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Transient atmosphere-only simulations over the last millennium constrained by proxies

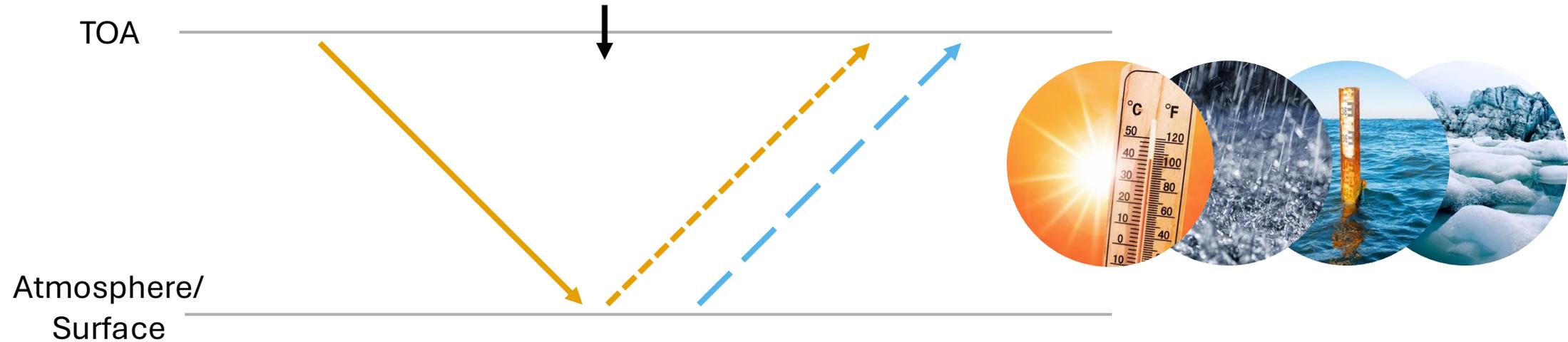
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Earth's energy imbalance (EEI) is a fundamental climate metric



$\sim 340 \text{ W m}^{-2}$

$\sim 100 \text{ W m}^{-2}$

$\sim 240 \text{ W m}^{-2}$

(present-day values)

$$\text{EEI} = \text{incoming solar} - \text{reflected SW} - \text{outgoing LW}$$



Energy imbalance

Reflected solar radiation Thermal radiation

Positive = net gain
Negative = net loss

Separation of forcing and response

$$EEI = F + R(T)$$

Radiative forcing

Independent of surface temperature
CO₂, volcanic, orbital, ...

Climate feedback parameter

$$R = \lambda \bar{T}$$

Radiative response/feedback

Varies with surface temperature
(**global mean** and pattern)

will be important later

The last millennium (850–2000) provides context for recent energy budget trend

The 2012-2024 EEI is $+1.0 \text{ W m}^{-2}$ (Forster et al. 2025)

- How much is anthropogenic vs natural variability?
- How unprecedented is this imbalance?

→ **Natural (pre-1850) variability provides context!**

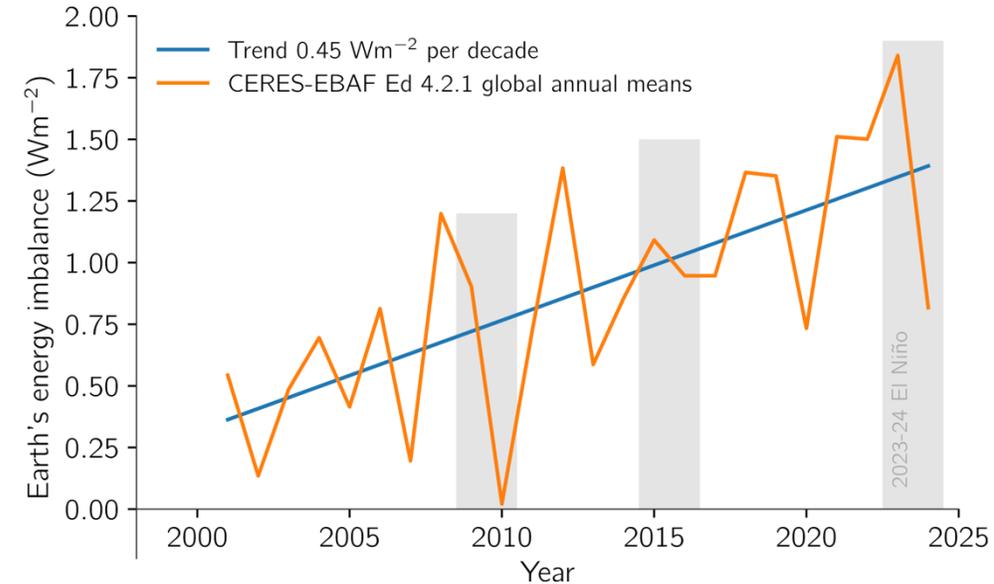


Figure from Mauritsen et al. (2025)

Science questions:

Over the last millennium, ...

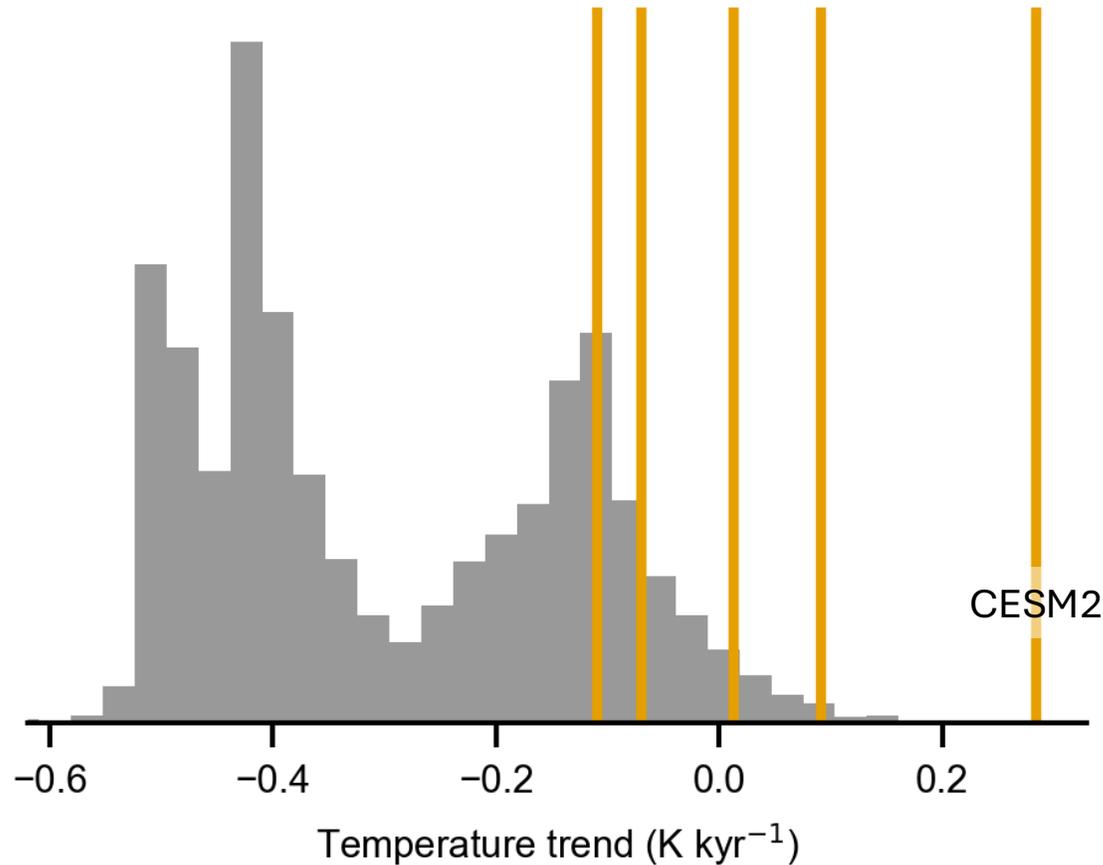
1. How did the **energy imbalance** vary?
2. What were the relative contributions of **F** and **R**?
3. What controlled time variations in **R**?

$$\mathbf{EEI} = \mathbf{F} + \mathbf{R(T)}$$

Coupled models misrepresent GMST and energy imbalance

Wrong temperature trend

GMST trend (850–1850) in CMIP6 past1000



■ Proxies (PAGES 2k, 2019) — Coupled simulations

Underestimated radiative response

EEl trend (2001–2022) in CMIP5/6 large ensembles

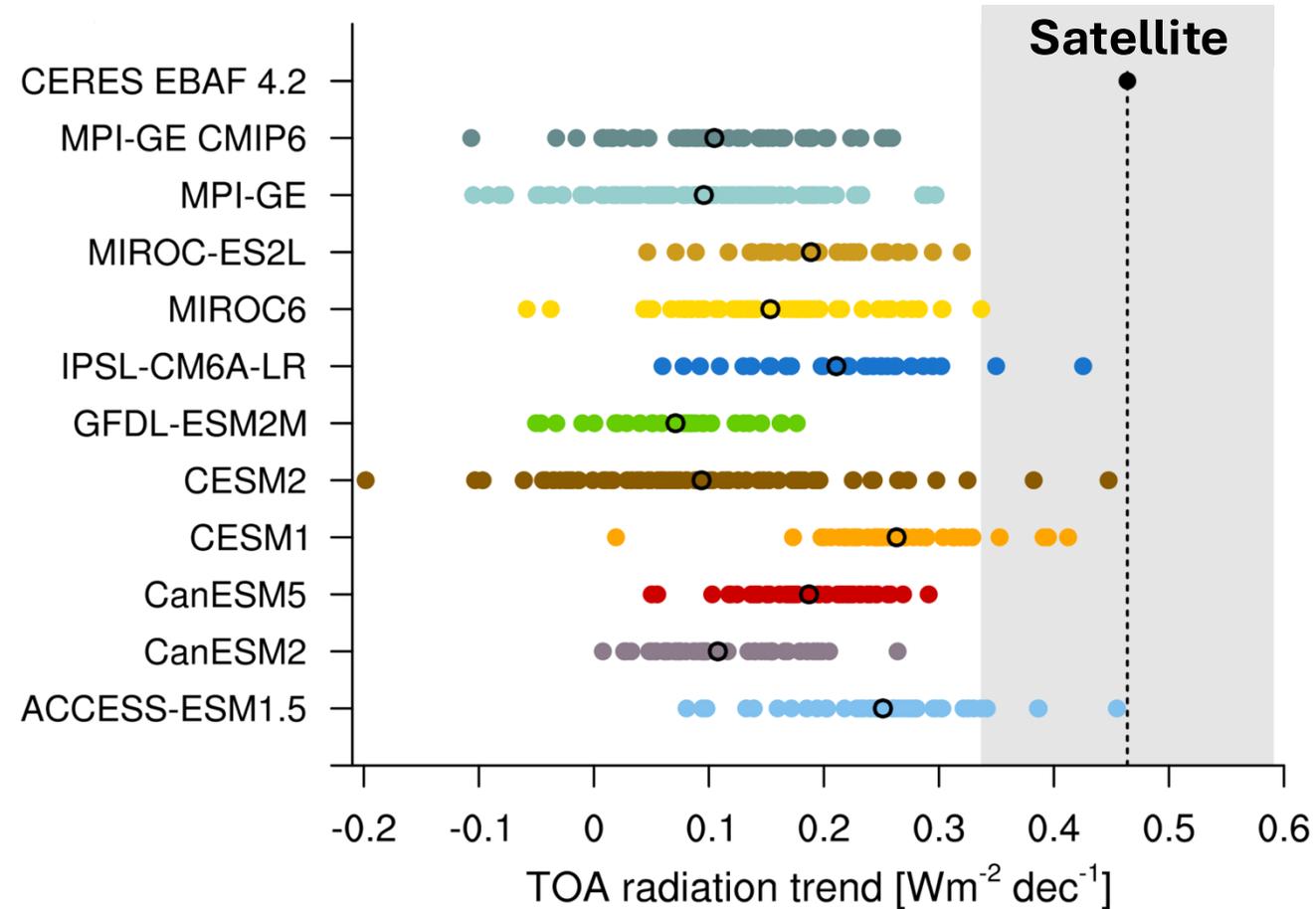


Figure from Olonscheck & Rugenstein (2024)

