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A Last-Millennium Reconstruction of Top-of-Atmosphere Radiation Fields

Low-Frequency Variability of Earth's Energy Budget

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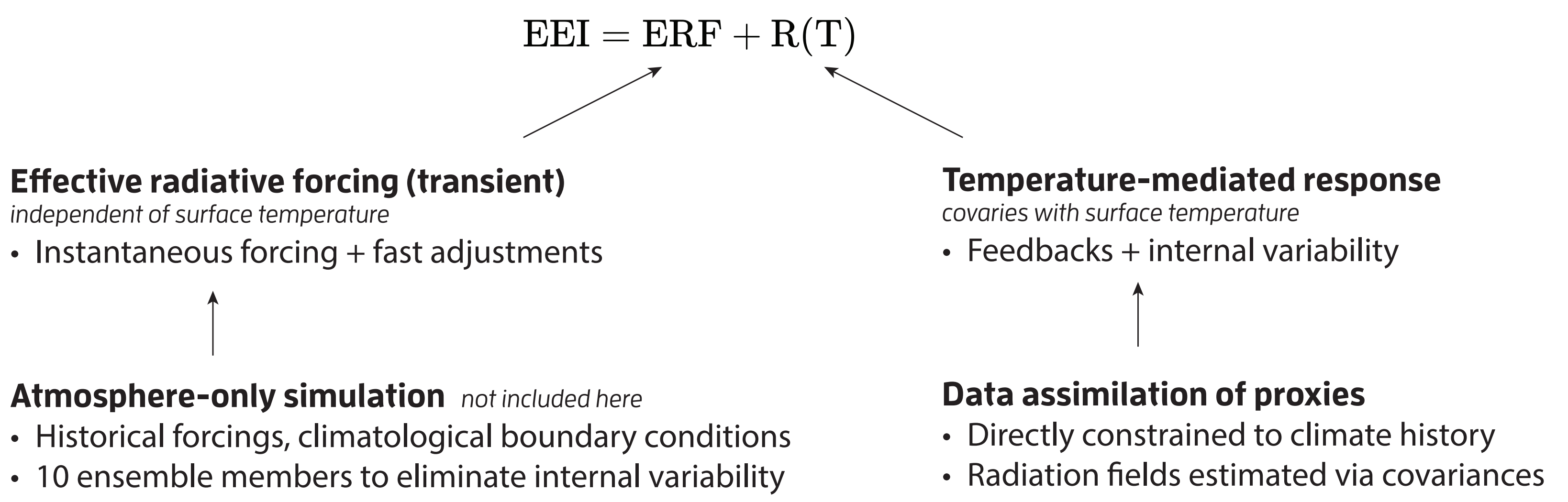
Key findings

- Earth responded to the forced **cooling of -0.21 K/kyr over the last millennium** with albedo loss in the (sub)tropics, albeit offset by sea ice growth in West Antarctica. The **net outgoing response is -0.5 (W/m²)/kyr** (i.e., energy gain) and the **feedback is -2.3 (W/m²)/K** (Figure 6).
- Cooling mainly occurred at high latitudes, accompanied by **strong cooling of the North Pacific and Atlantic.** The tropics and subtropics show no temperature trend (Figure 6).
- **AMO and PDO have distinct OLR signatures,** despite similar SST patterns in the tropical Pacific. PDO-like variability is strongly linked to OLR at timescales < 200 yr while AMO-like variability has a weaker OLR signature at <20 yr than in the 20–200-yr band (Figure 5).

1. Motivation

- **Earth's energy imbalance (EEI) at the top of the atmosphere (TOA) is a key climate metric** but has only been well-observed for the past twenty years, a period of strong greenhouse gas forcing. This **short record limits the understanding of low-frequency energy variability**.
- Loeb et al. (2020) demonstrated the feasibility of reconstructing TOA radiation given sea surface temperatures and historical forcings, linked through clouds and surface albedo.
- We present preliminary results of reconstructed seasonal **temperature and TOA radiation fields over the last millennium** (850–2000 CE) using PAGES2k and CoralHydro2k proxies.

