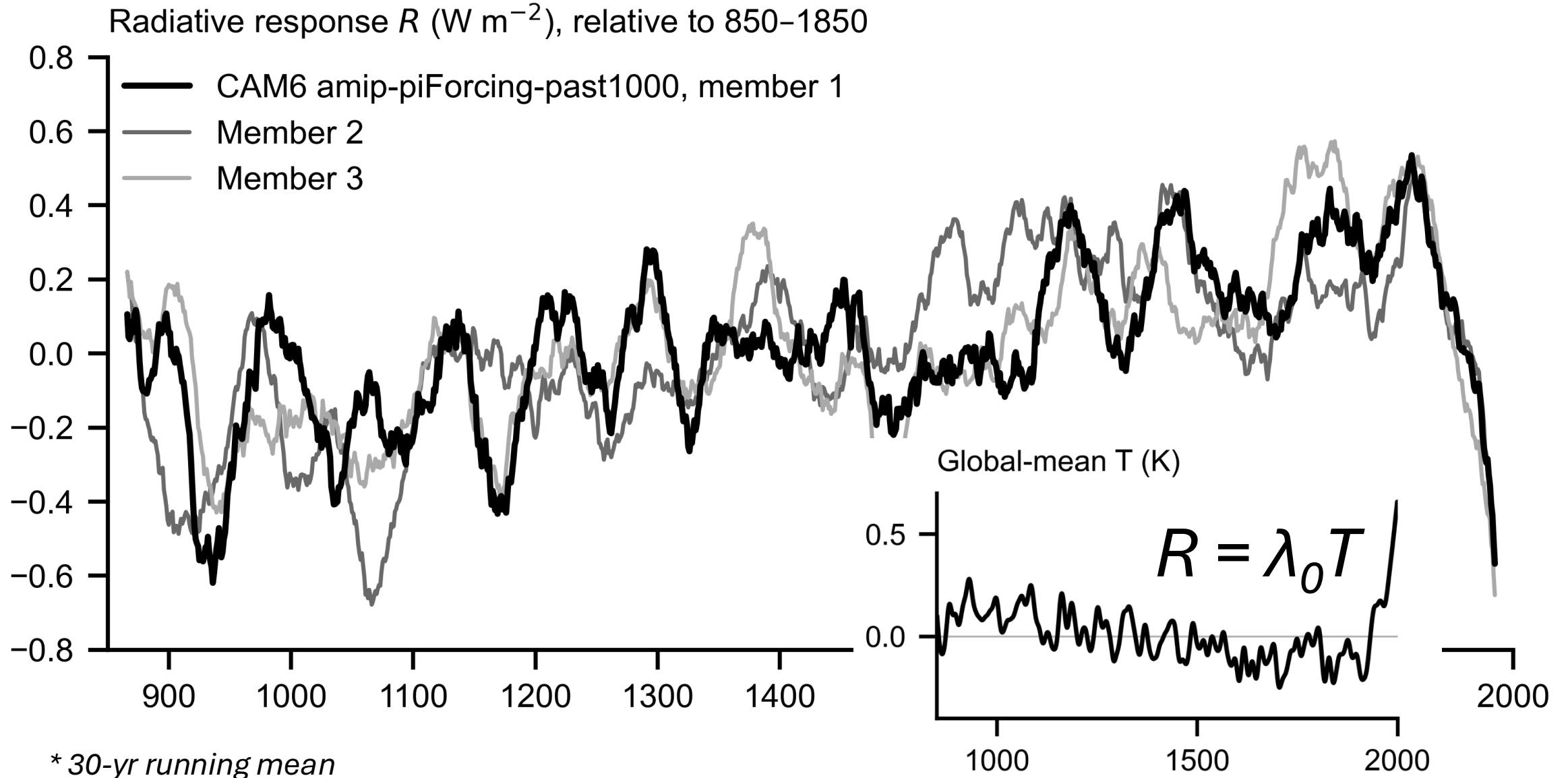
* 20-yr lowpass, shading = member spread