Atmosphere-only models with prescribed SST + sea ice successfully track the energy imbalance

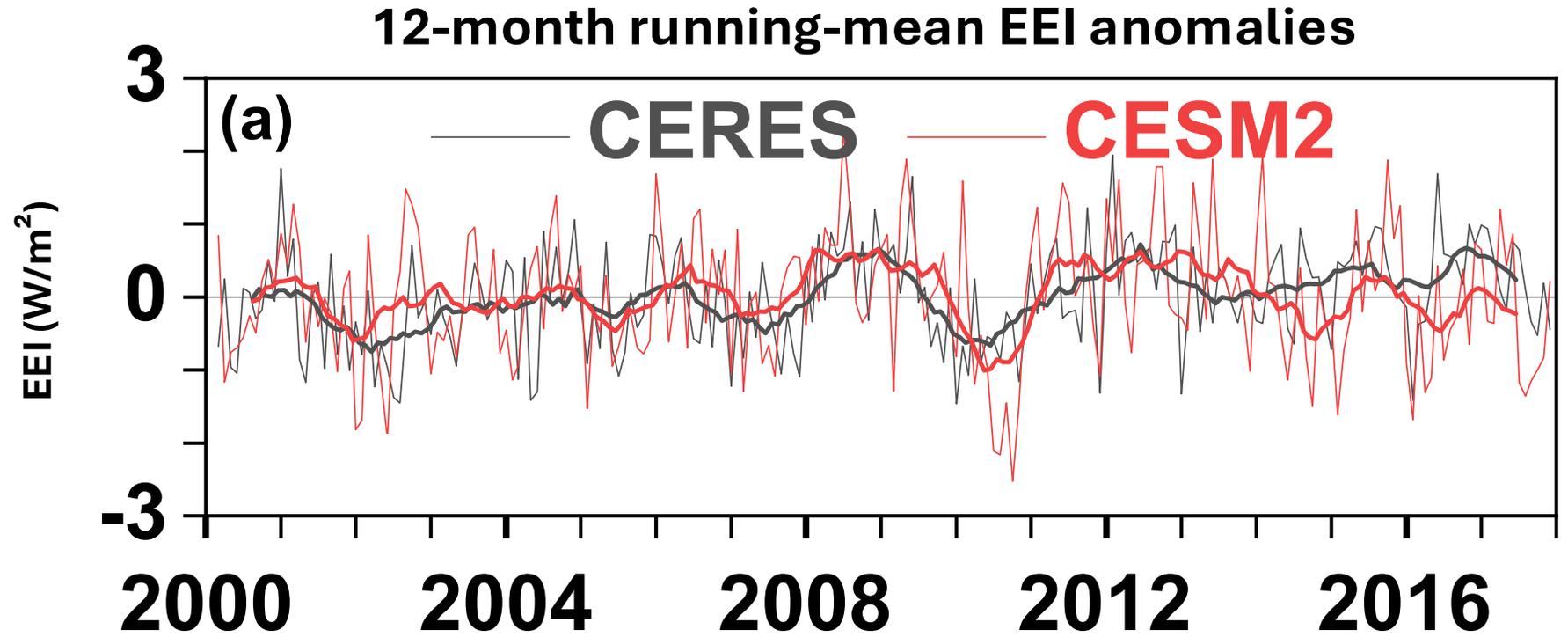


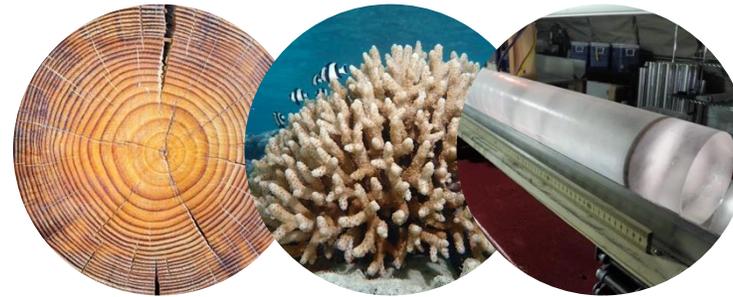
Figure from Loeb et al. (2020)

+ we can separate forcing and response

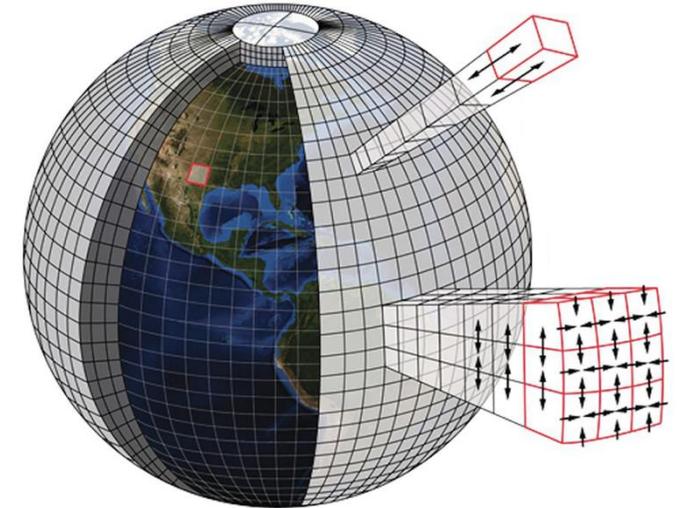
Novel atmosphere-only simulation over the last millennium

We present **transient atmosphere-only simulation over 850–2000 CE**

- SST and sea ice constrained by proxies
- With separated **forcing** and **response**



+

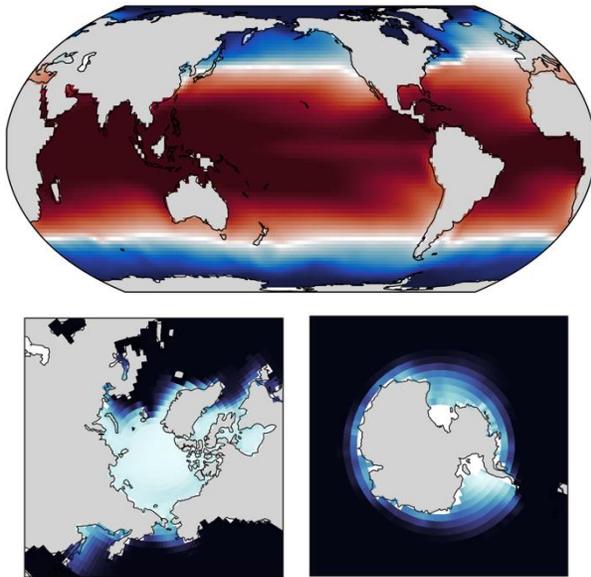


Agenda

- Simulation setup
- **Forcing** and **radiative response** over the last millennium
- Clouds controlled by SST patterns
- Variations in the feedback parameter λ

Novel atmosphere-only simulation over the last millennium

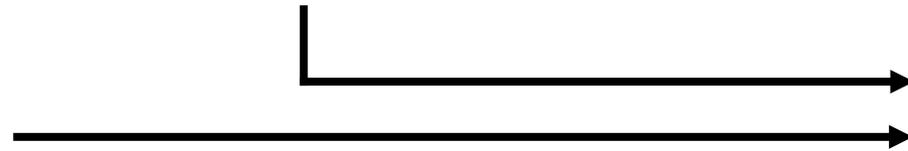
Seasonal, spatial SST and sea ice reconstruction



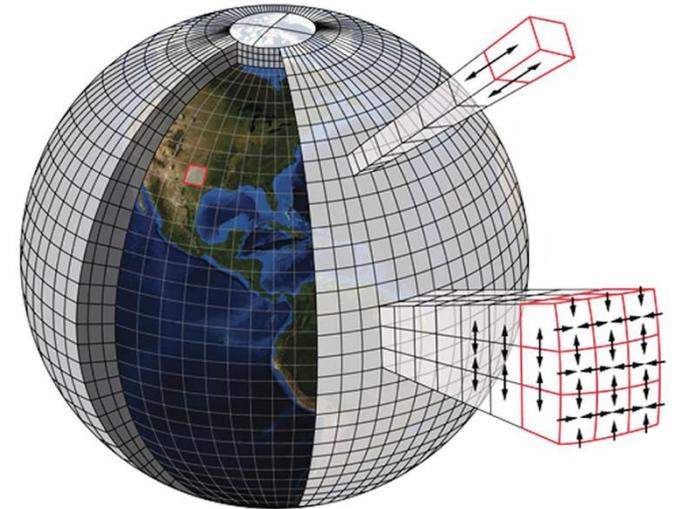
*From data assimilation of proxies
(Stiller & Hakim, in review)*

CMIP6 past1000 forcings

- Volcanic aerosols
- Greenhouse gases
- Solar
- Orbital
- Ozone
- Land use/land change



