Coupled Seasonal Data Assimilation of Sea Ice, Ocean, and Atmospheric Dynamics over the Last Millennium

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Motivation and Importance

- A longer, global, gridded and **seasonal** climate dataset is needed:
  1. Instrumental datasets are short and forced by global warming.
  2. Sample sizes (PDO, AMO, ENSO) are limited.
  3. The internal and forced variability is mixed.
  4. Climate models are tuned to instrumental era.
  5. Decadal forecasts lack information.
- Importance: 1. The first seasonal reanalysis dataset over the Last Millennium. 2. The first reconstruction of Northern Hemisphere sea ice volume over the Last Millennium.

Method and Data

Climate Model Emulator – Linear Inverse Model (LIM)

- Coupled online Data Assimilation (DA) with climate model is computationally too demanding to be acceptable.
- LIM is an empirically determined estimate of a dynamical system linearized about its mean state with a stochastic closure.
- The LIMs' advantages: low cost and high forecasting skill.
- Train the LIMs on CCSM4 and MPI-ESM-R last millennium simulation to do 3 months lead forecast (MAM, JJA, SON, DJF).

$$\frac{d\mathbf{x}}{dt} = \mathbf{Lx} + \boldsymbol{\xi} \qquad \mathbf{x} = [\mathbf{PC}_{\mathrm{TAS}}^{T}, \mathbf{PC}_{\mathrm{TOS}}^{T}, \mathbf{PC}_{\mathrm{OHC300}}^{T}, \mathbf{PC}_{\mathrm{SIT}}^{T}, \mathbf{PC}_{\mathrm{SIC}}^{T}]^{T}$$

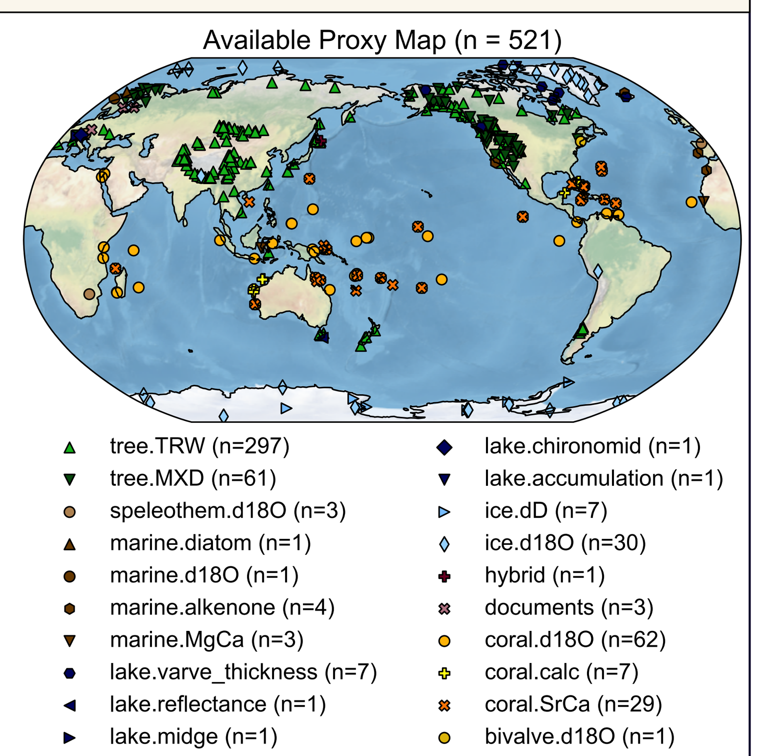
(Penland et al. 1993)

Proxy Data and Proxy System Model (PSM)

- The PAGES2k V2 dataset, which includes (sub)annual temperature-sensitive multi-proxy data, is used.
- Linear PSMs are calibrated using instrumental temperature ($\mathbf{x}$) and proxy data ($\mathbf{y}$) and linear regression (Threshold: $r > 0.05$).