The forcing is dominated by volcanic eruptions

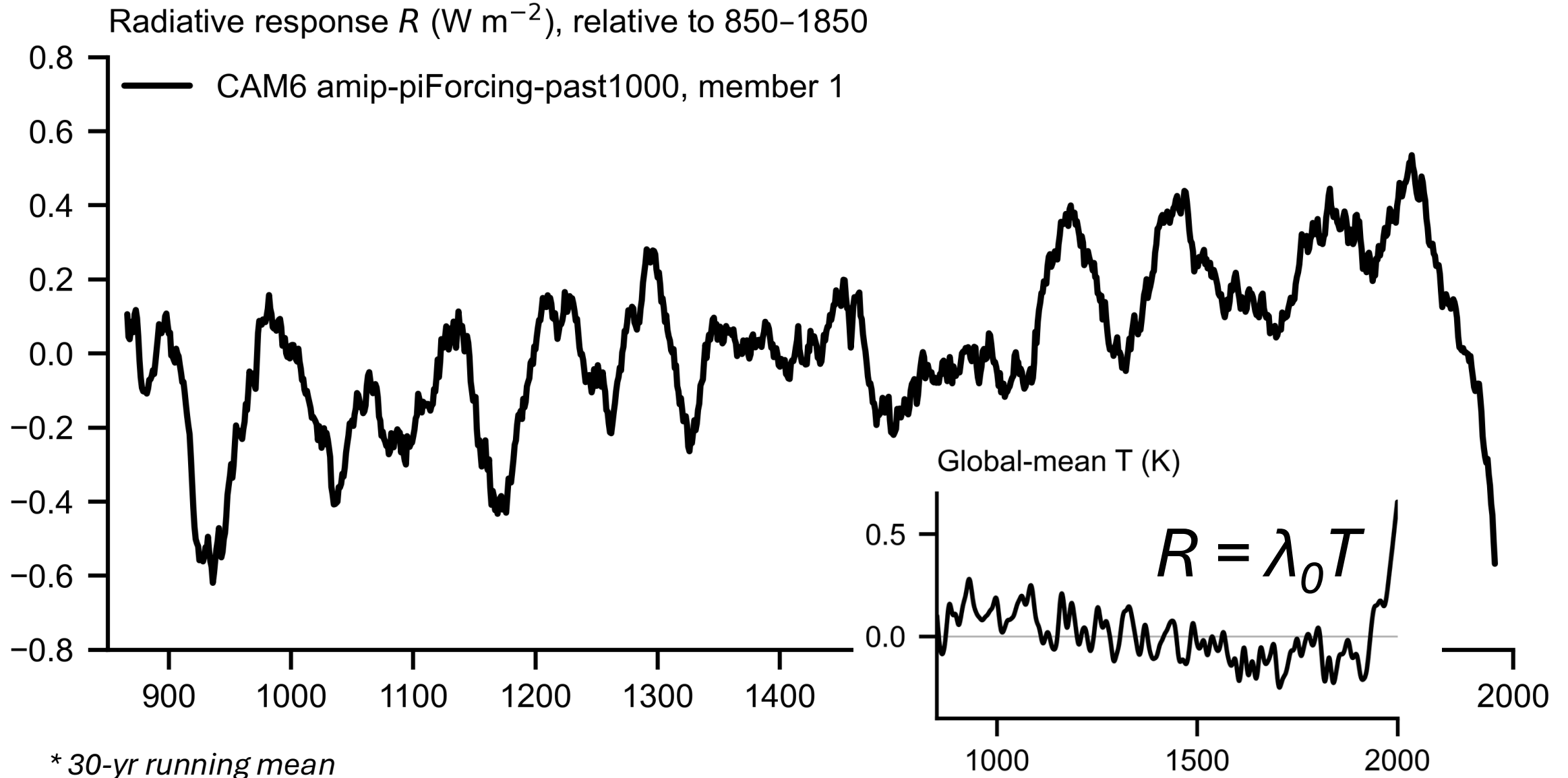


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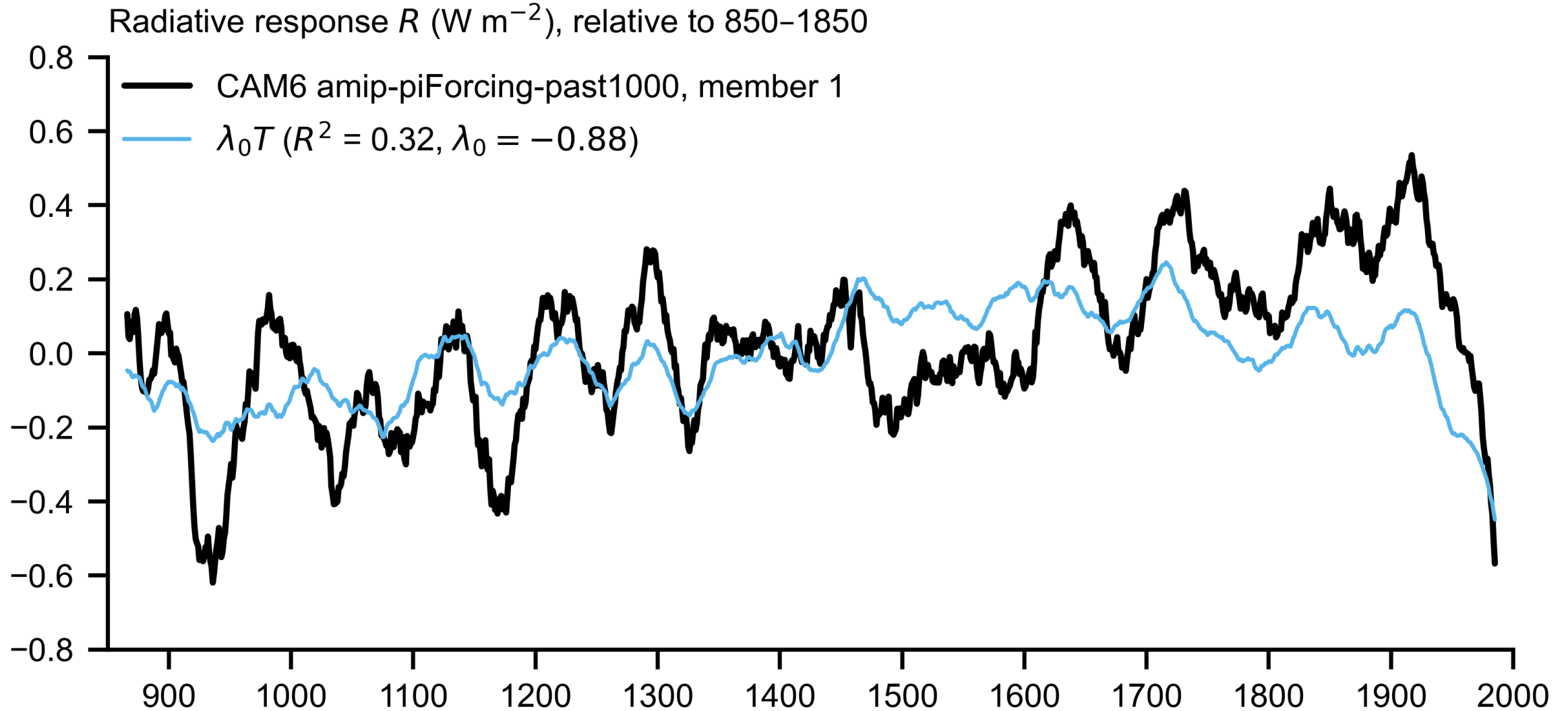
The radiative response has a millennial trend