Atmosphere-only model

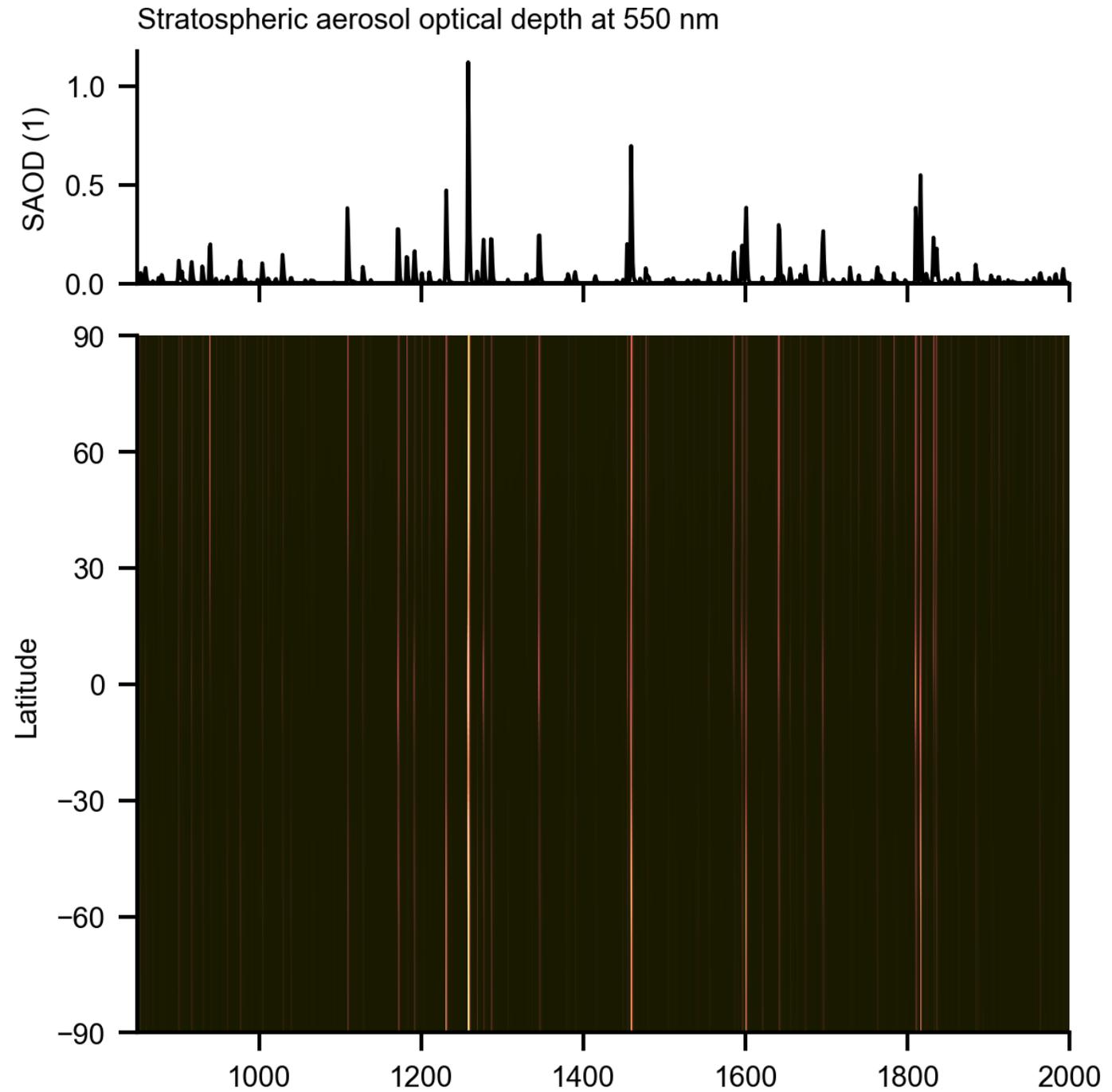


CESM2/CAM6
(2 deg, low top)

Volcanic forcing

Ens. mean of WACCM6 past1000

- 5-day zonal means
- As for CESM2 historical runs
- Method described in Danabasoglu et al. (2020)



Two ensembles of simulations to separate F and R

amip-past1000
Transient SST from DA
Transient forcing
 6×1150 years

amip-piForcing-past1000
Transient SST from DA
Pre-industrial forcing
 6×1150 years

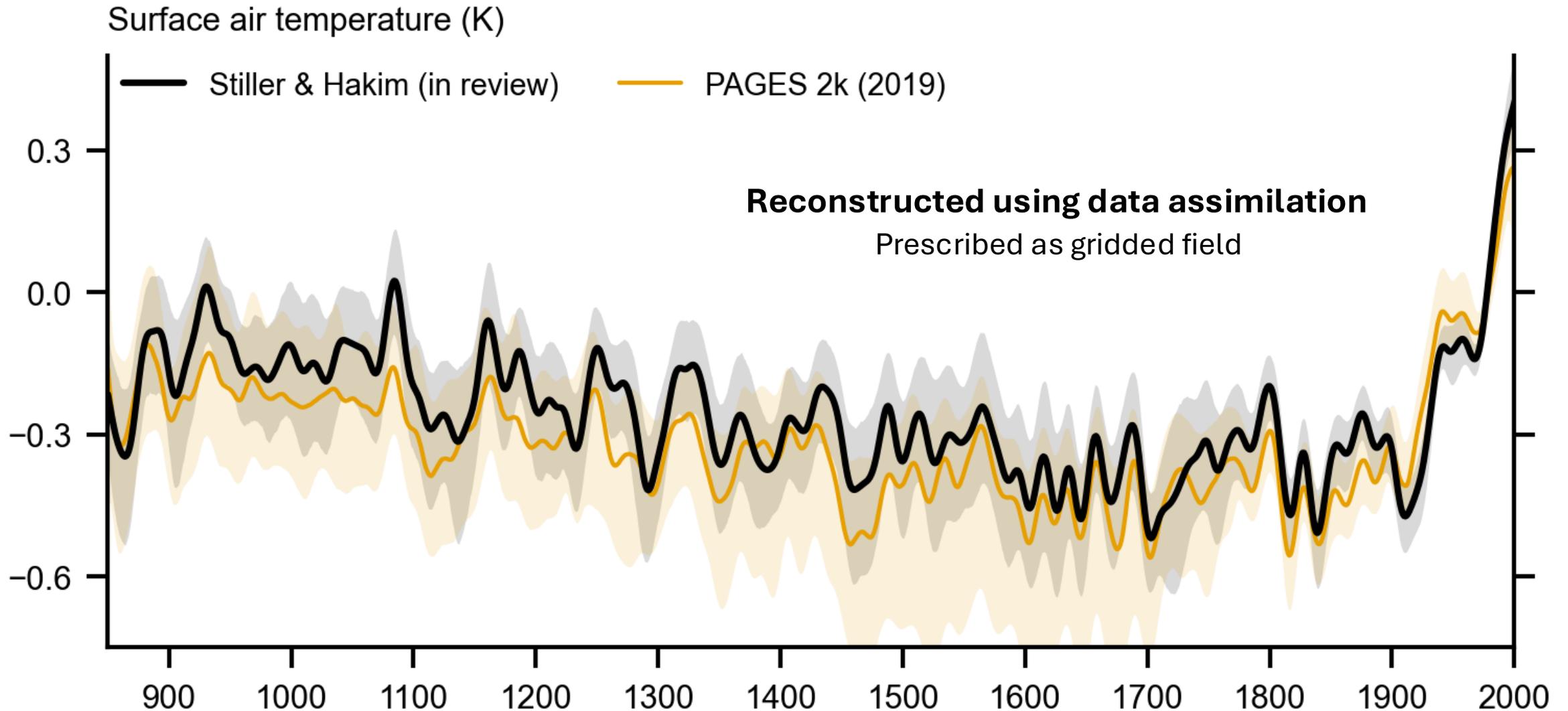
$$F = \boxed{F + R(T)} - \boxed{R(T)}$$

$$R = \boxed{R(T)} - \boxed{0}$$

Climatology

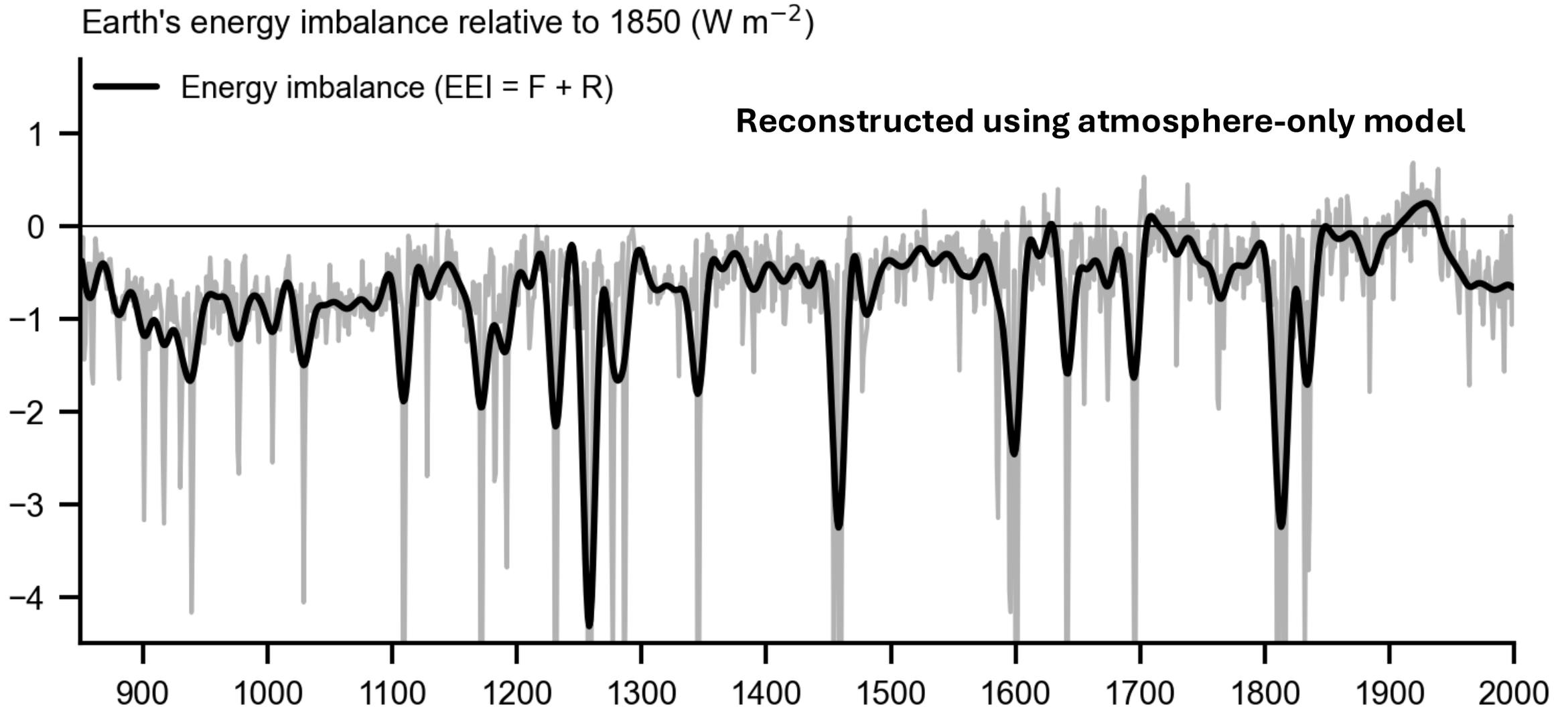
sampling uncertainty by
prescribing ensemble of SSTs