2. Decomposition of TOA radiation



$$\mathrm{EEI} = \mathrm{ERF} + \mathrm{R(T)}$$

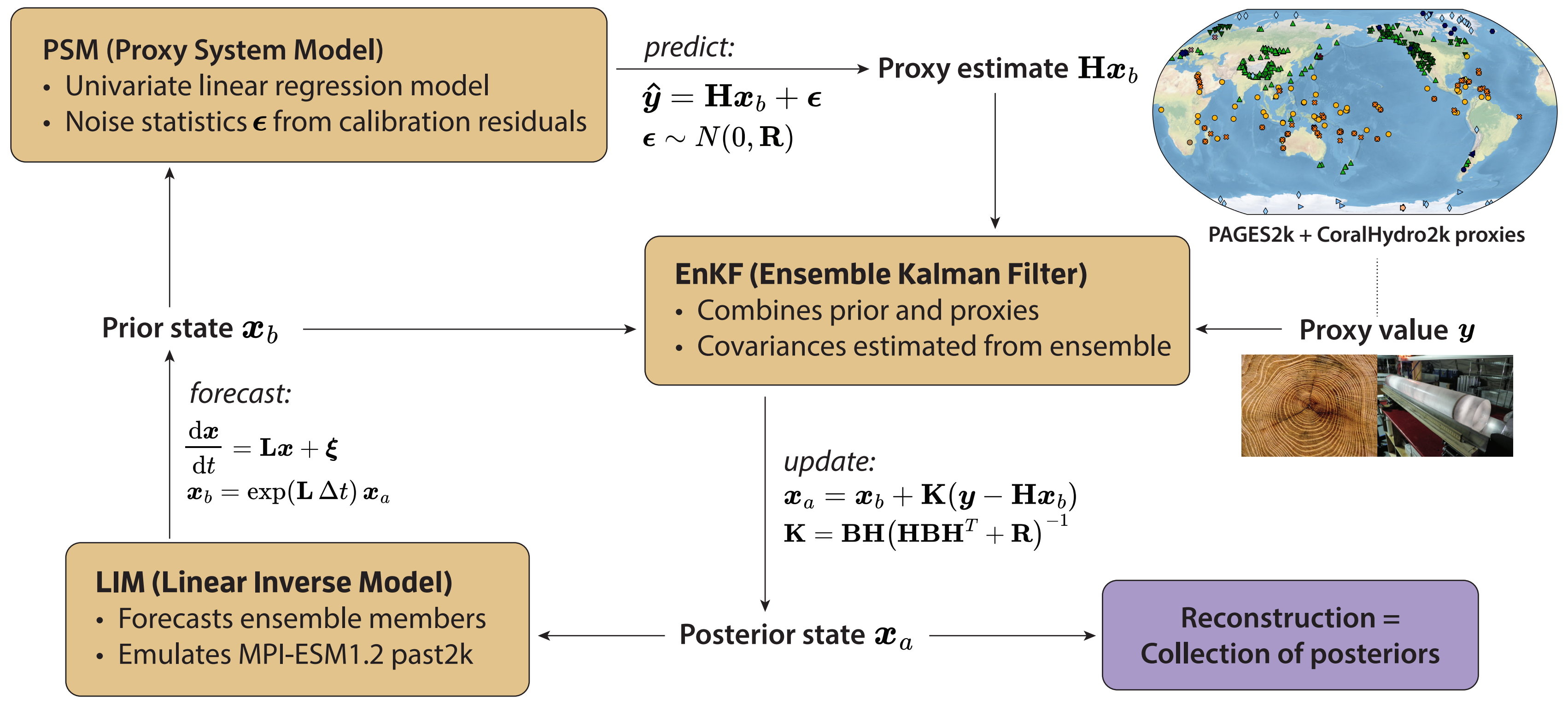
Effective radiative forcing (transient)
independent of surface temperature
- Instantaneous forcing + fast adjustments

Atmosphere-only simulation *not included here*
- Historical forcings, climatological boundary conditions
- 10 ensemble members to eliminate internal variability

Temperature-mediated response
covaries with surface temperature
- Feedbacks + internal variability

Data assimilation of proxies
- Directly constrained to climate history
- Radiation fields estimated via covariances

Figure 1 The EEI and its constituent shortwave (SW) and longwave (LW) fields can be decomposed into two components, which we reconstruct separately. The transient effective radiative forcing (ERF; Forster et al., 2016) will be reconstructed using CESM2/CAM6.