The radiative response has a millennial trend

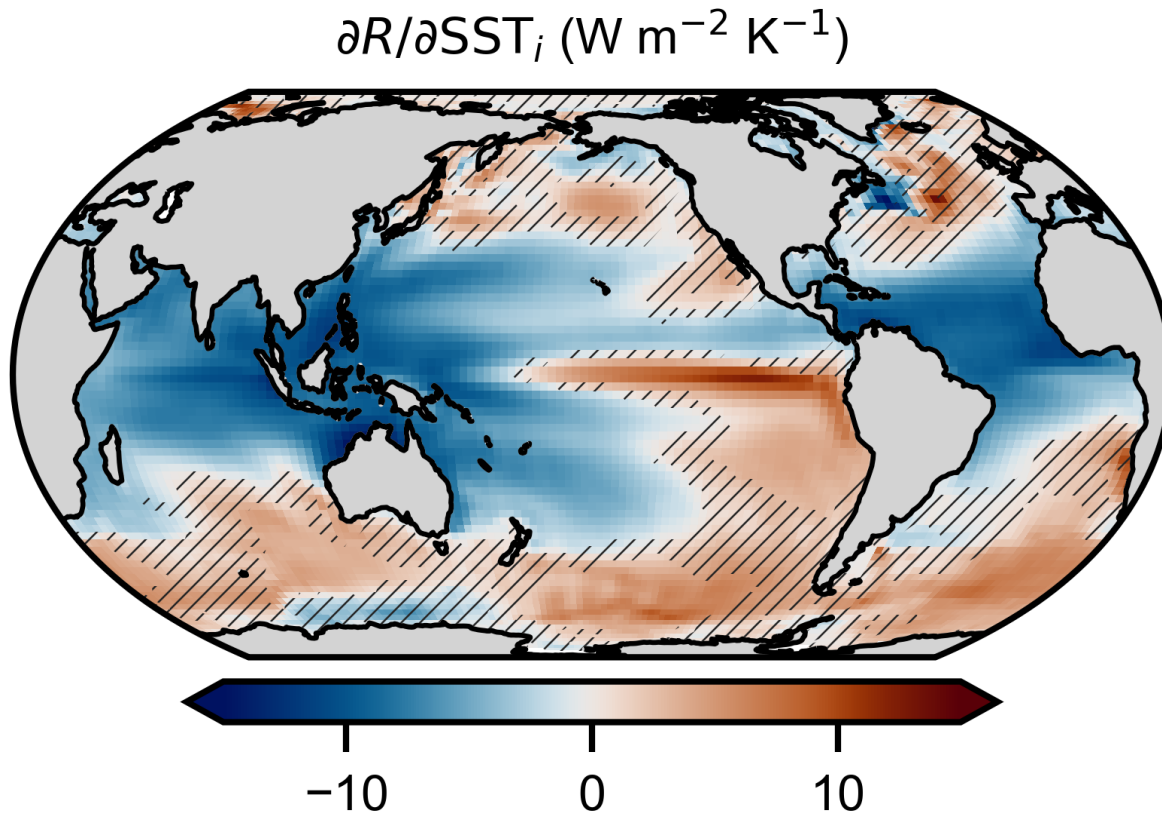


Global T explains some of the radiative response, but not all



* 30-yr running mean

Regional feedbacks from empirical Green's function



* *Hatching = member-fits disagree in sign*

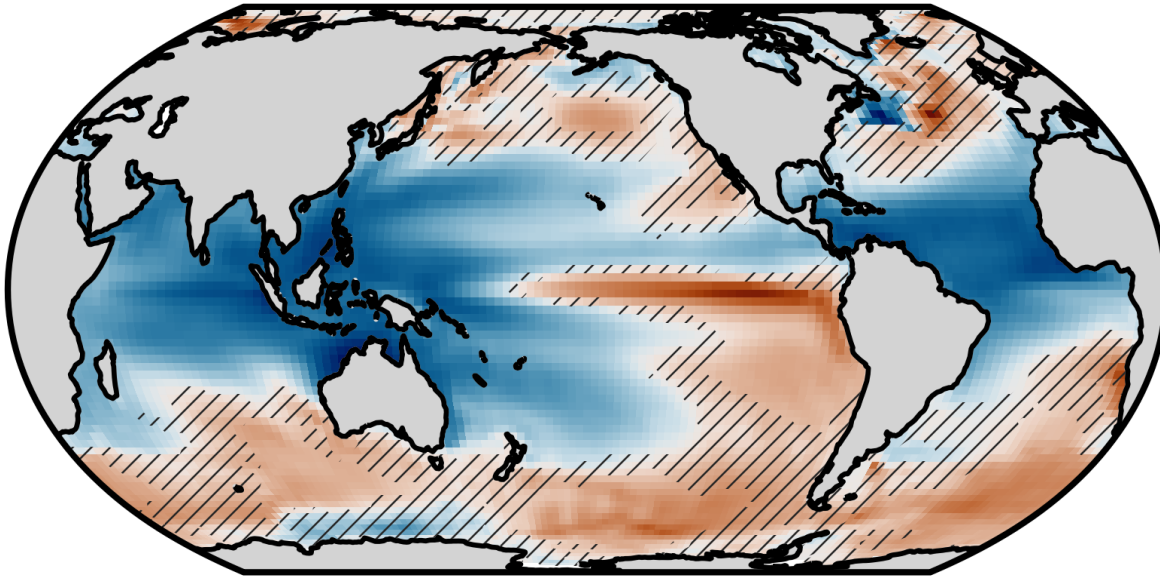
AMIP ridge regression

(Kang et al., 2023; Ceppi & Nowack, 2021; Fredericks et al., 2026)