Prescribed surface temperatures cool over 850–1850



* Ensemble mean, anomalies relative to 1961-1990, 20-yr low-pass

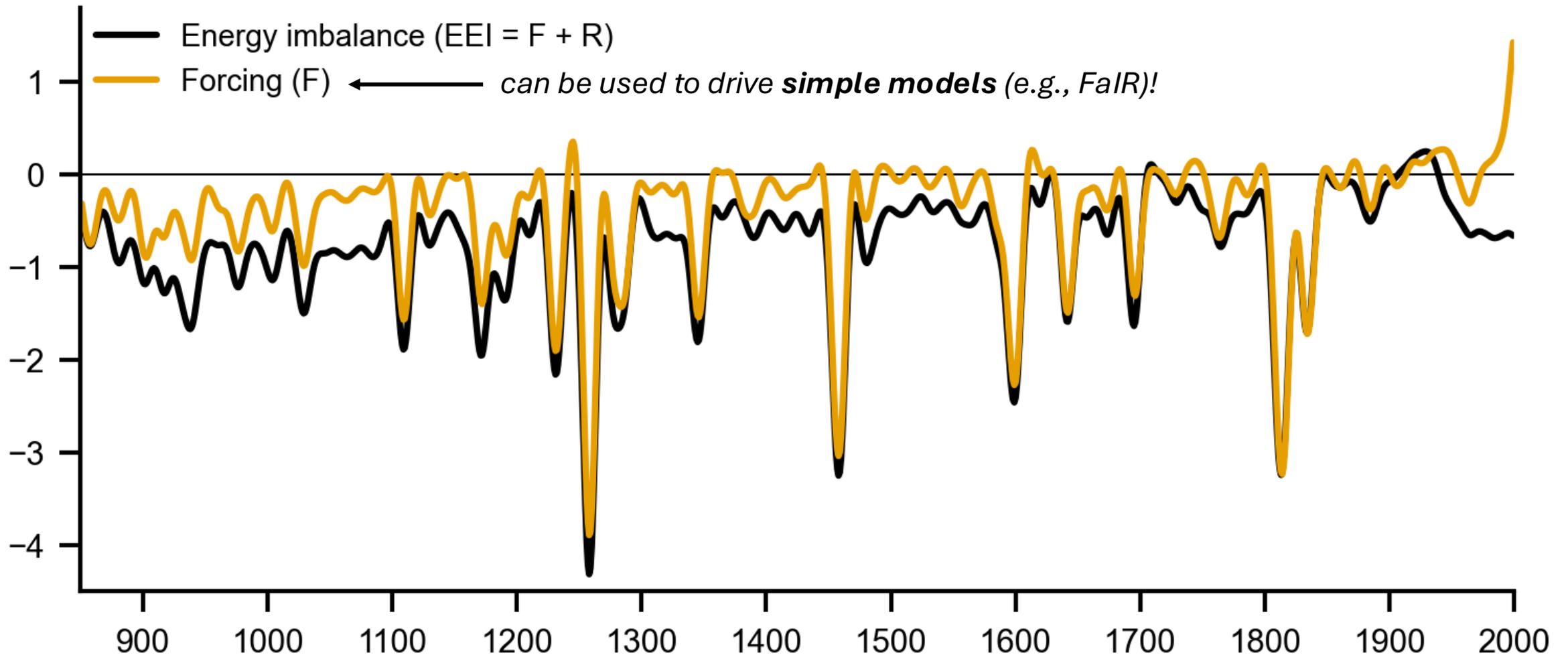
Energy loss associated with cooling trend



* Ensemble mean, 20-yr low-pass in bold, annual in light gray

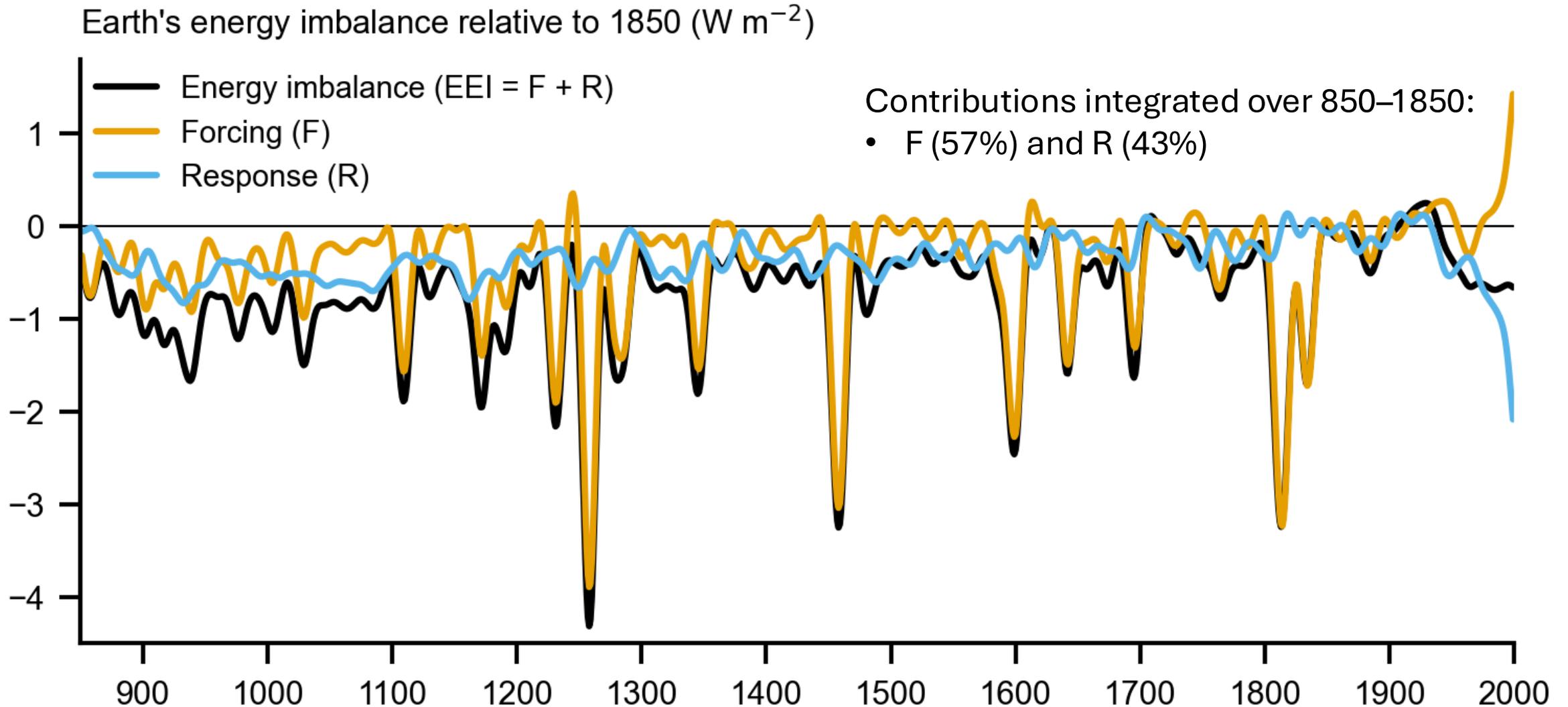
Forcing is dominated by volcanic eruptions

Earth's energy imbalance relative to 1850 (W m^{-2})