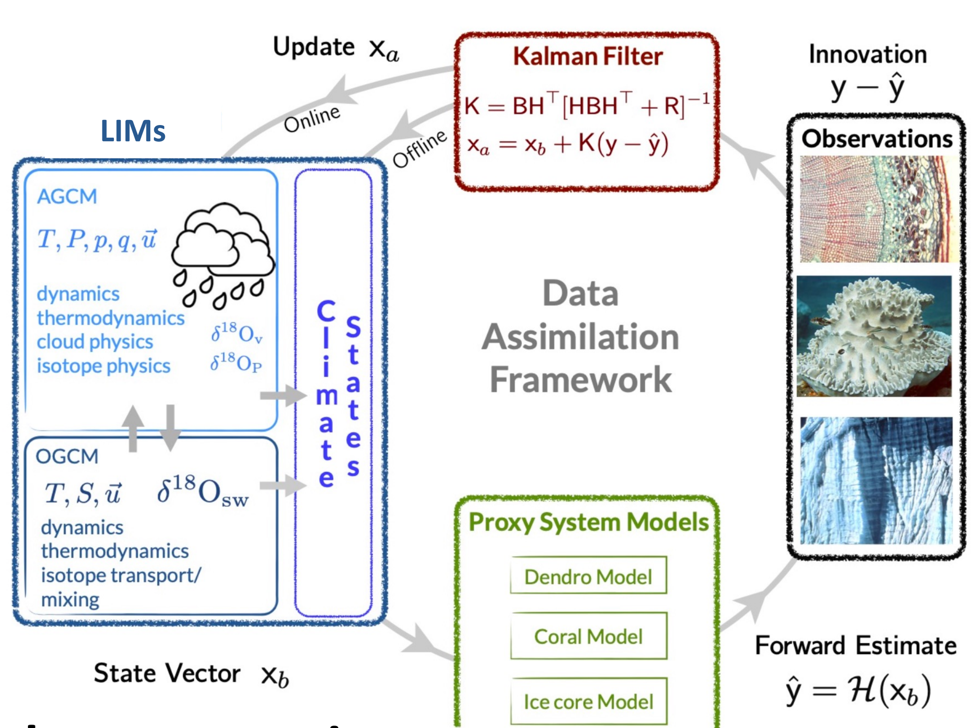
$$\mathbf{y} = \mathbf{H}\hat{\mathbf{x}} + \mathbf{b} + \boldsymbol{\epsilon}$$

- The residuals ($\boldsymbol{\epsilon}$) are used to estimate error covariance matrix.



Online Data Assimilation (DA) Framework

- The LIM generates the forecast as the "prior", while the Ensemble Kalman Filter produces the "posterior" by combining the "prior" with proxy data.
- The LIM uses the "posterior" to generates the next time forecast.
- **Online DA has memory of the past proxies.**