- Global mean removed, which is absorbed by T
- On 10-yr means
- ~7000 member-years
- Held-out skill (30-yr R): $R^2 = 0.84$

Regional feedbacks from empirical Green's function

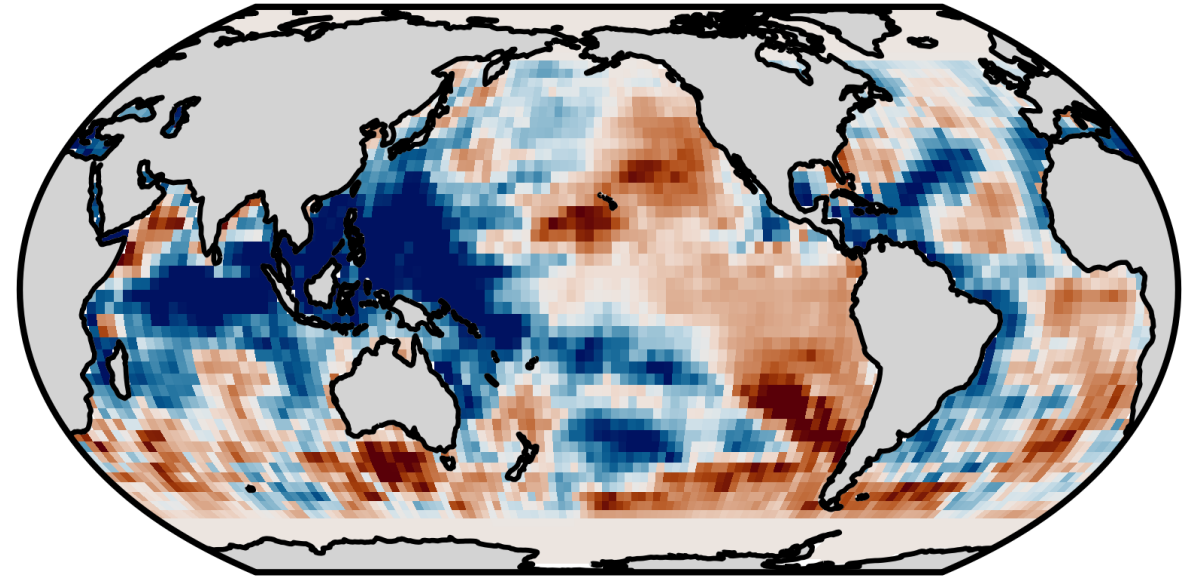
$$\partial R / \partial \text{SST}_i \text{ (W m}^{-2} \text{ K}^{-1}\text{)}$$



-10 0 10

CAM6 amip-piForcing-past1000
(this work)