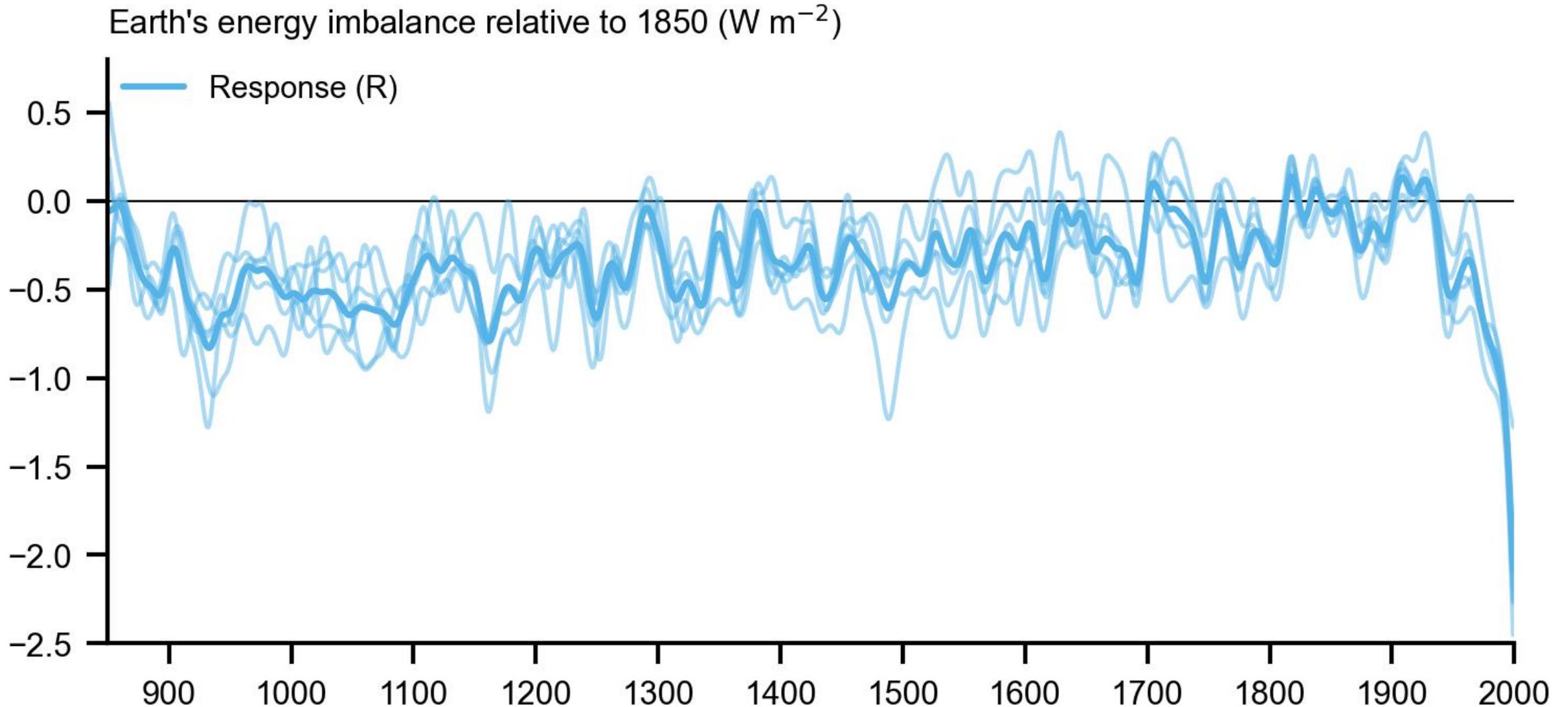
* Ensemble mean, 20-yr low-pass

Radiative response contributes 40% to the energy loss



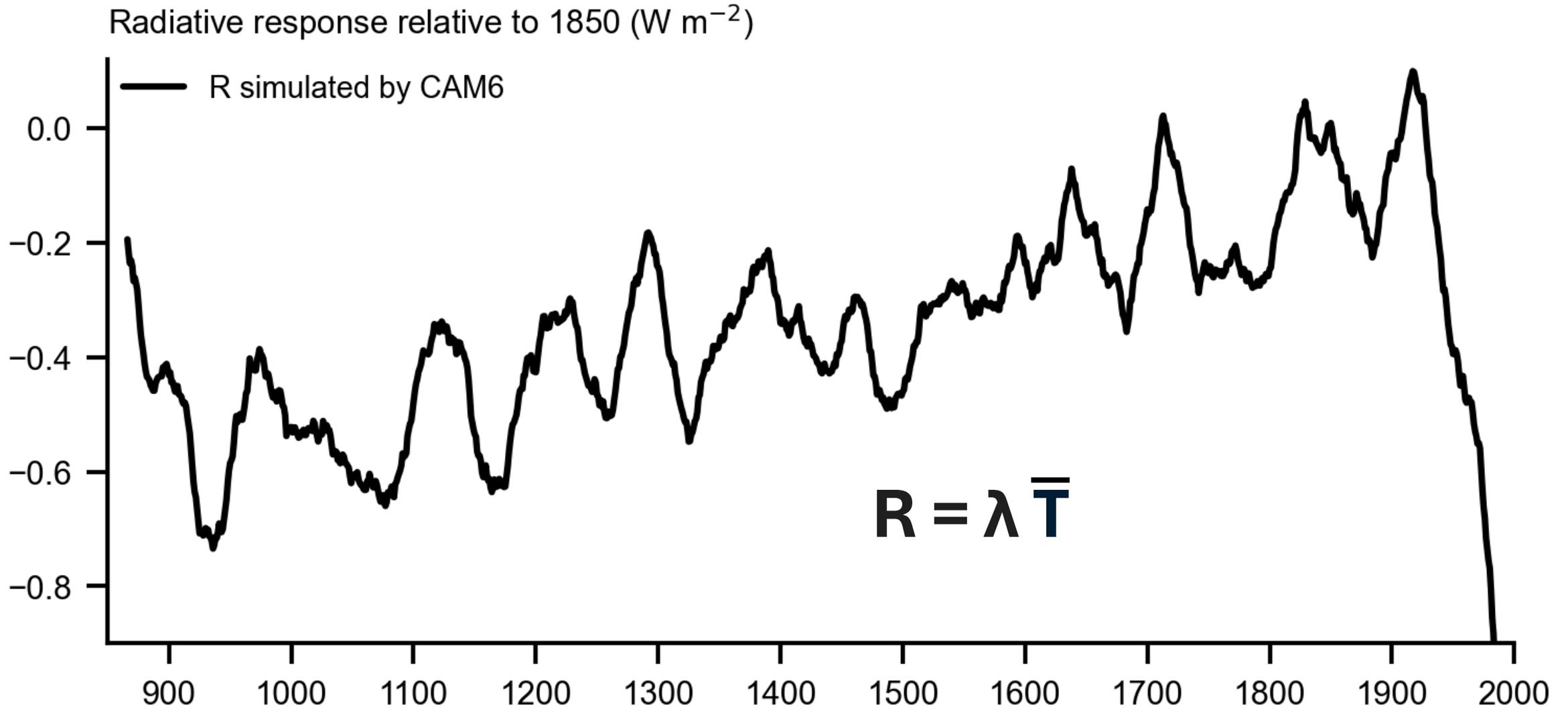
* Ensemble mean, 20-yr low-pass

Radiative response contributes 40% to the energy loss



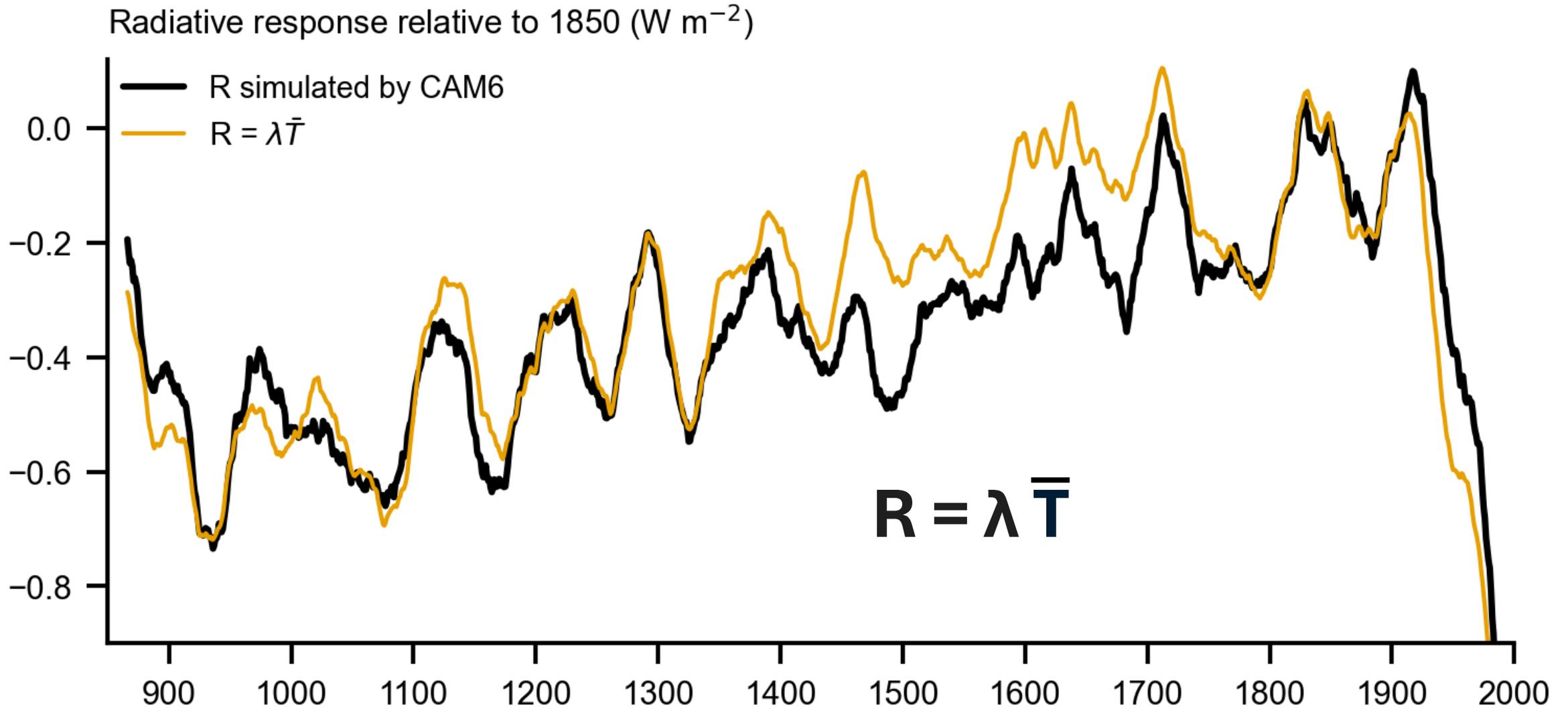
* Ensemble mean + 6 ensemble members, 20-yr low-pass

Radiative response contributes 40% to the energy loss



* Ensemble mean, 30-yr running mean

Radiative response is only partially explained by global-mean T



* Ensemble mean, 30-yr running mean

SST pattern, rather than global-mean T, controls low clouds

Low clouds reflect shortwave radiation

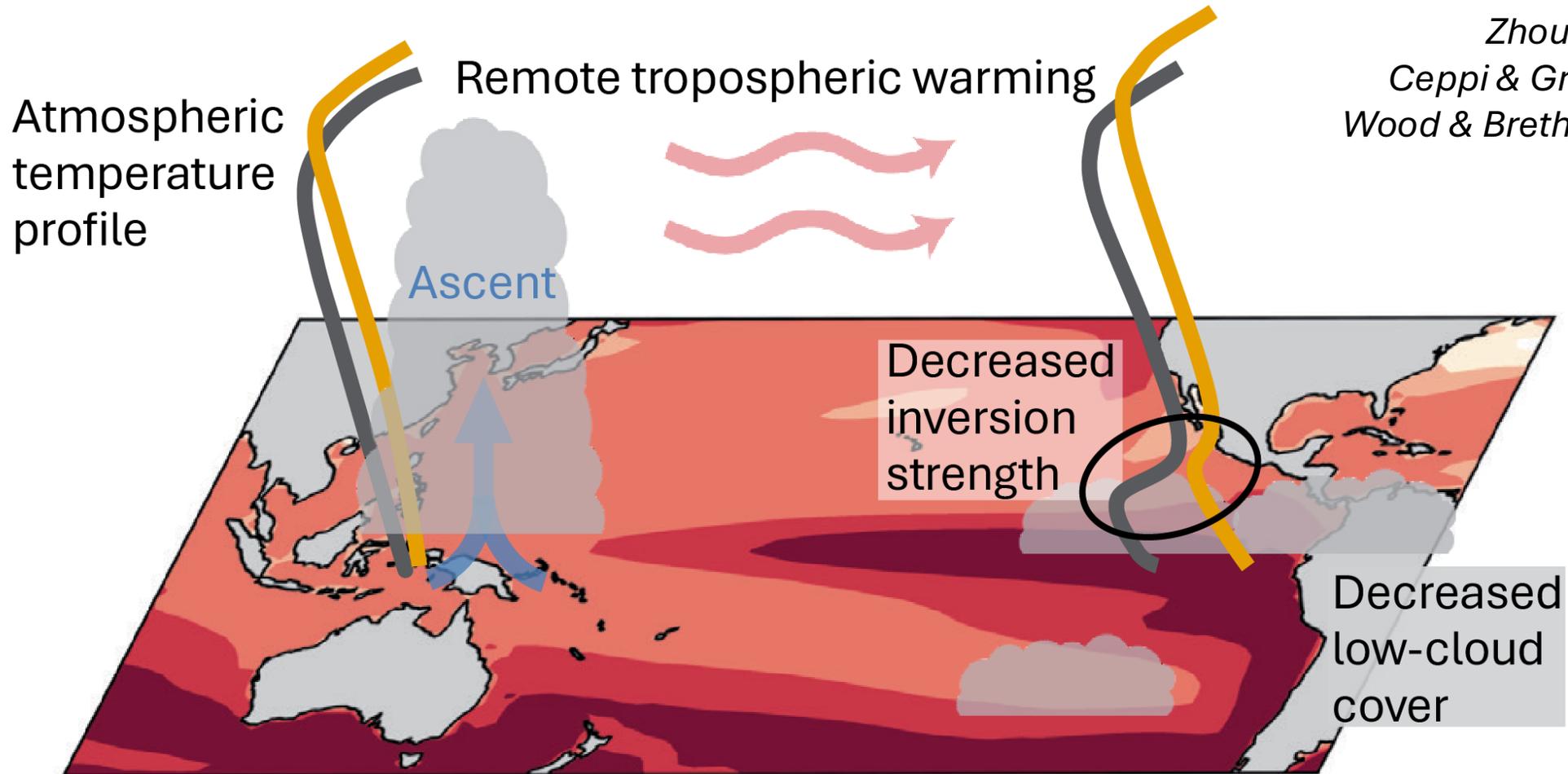
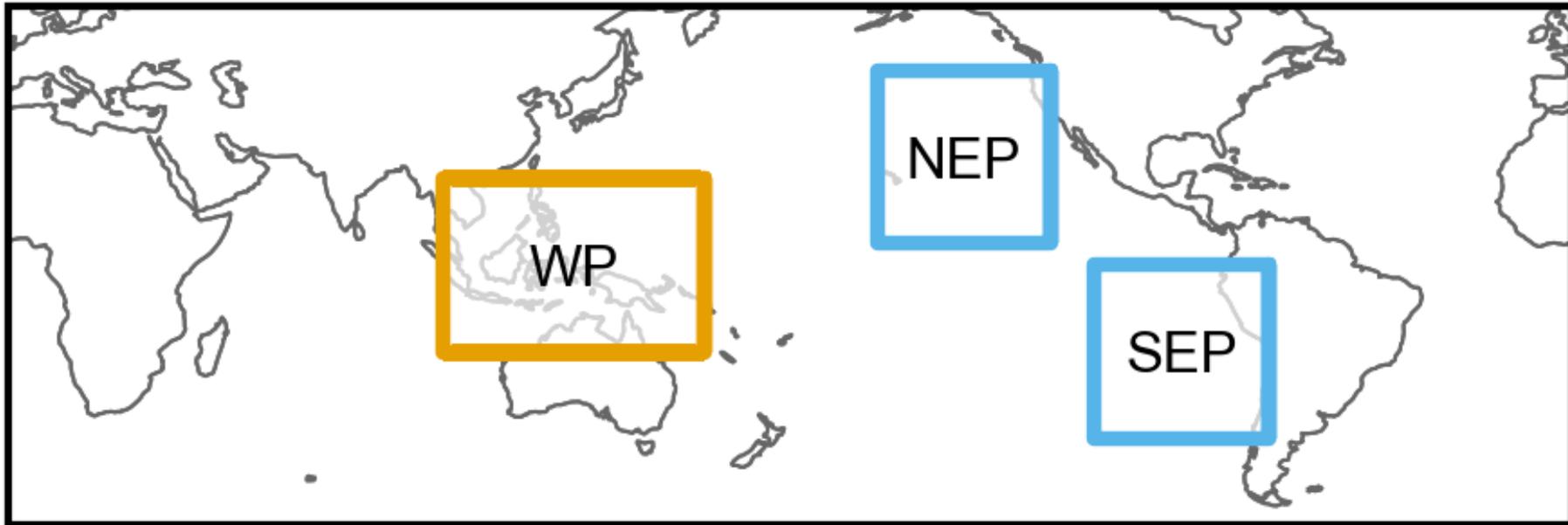