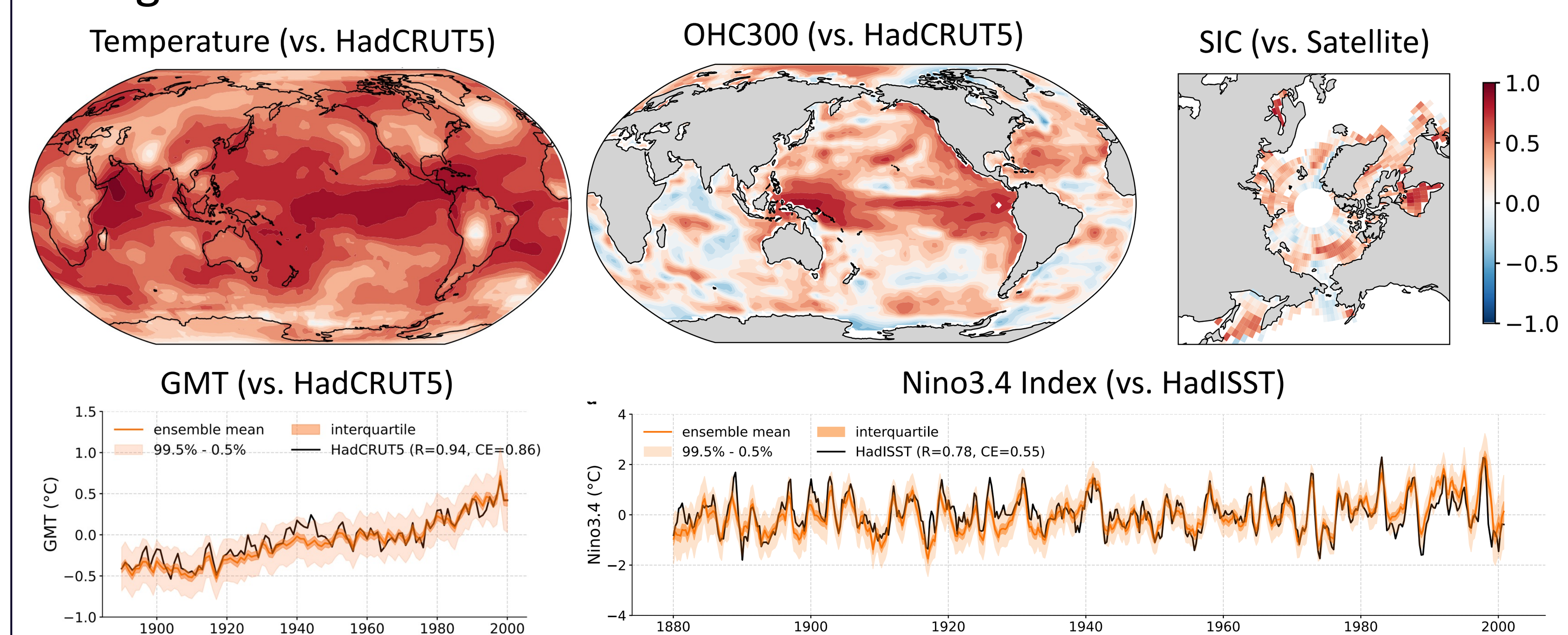


(Hakim et al. 2016)

Verification

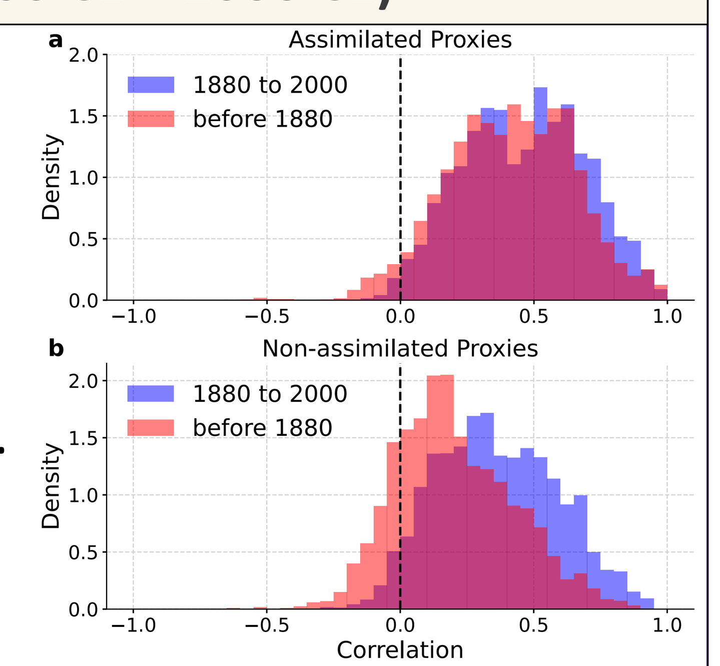
Instrumental Verification (DA vs. Observation, 1880 CE – 2000 CE)

- Temperature with direct observation has high reconstruction skill.
- Ocean heat content from 0m to 300m (OHC300) and sea ice concentration (SIC) exhibit high skill in dynamic regions.
- Global mean temperature (GMT) and ENSO (Nino3.4) also shows high skill.