PSM (Proxy System Model)
- Univariate linear regression model
- Noise statistics $\boldsymbol{\epsilon}$ from calibration residuals

predict:
$\hat{\boldsymbol{y}} = \mathbf{H}\boldsymbol{x}_b + \boldsymbol{\epsilon}$
$\boldsymbol{\epsilon} \sim N(0, \mathbf{R})$

Proxy estimate $\mathbf{H}\boldsymbol{x}_b$

PAGES2k + CoralHydro2k proxies

Prior state $\boldsymbol{x}_b$

EnKF (Ensemble Kalman Filter)
- Combines prior and proxies
- Covariances estimated from ensemble

Proxy value $\boldsymbol{y}$

forecast:
$\frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}t} = \mathbf{L}\boldsymbol{x} + \boldsymbol{\xi}$
$\boldsymbol{x}_b = \exp(\mathbf{L}\,\Delta t)\,\boldsymbol{x}_a$

update:
$\boldsymbol{x}_a = \boldsymbol{x}_b + \mathbf{K}(\boldsymbol{y} - \mathbf{H}\boldsymbol{x}_b)$
$\mathbf{K} = \mathbf{BH}\left(\mathbf{HBH}^T + \mathbf{R}\right)^{-1}$

LIM (Linear Inverse Model)
- Forecasts ensemble members
- Emulates MPI-ESM1.2 past2k

Posterior state $\boldsymbol{x}_a$

Reconstruction = Collection of posteriors

Figure 2 We use online data assimilation to combine information from proxies and a model. The reconstruction includes 2-m air temperature (SAT), sea surface temperature (SST), reflected TOA SW radiation (RSW), outgoing TOA LW radiation (OLR), and the upper ocean heat content.