Figure adapted from IPCC AR6, Chapter 7

Pattern Stability Index quantifies inversion strength

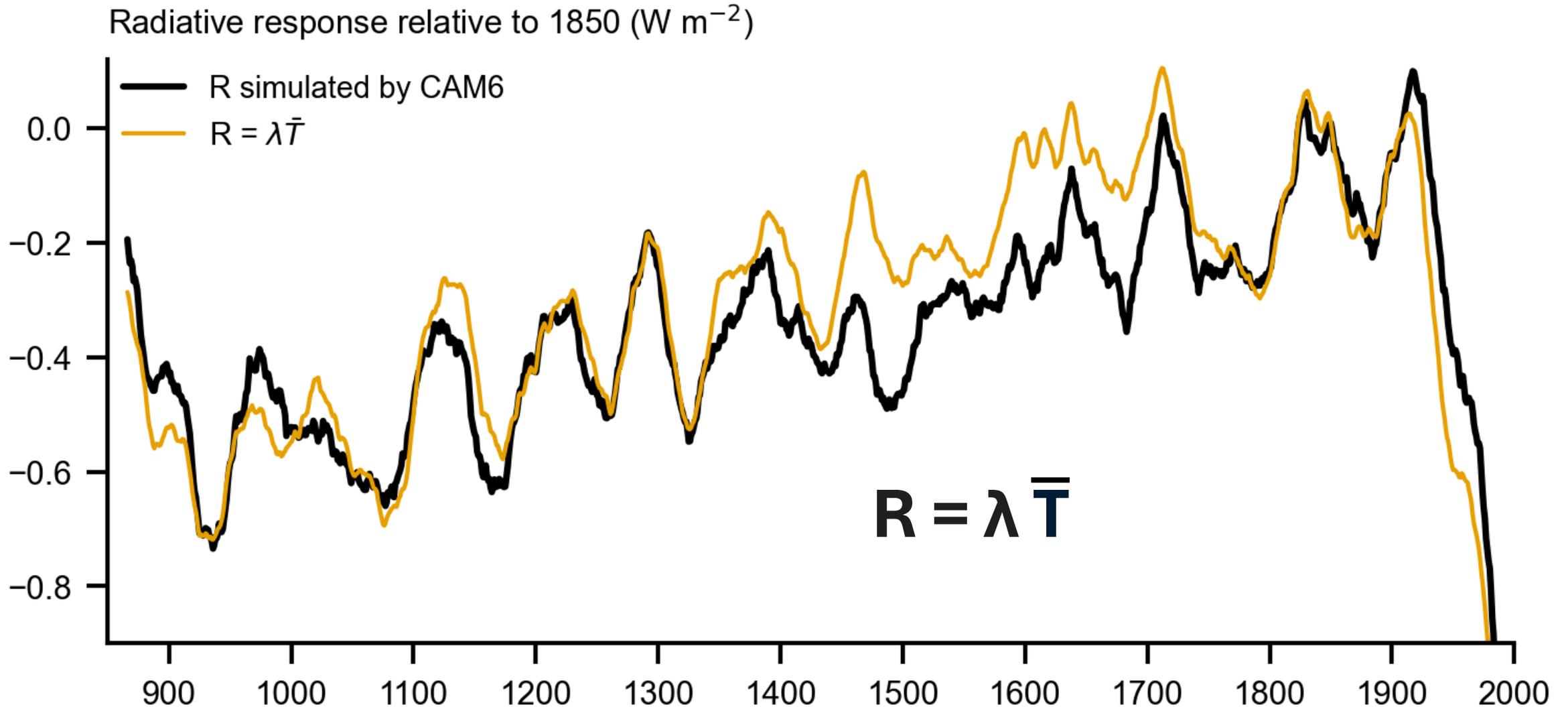
(where low clouds are located)

“How much warmer is the **West Pacific** than the **East Pacific**?”



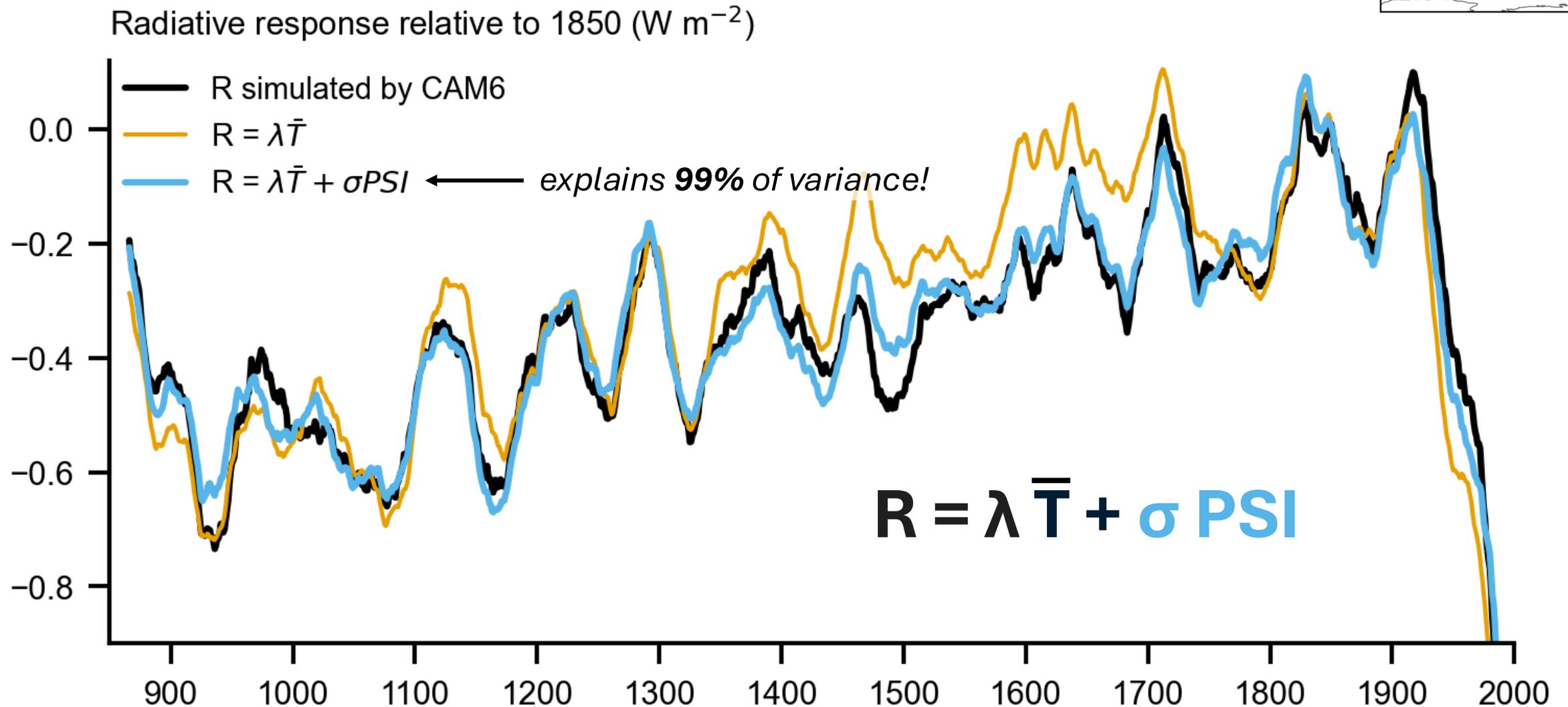
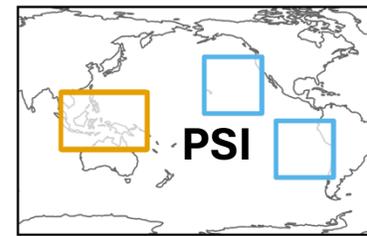
Pattern Stability Index:
$$PSI = \overline{WP} - \frac{\overline{NEP} + \overline{SEP}}{2}$$

Radiative response is only partially explained by global-mean T



* Ensemble mean, 30-yr running mean

Radiative response strongly depends on SST pattern



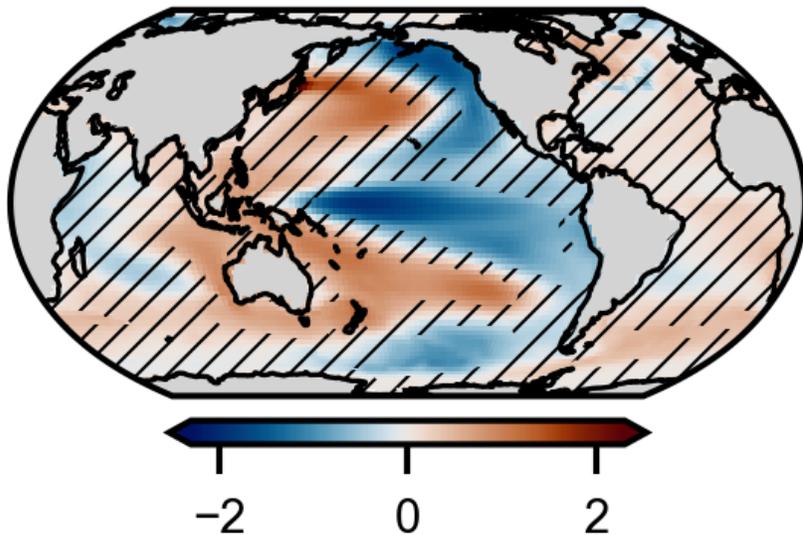
* Ensemble mean, 30-yr running mean

Radiative response strongly depends on SST pattern

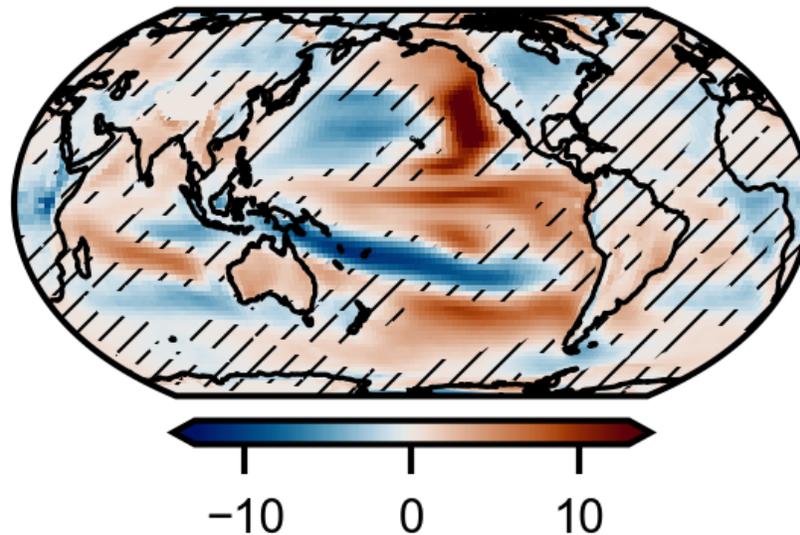
What SSTs and cloud patterns are associated with the PSI?