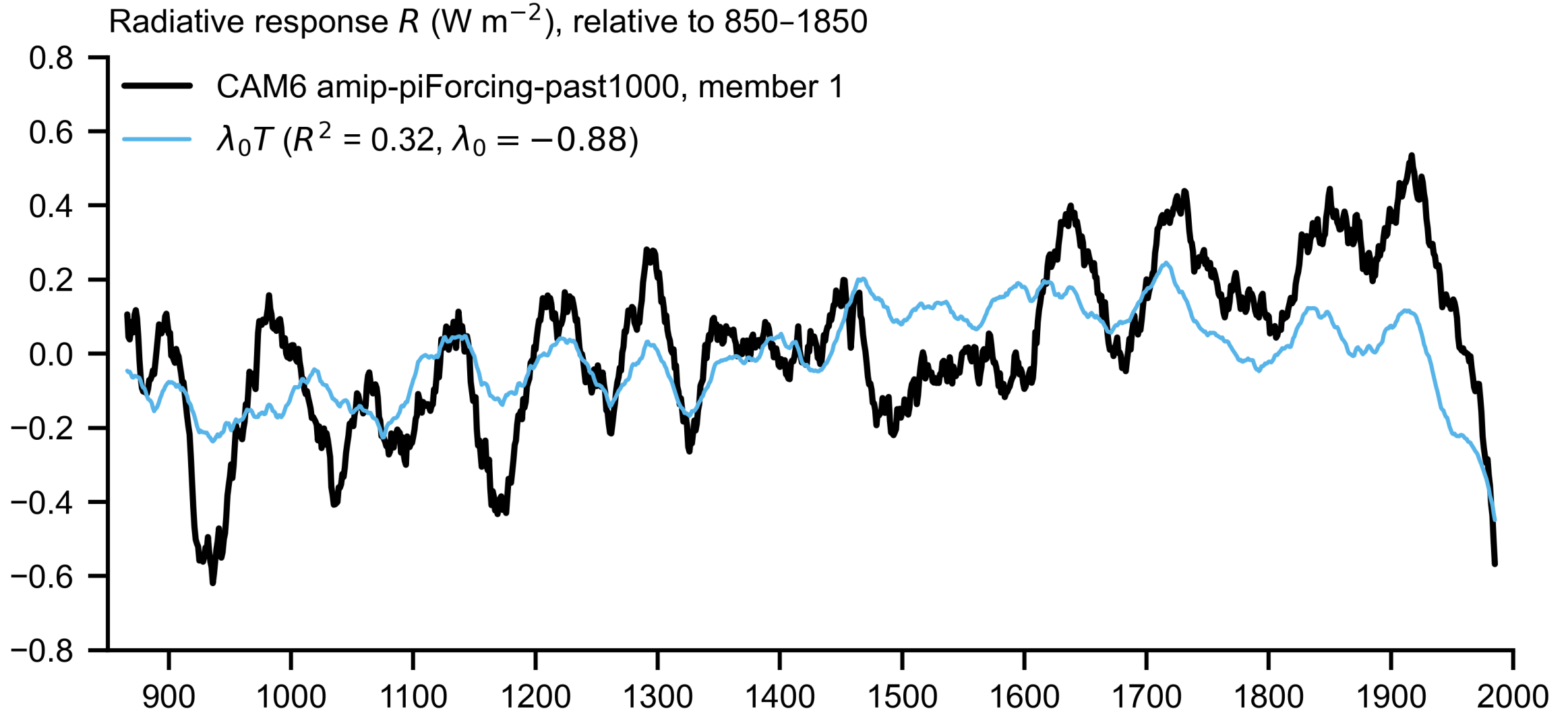
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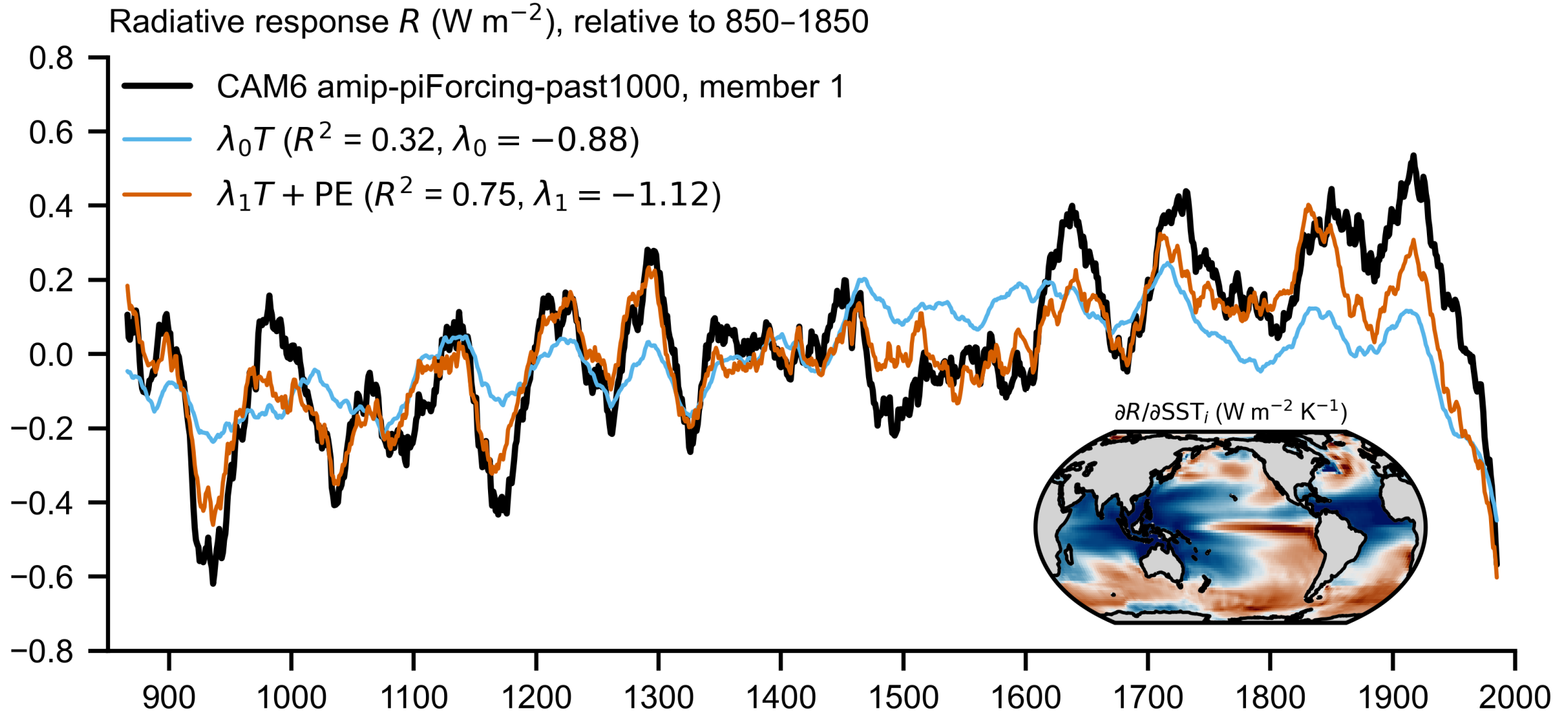
CAM6 historical amip-piForcing
(Kang et al., 2023)