3. Results: Surface temperature reconstruction

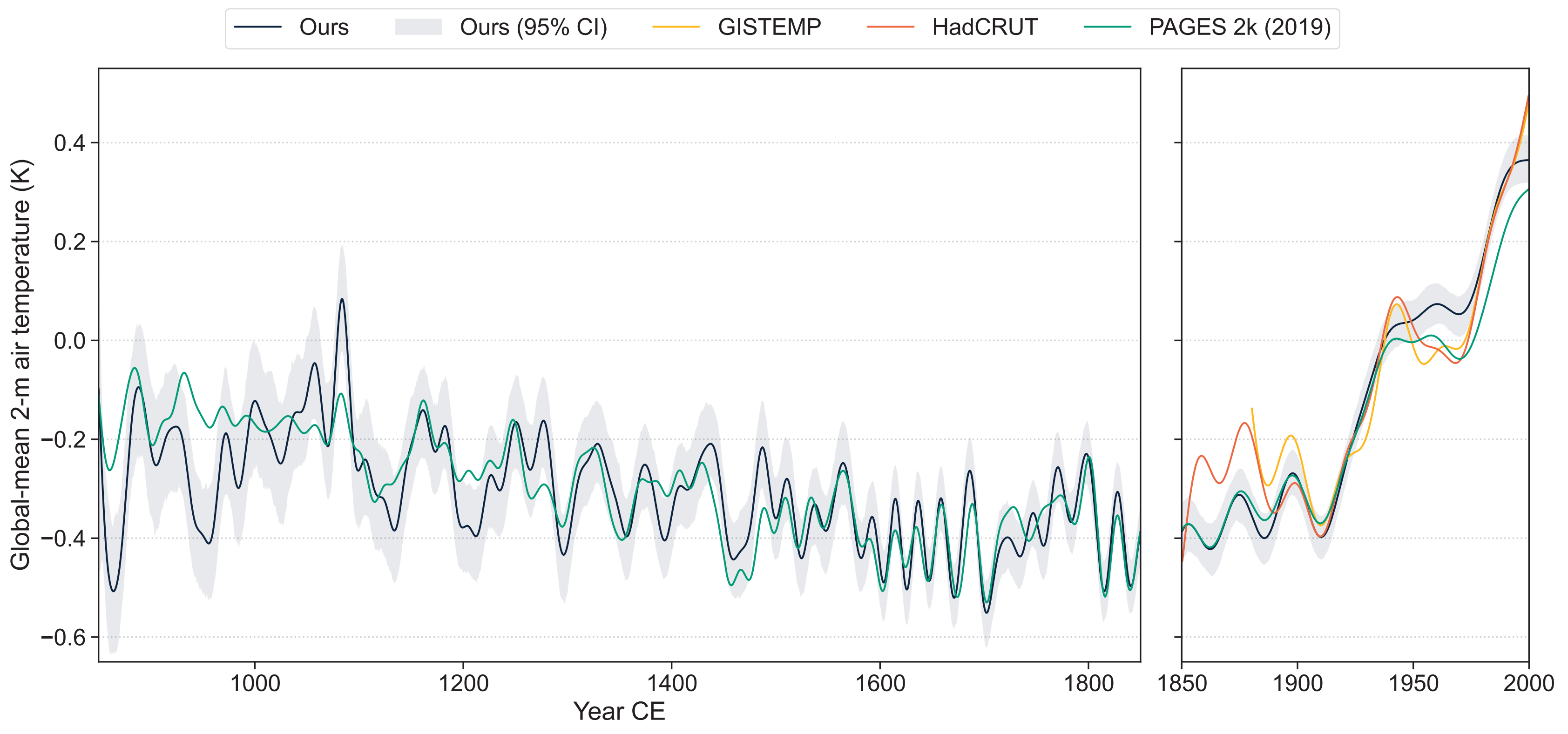


Figure 3 Global-mean 2-m air temperature anomalies relative to 1951–1980 (20-year lowpass-filtered). Over 850–1850 CE, the surface cooled by -0.21 K/kyr (NH: -0.29 K/kyr, SH: -0.12 K/kyr).

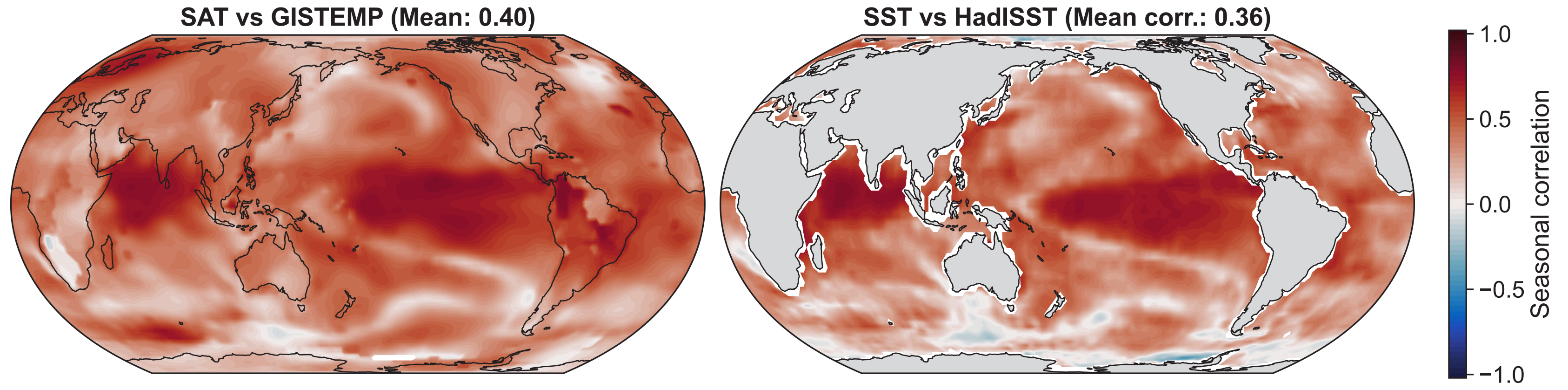


Figure 4 Seasonal correlations between our reconstruction and the instrumental GISTEMP (left, for SAT over 1880–2000 CE) and HadISST (right, for SST over 1870–2000 CE) datasets.