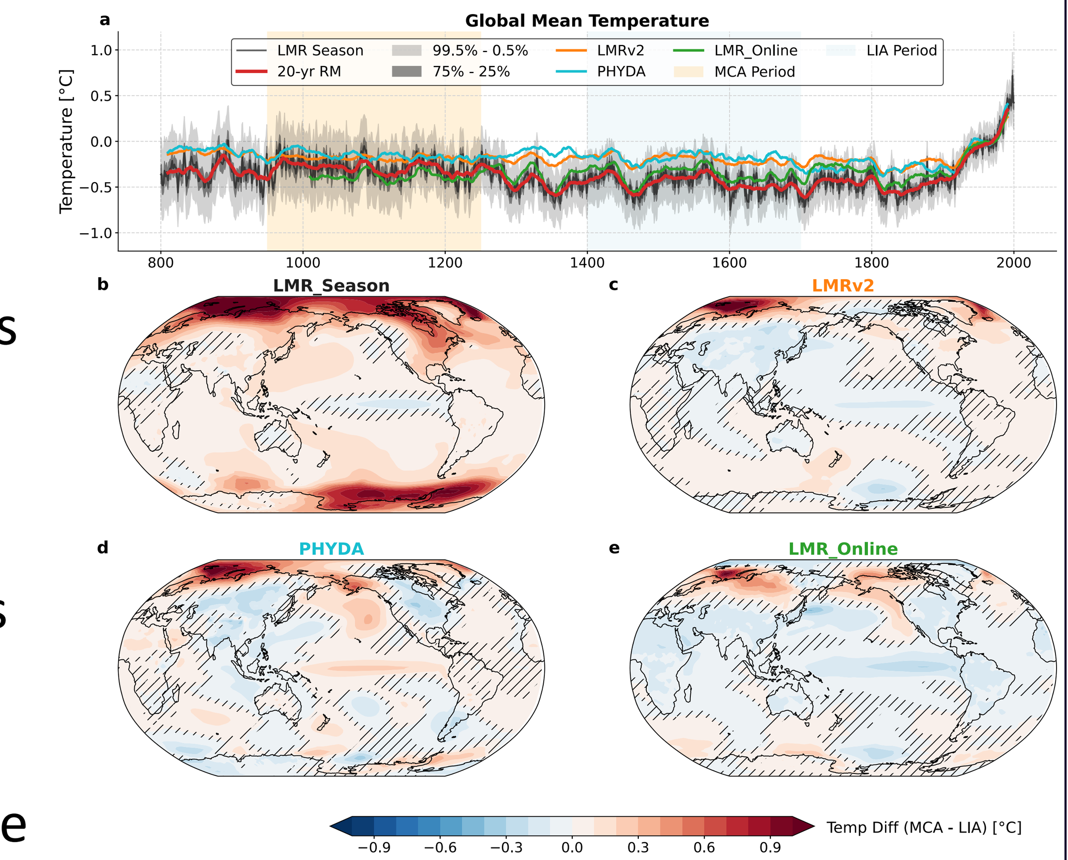
Independent Verification (DA vs. Proxy, 800 CE – 2000 CE)

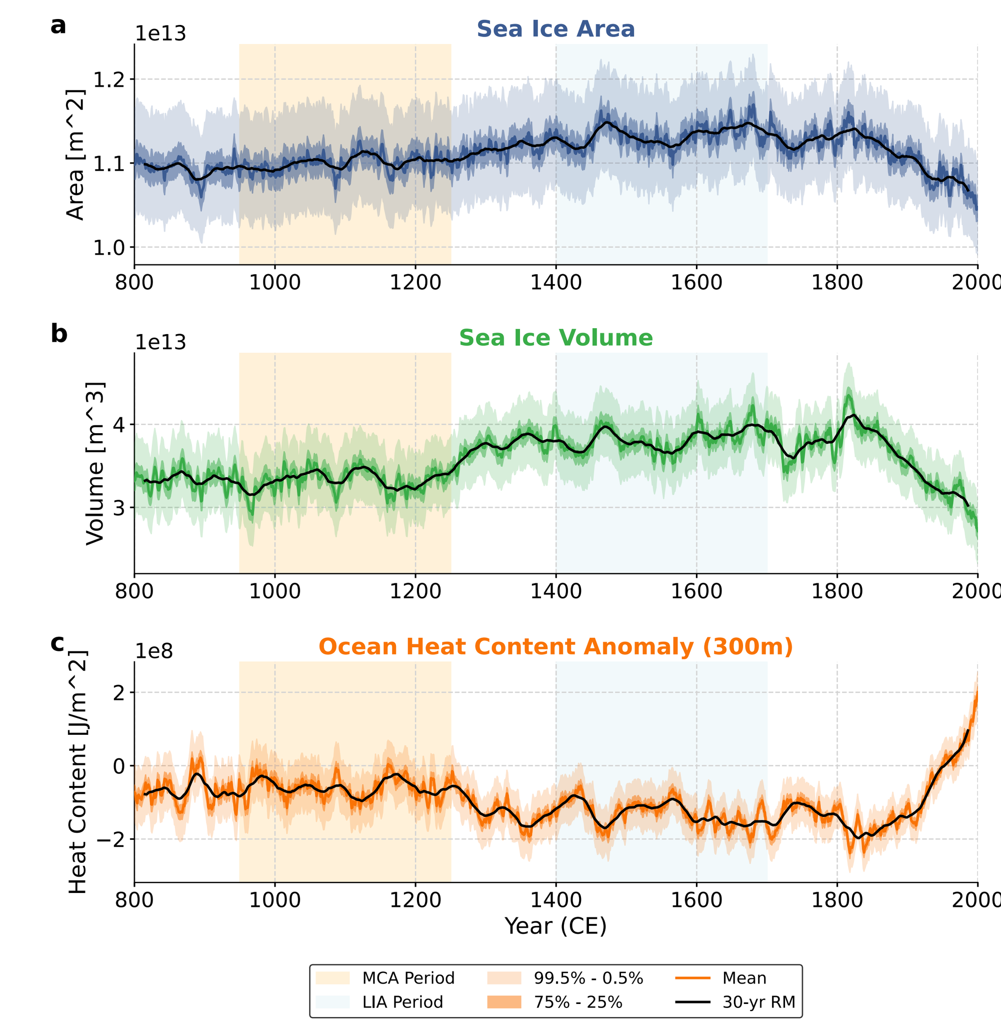
- Monte Carlo Sampling: exclude 25% of proxies for 50 DA cycles.
- Compare reconstructed proxy values with raw proxy values.
- Assimilated Proxies (**a**): Stable performance; median correlation ~ 0.4.
- Non-Assimilated (indpt) Proxies (**b**): Similar trends with a little difference
- **Robustness of DA from 800 to 2000.**