Global T explains some of the radiative response, but not all



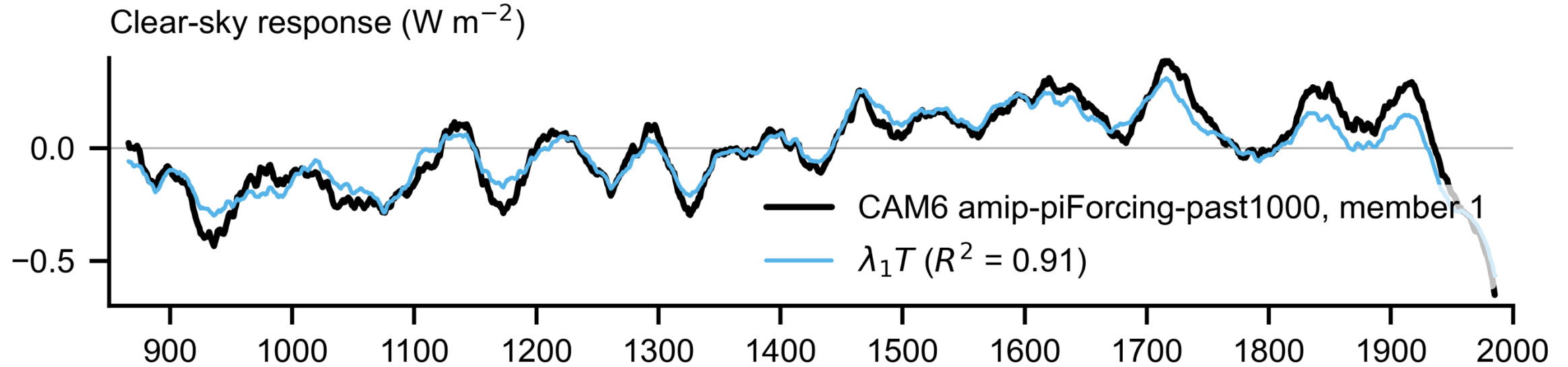
* 30-yr running mean

The SST pattern explains the rest of the radiative response



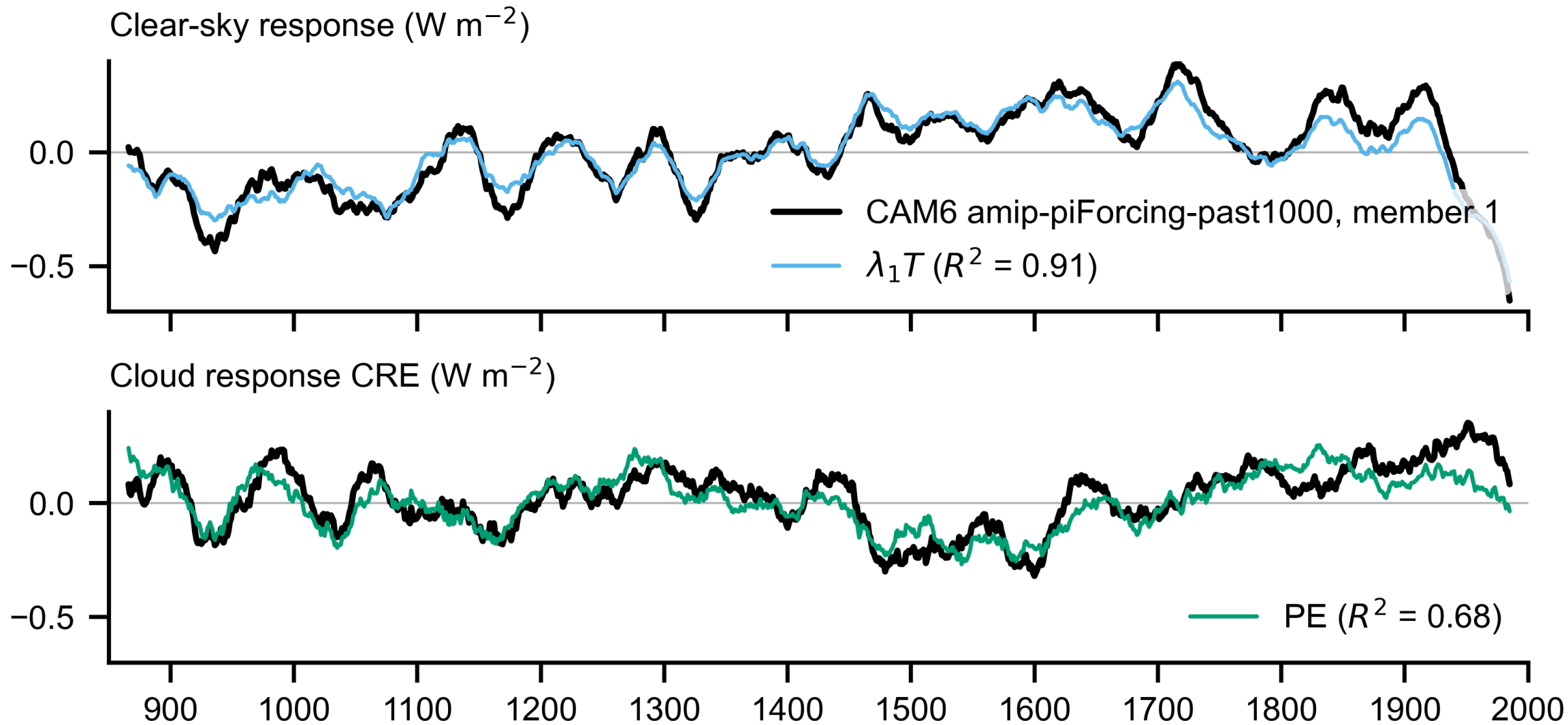
* 30-yr running mean

Clear sky follows T, clouds follow the pattern



* 30-yr running mean

Clear sky follows T, clouds follow the pattern



* 30-yr running mean

Two perspectives on the **pattern effect**

Explicit-PE perspective

$$R = \lambda_1 T(t) + \text{PE}(t)$$

(e.g., Ceppi & Gregory, 2019;
Fueglistaler, 2019; Meyssignac et al., 2023,
Stevens et al., 2026)

Time-varying- λ perspective

$$R = [\lambda_1 + \Delta\lambda(t)]T(t)$$

(e.g., Zhou et al., 2016; Andrews et al., 2022)