5. Pseudoproxy experiment

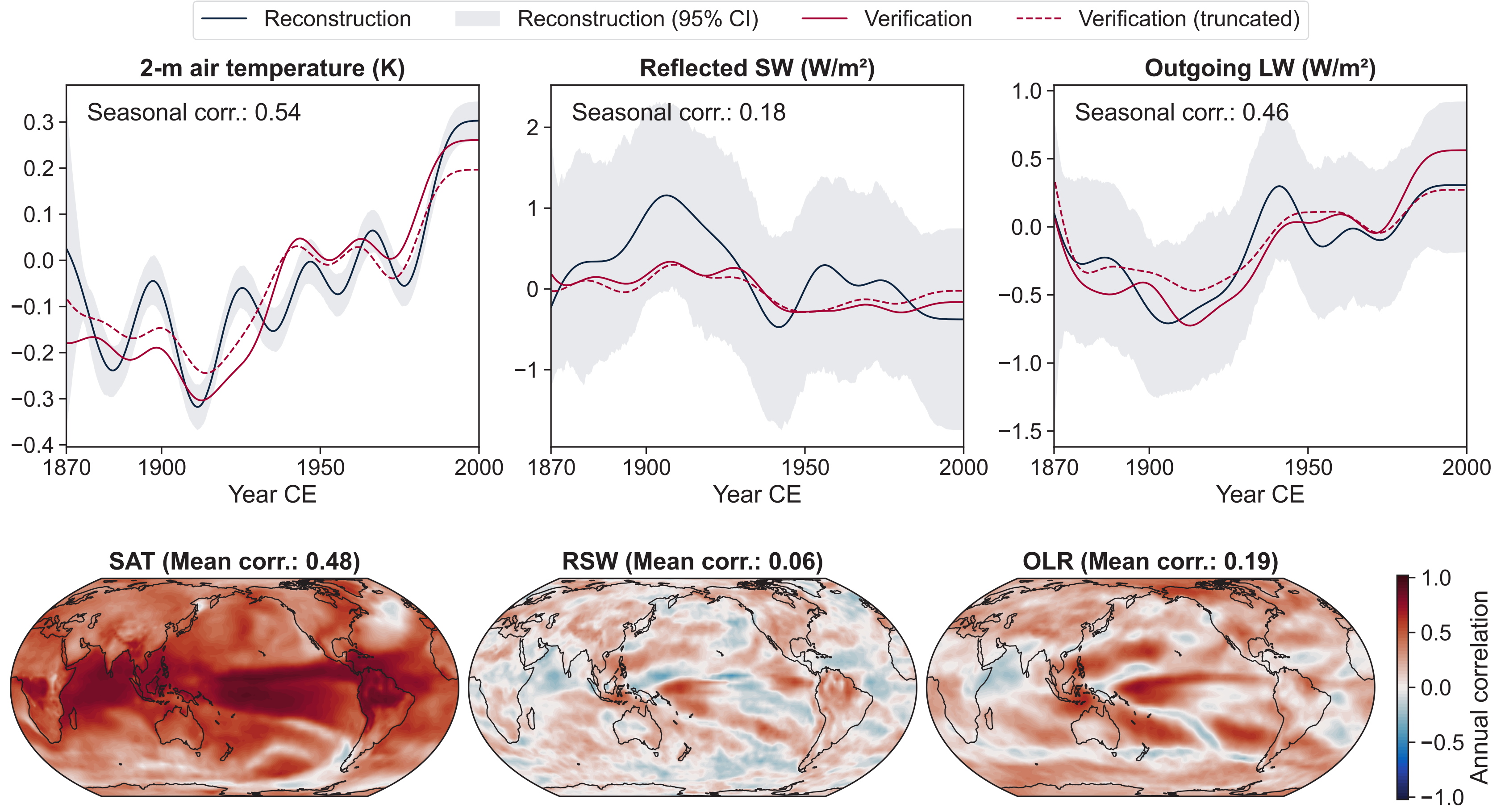


Figure 7 Pseudoproxy experiment with pseudoproxies from the CESM2 CMIP6 amip-piForcing simulation (no ERF). *Top*: global means (20-year lowpass-filtered). *Bottom*: annual correlations.