Medieval Climate Anomaly (MCA) and Little Ice Age (LIA)

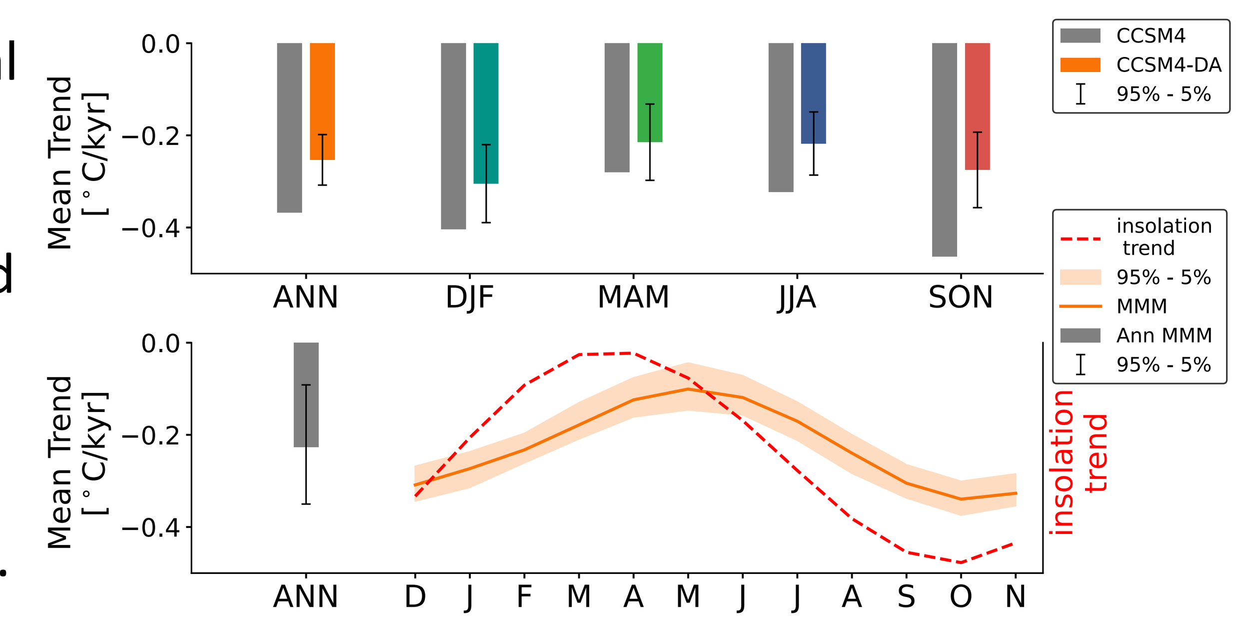
- MCA (warm) and LIA (cold) are two distinguished periods.
- Our DA (LMR Season, **b**) successfully reconstructs the global warming and east pacific cooling pattern (MCA - LIA). But other three DA products (**c, d, e**) can not.
- This derives from the seasonal dynamics of the LIMs (pronounced polar amplification) and seasonal update strategy.
- North Hemisphere (NH) SIA increased 3%; NH SIV increased 10%. OHC300 also shows MCA-LIA difference.
- The cooling trend concluded in the early 19th century, followed by the onset of a warming trend.