$$\Delta\lambda(t) = \frac{\text{PE}(t)}{T(t)}$$

Two perspectives on the **pattern effect**

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Time-varying- λ perspective

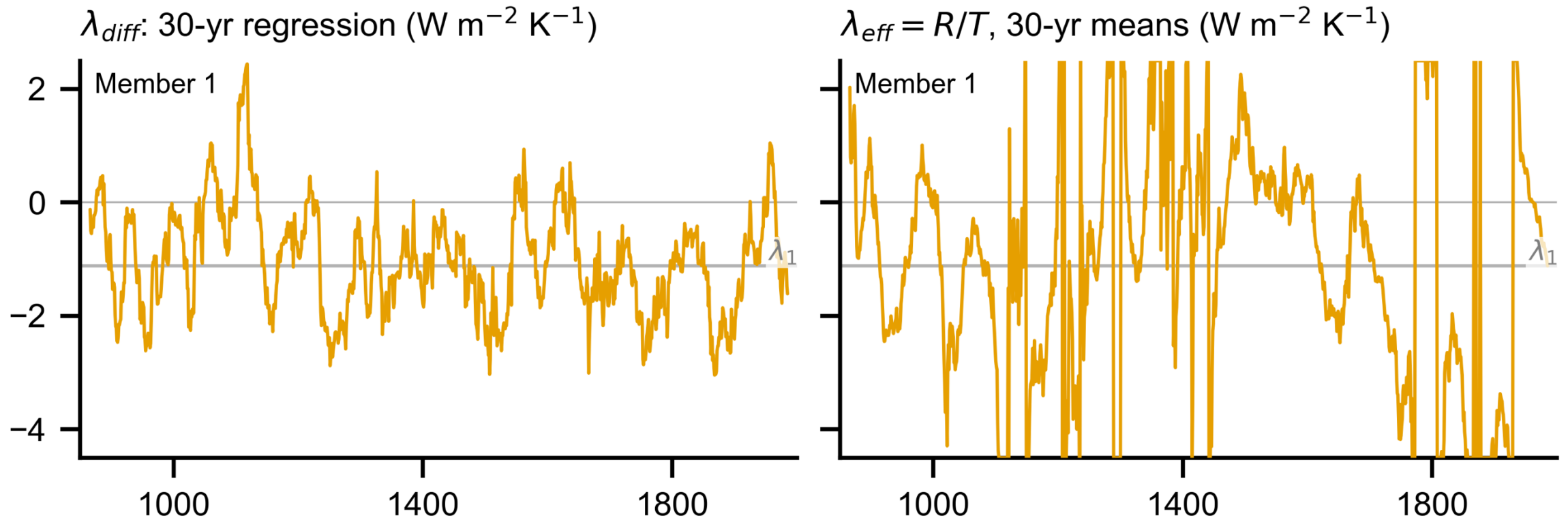
$$R = [\lambda_1 + \Delta\lambda(t)]T(t)$$

Defining $\lambda(t)$ only makes sense if PE and T are related!

$$\Delta\lambda(t) = \frac{\text{PE}(t)}{T(t)}$$

Time-varying λ is meaningful only if the pattern follows T

What happens if we estimate $\lambda(t)$ over the last millennium?