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4. Results: Multidecadal to millennial variability of TOA radiation

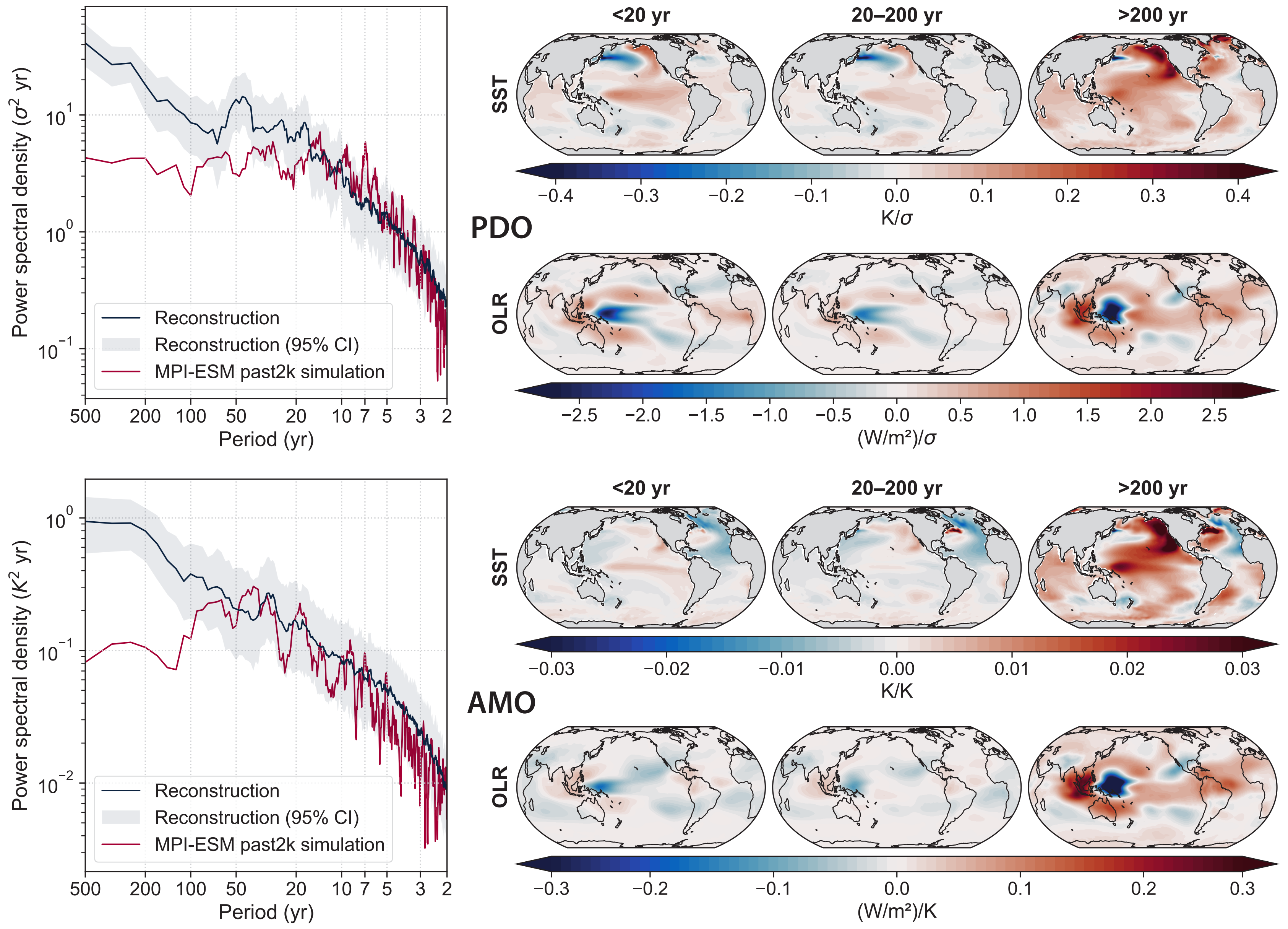

Figure 5 *Left*: Power spectra of Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) indices over 850–1850 CE. *Right*: Regression of SST and OLR onto the filtered indices at different passbands. The multicentennial patterns are likely due to global temperature trends.

