



Uncovering Insights from the Last Millennium Using Coupled Seasonal Data Assimilation of Sea Ice, Ocean, and Atmospheric Dynamics

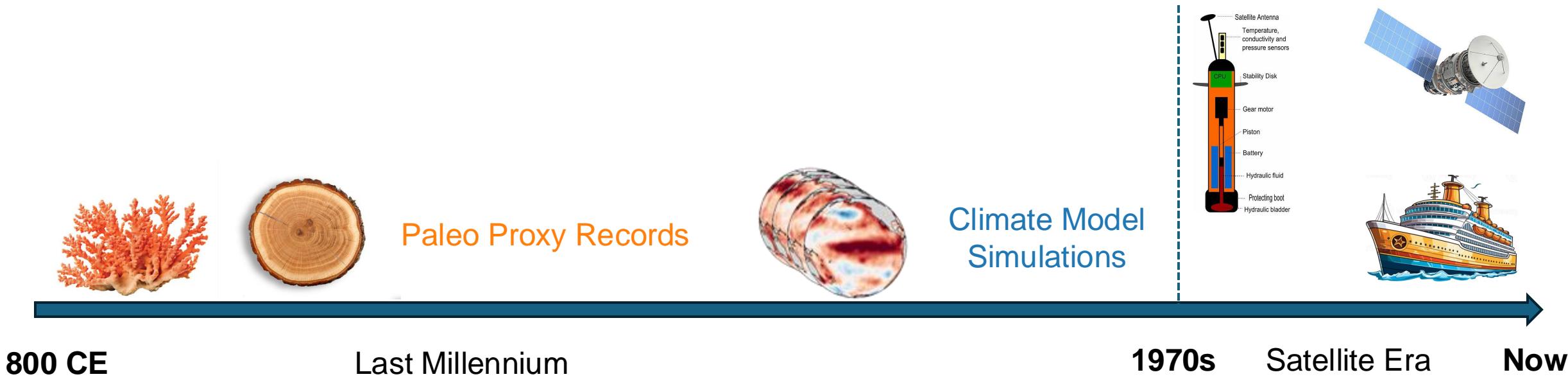
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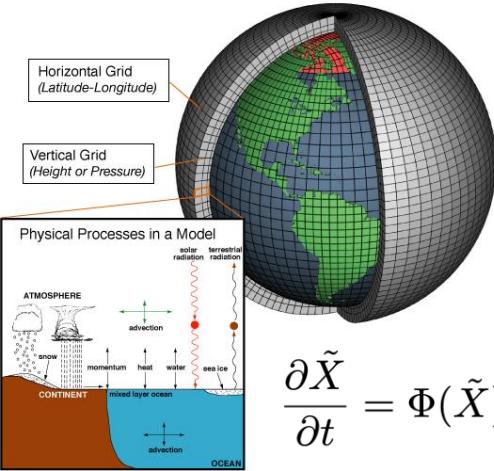
Motivation



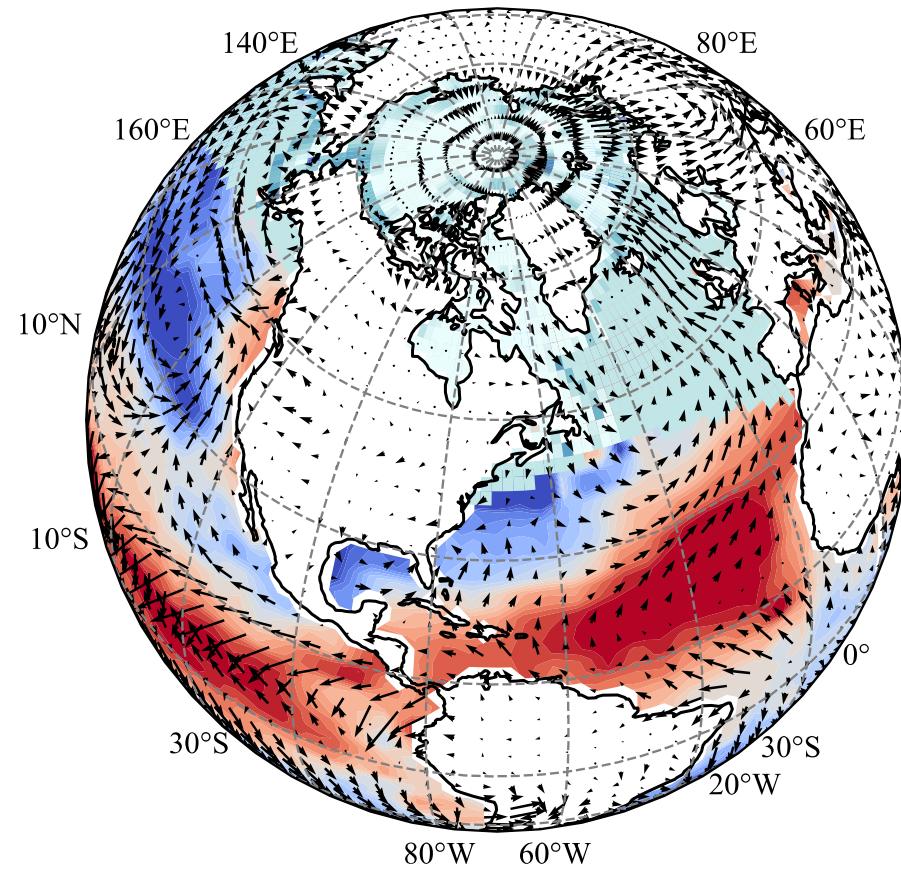
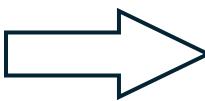
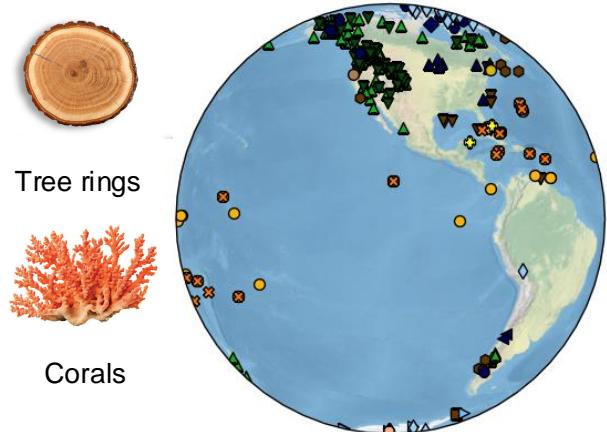
- Satellite era is short (1970s ~ Now).
- Climate variability (e.g., ENSO, PDO and AMO) is poorly sampled.
- The internal and forced variability is mixed.
- A gridded seasonal reanalysis over the last millennium is crucial.