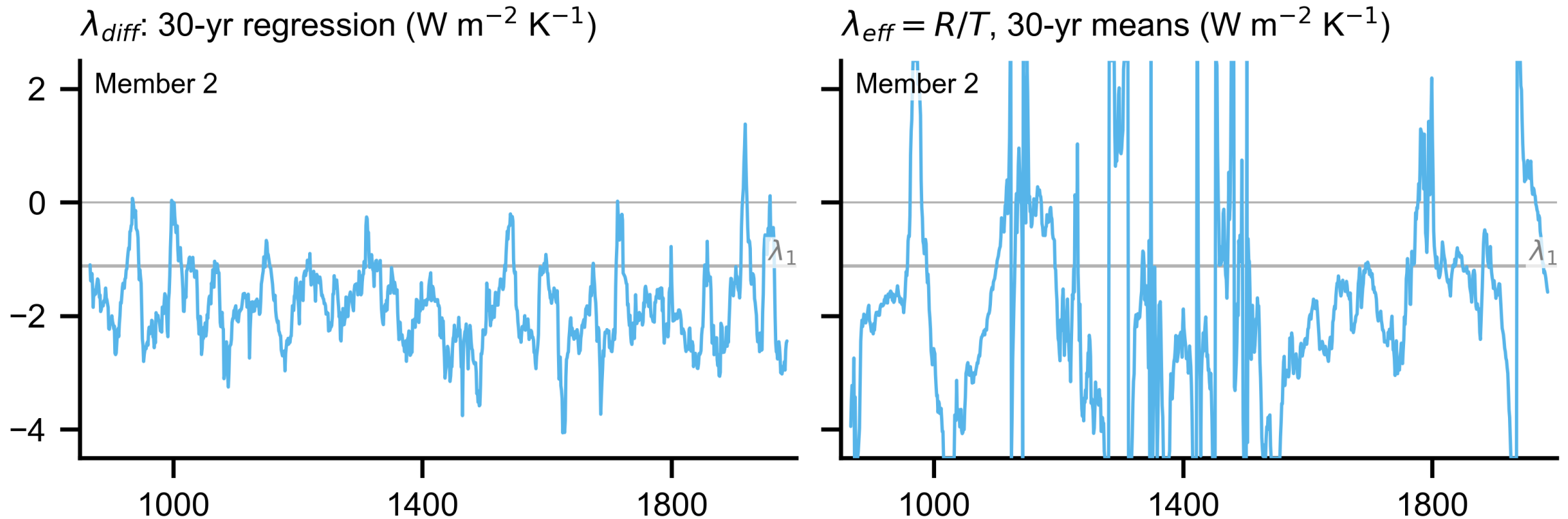


PE attributed to T variability in window
→ random regression slope

PE attributed to window-mean T
→ division by zero

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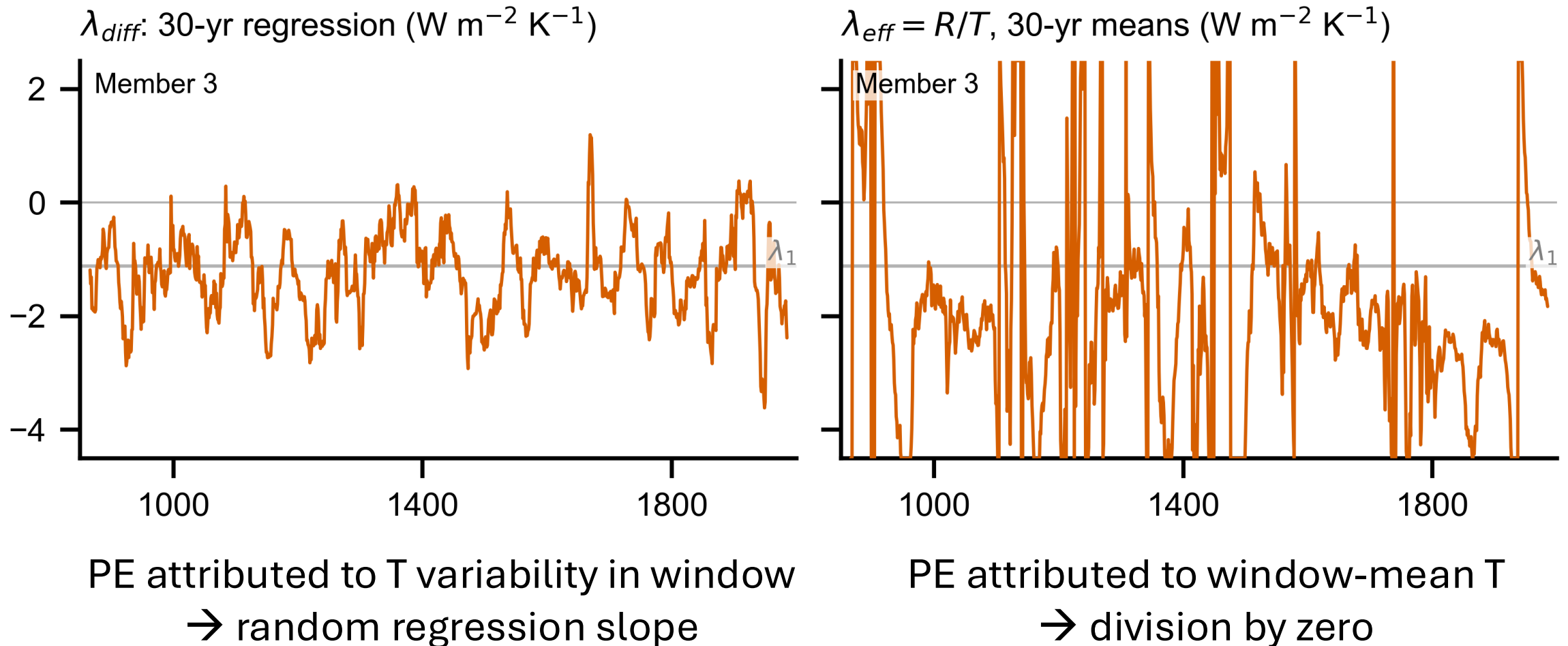


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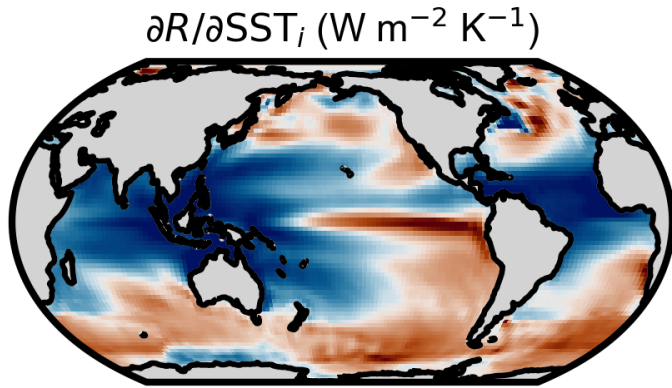
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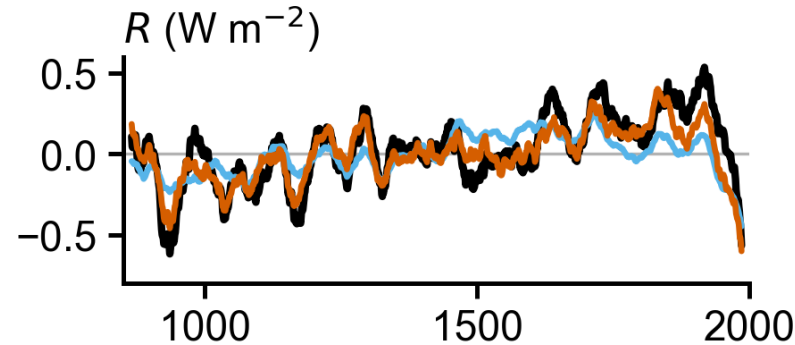
Conclusion: Feedbacks over the last millennium

Physics



Similar regional sensitivities from two very different records

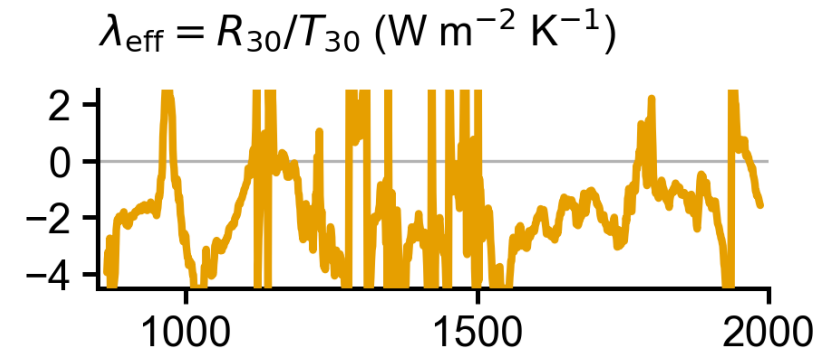
Pattern effect



$$R = \lambda_1 T(t) + \text{PE}(t)$$

The pattern effect is a first-order term over the last millennium

Time-varying λ



$$R = [\lambda_1 + \Delta\lambda(t)]T(t)$$

Meaningful only if the pattern follows T
(holds under forced warming,
not under internal variability)