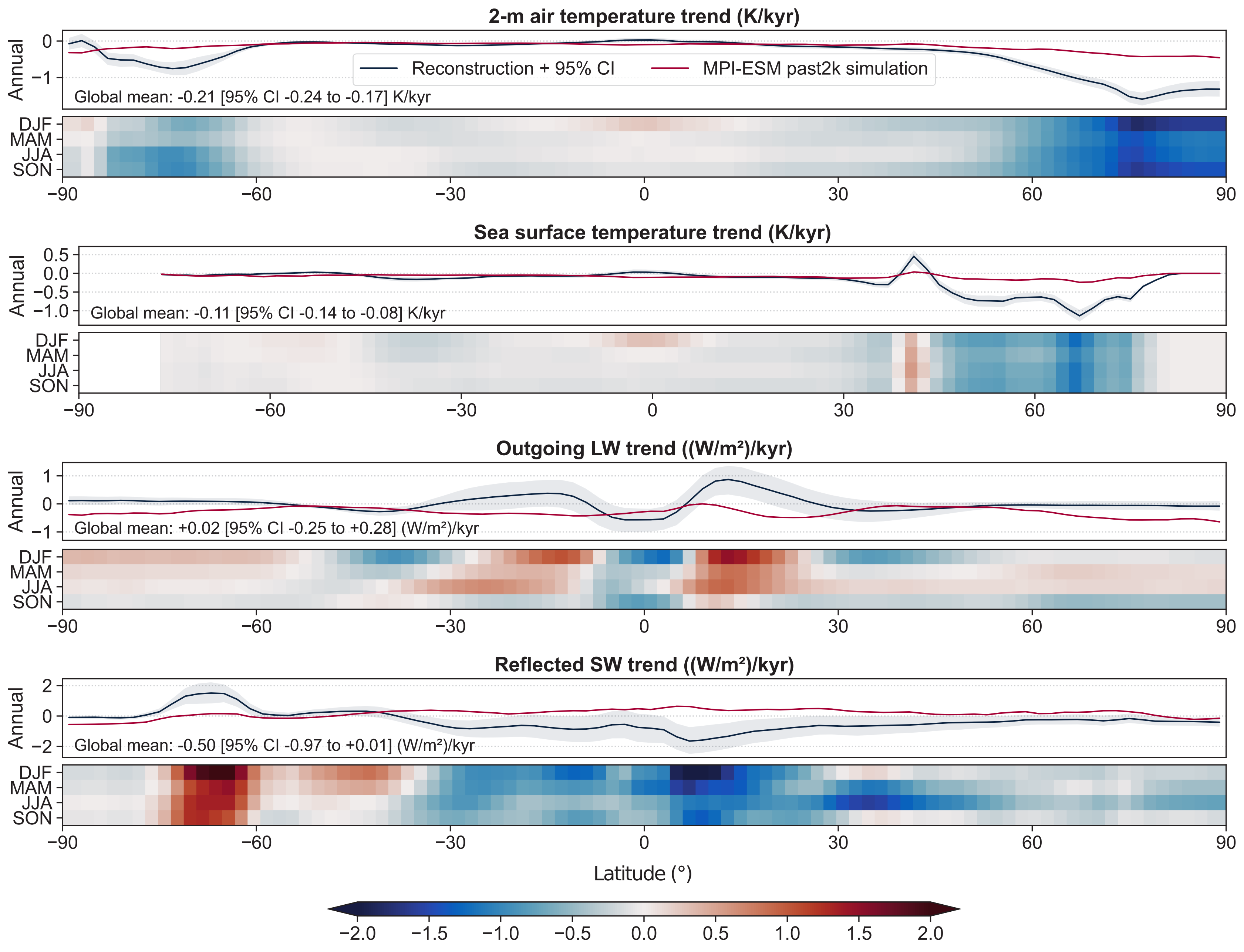

Figure 6 Millennial trends in zonal means over 850–1850 CE. Radiation is positive upwards. Seasonal variations are likely forced by insolation changes due to axial precession (Lücke et al., 2020).