Linear regression onto PSI of...

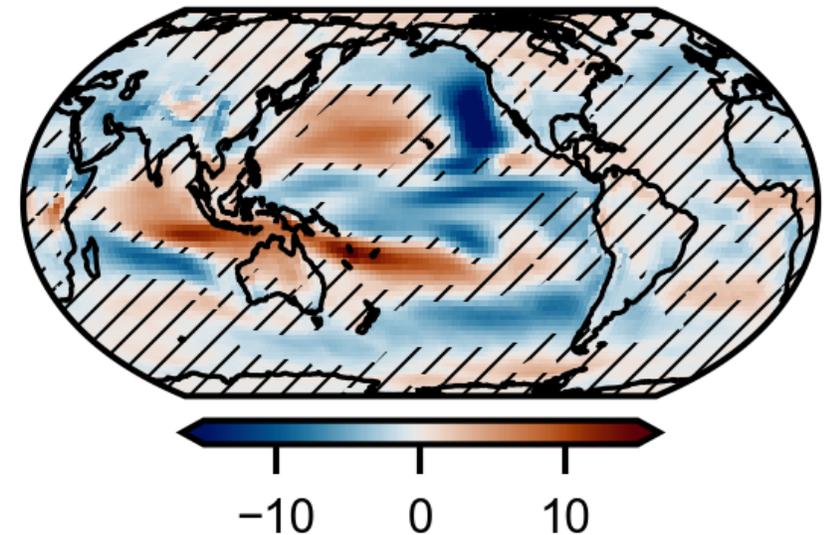
SST (K K^{-1})



Low clouds ($\% \text{K}^{-1}$)



EEI ($\text{W m}^{-2} \text{K}^{-1}$)



IPO = Interdecadal Pacific Oscillation

* Ensemble mean, 10-yr running mean, hatching denotes non-significant ($\alpha = 5\%$) regions

Two perspectives on the pattern effect

Fixed feedback parameter λ_0
Explicit **pattern effect term**

$$R = \lambda_0 \bar{T} + \sigma \text{PSI}$$

Ceppi & Gregory (2019)
Fueglistaler & Silvers (2021)
Kawaguchi & Ceppi (2025)

Time-varying feedback parameter $\lambda(t)$

$$R = \lambda(t) \bar{T}$$

Gregory & Andrews (2016)
Zhou et al. (2016)
Gregory et al. (2020)
Andrews et al. (2022)

Note: $\lambda(t)$ is a “differential” feedback parameter, which differs conceptually from the “effective” feedback parameter λ_0 (Rugenstein & Armour, 2021)

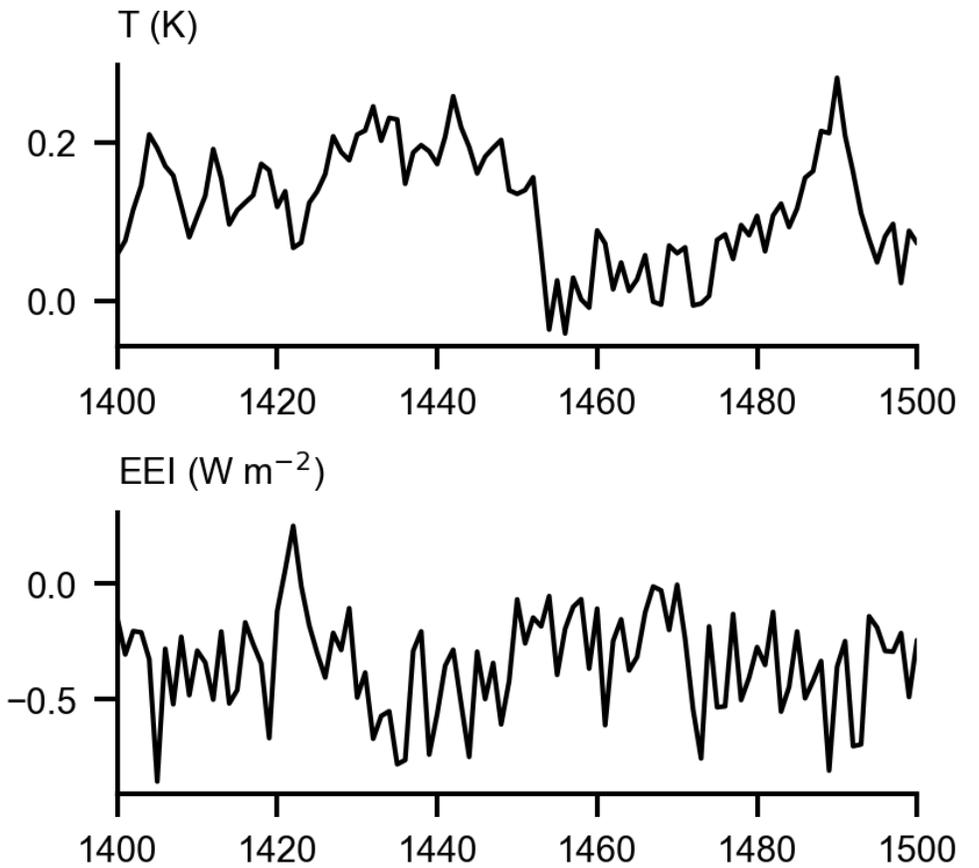
Estimating the time-varying feedback parameter

$$EEI = F + \lambda T$$

*Simulation with $F = 0$
(amip-piForcing)*



$$\lambda \approx \frac{EEI}{T}$$

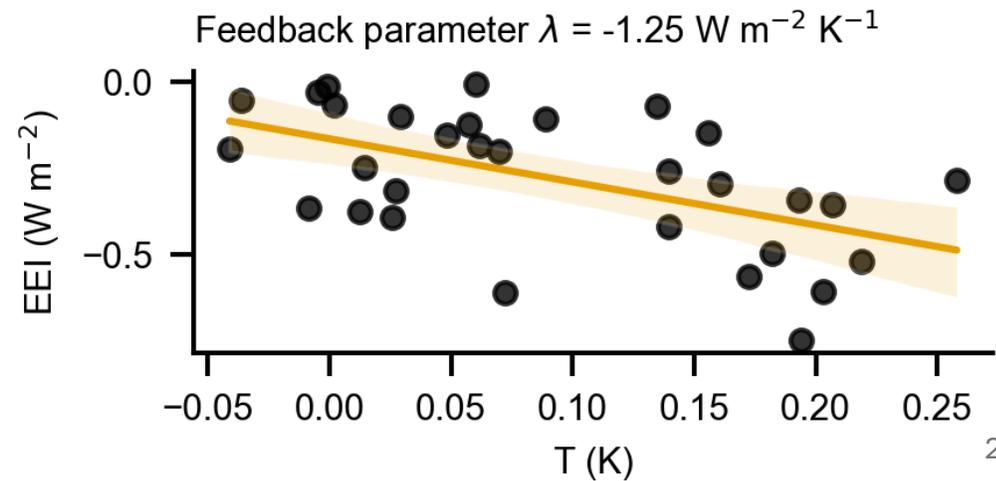
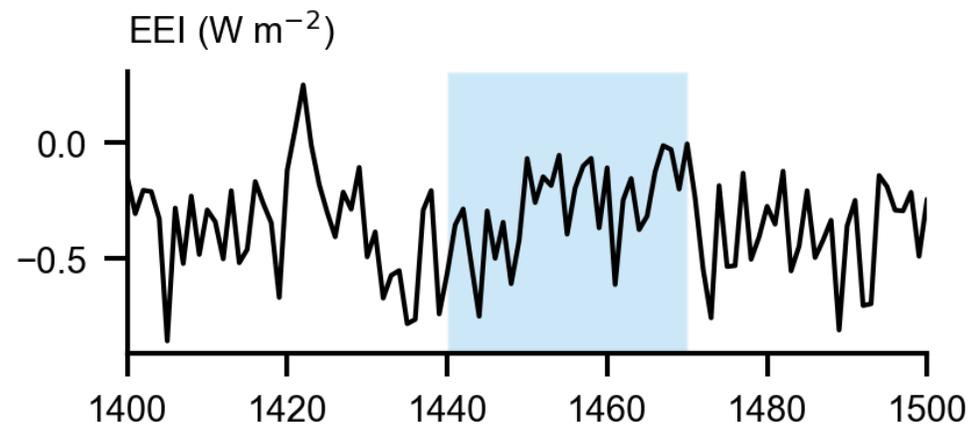
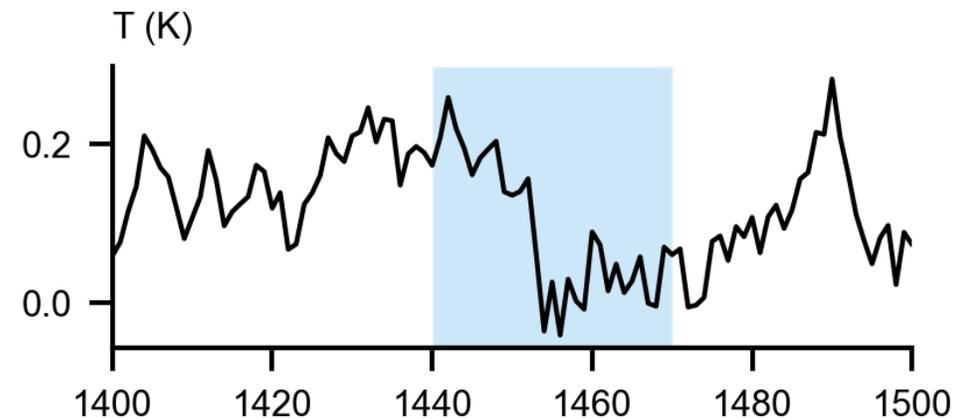