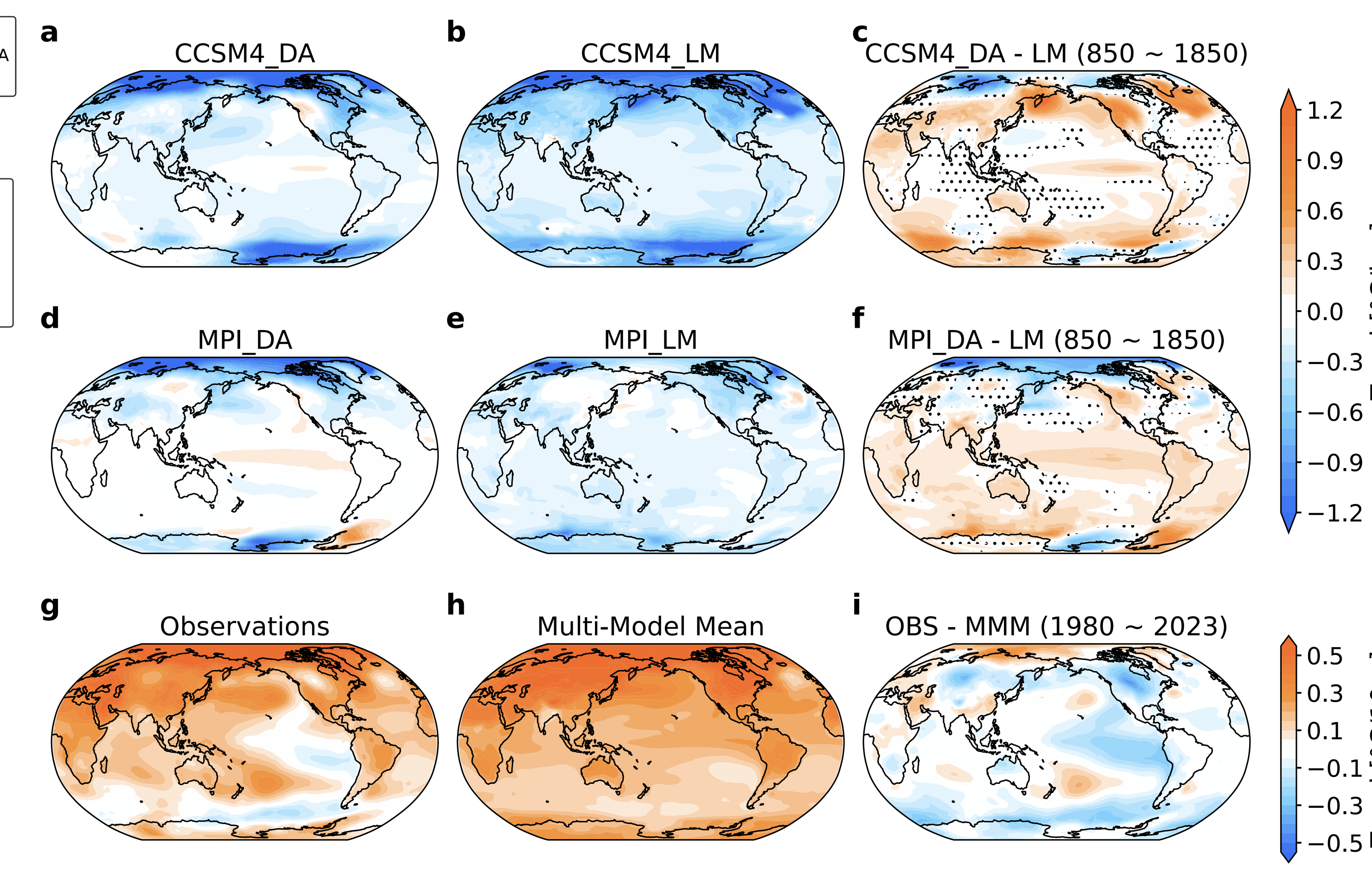




Temperature trends over the last millennium and their implications for the trends from 1980 to the present

- Last Millennium seasonal trend difference is a delayed response to the seasonal insolation trend difference (Lücke et al. 2021).
- DA gets this seasonal trend difference (MAM with least cooling trend).
- The last millennium temperature trend difference (**c, f**) between DA and model shows the similar pattern from the difference (**i**) between multi-observations and multi-model mean (1980 – 2023) with a negative sign.
- The similarity (La Niña-like cooling + Southern Ocean cooling + Arctic warming) between (**i**) and (**c, f**) may denote that climate model's systematic bias responded to the extra forcing.





(Sweeney et al. 2024)