Estimating the time-varying feedback parameter

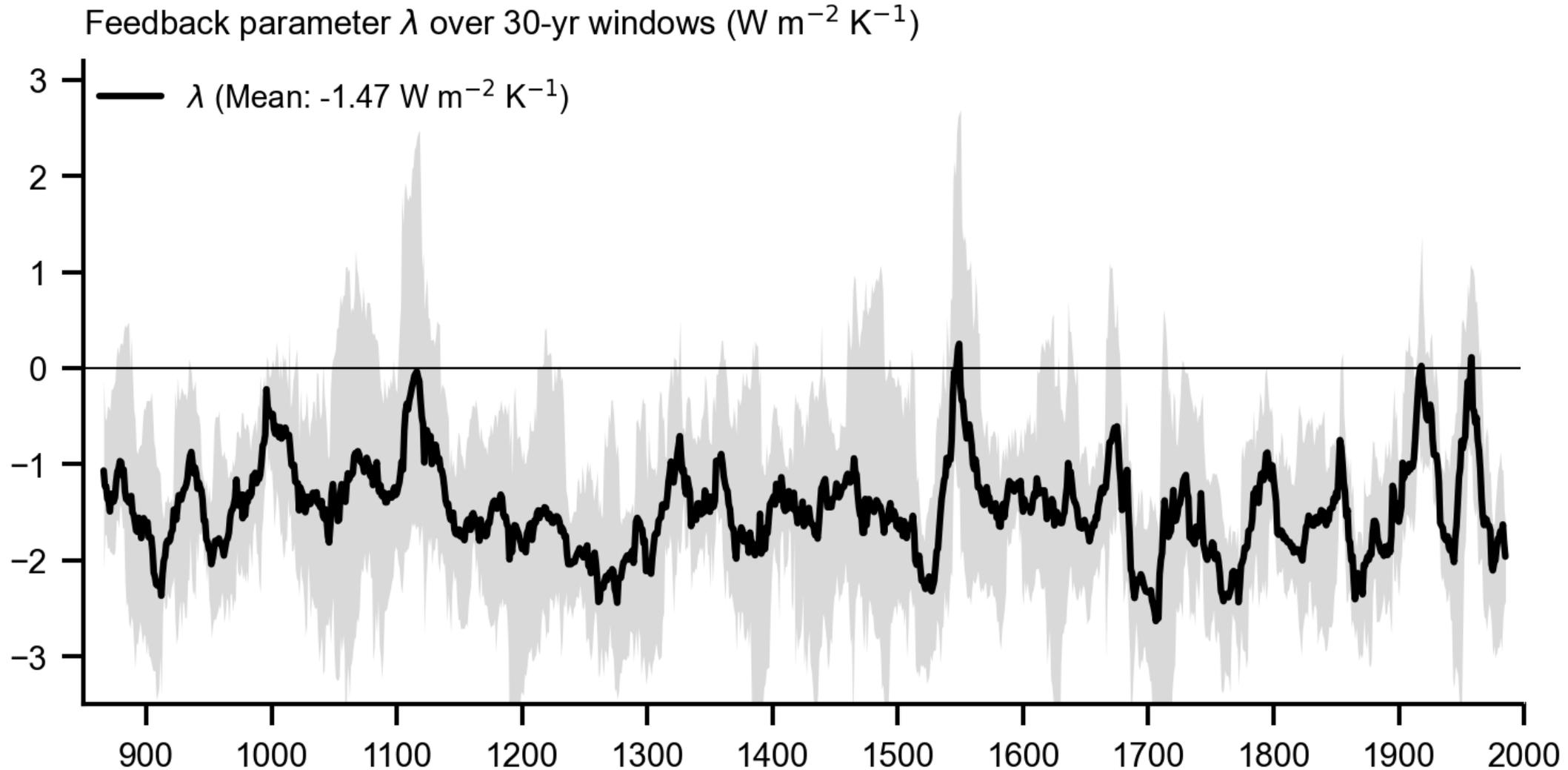
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$$\lambda \approx \frac{EEI}{T}$$

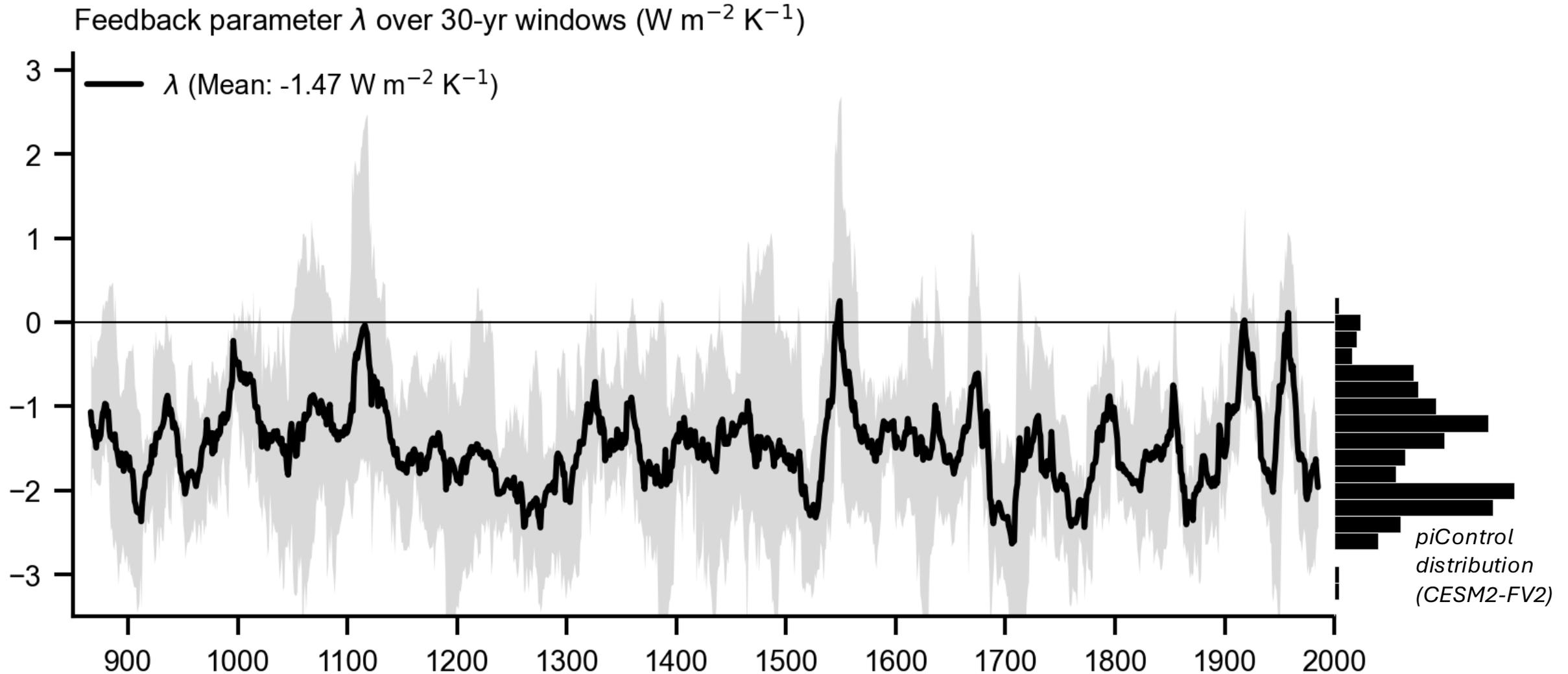


Multidecadal variations in λ are consistent with internal variability



* Shading denotes min-max ensemble range

Multidecadal variations in λ are consistent with internal variability



* Shading denotes min-max ensemble range

Why are transient atmosphere-only simulations useful for the paleoclimate?

Advantages:

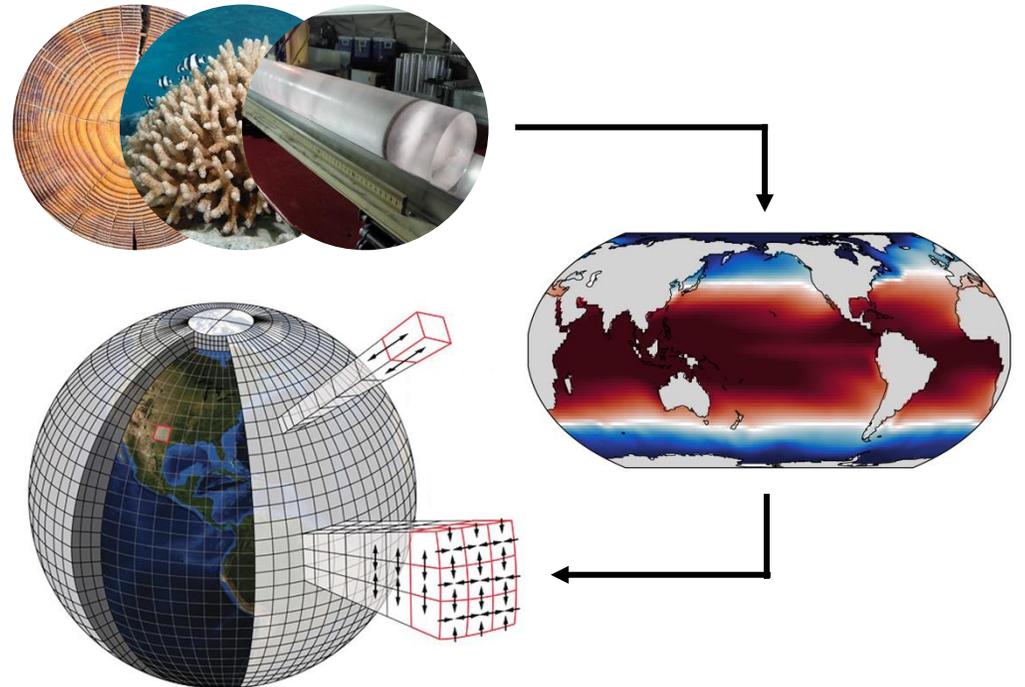
- Much cheaper than coupled simulations → allows large ensembles
 - Fully coupled CESM2 past1000 (2 deg, BWmaHIST): 3500 pe-hrs/SY
 - Atmosphere-only CAM6 amip-past1000 (2 deg, FHIST): 340 pe-hrs/SY
- Useful to investigate atmospheric variability constrained by proxies
- Can separate radiative forcing and response
- Directly extend historical AMIP simulations

Disadvantages:

- Limited to time periods with high-resolution proxy data (i.e., late Holocene)
- Volcanic surface cooling in proxy reconstruction is underestimated
 - Cooling may be overestimated in coupled models though
- Not useful for studying the absolute energy imbalance, only anomalies
 - Average EEI is $\sim 2 \text{ W m}^{-2}$, like in historical AMIP simulations

Conclusion

- **Transient atmosphere-only, proxy-constrained simulation** over the last millennium (850–2000 CE)
 - Seasonal SST + sea ice from Stiller & Hakim (in review, preprint on arXiv)



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Conclusion

- **Transient atmosphere-only, proxy-constrained simulation** over the last millennium (850–2000 CE)
 - Seasonal SST + sea ice from Stiller & Hakim (in review, preprint on arXiv)
- **Response contributed 43% to energy loss**
 - Associated with millennial-scale cooling trend
- **Response variability is influenced by Pacific SST patterns** through low clouds
 - Consistent with internal, not forced variability
- Rich opportunities for study of radiation, clouds, hydroclimate, seasonal to millennial variability, ...
- Transient atmosphere-only simulations allow us to cheaply study proxy-constrained variability

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