Objective

Global Climate Model



Global Proxy Records

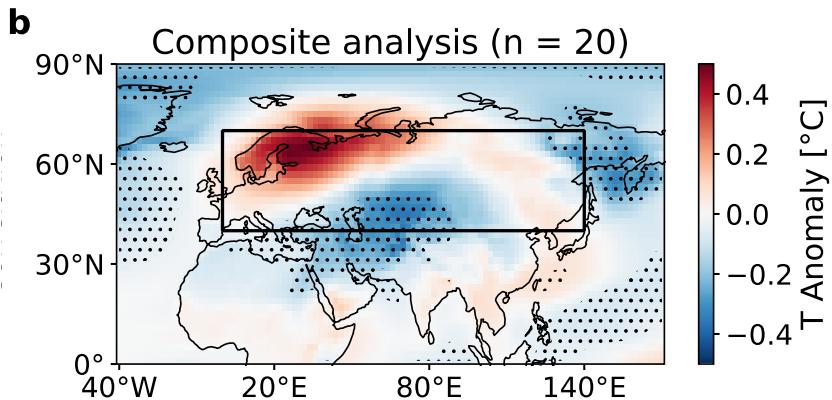
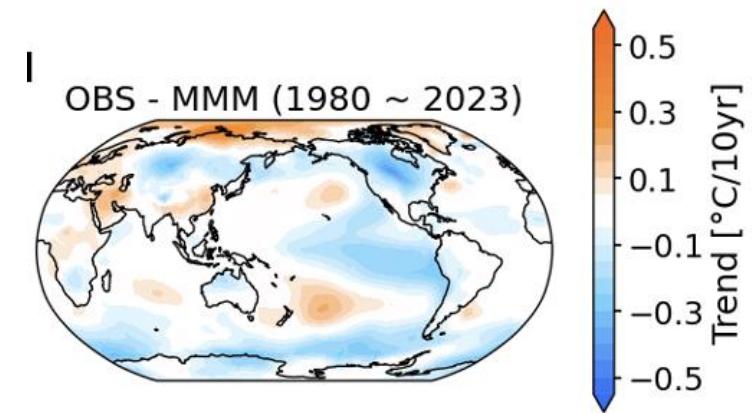


- Atmosphere, Sea-ice and Ocean coupled
- Spatially Gridded
- **1st** Seasonal Temporal Resolution
Reanalysis over the Last Millennium

Applications

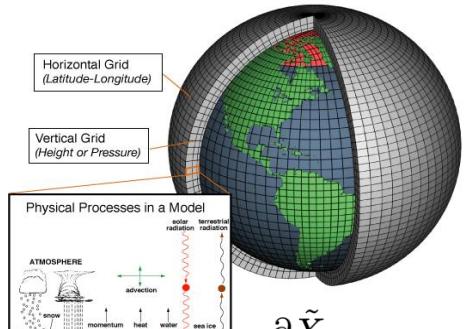


- Climate condition over the Last Millennium, **Medieval Climate Anomaly (Warm)**, Little Ice Age (Cold).
- Greenland's Vikings' history
- Recent temperature trend difference between climate models and observations.

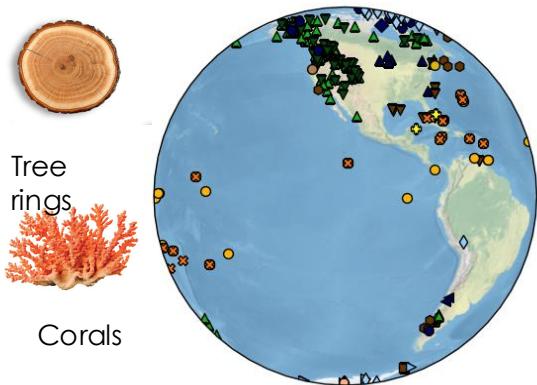


- How does the Eurasian temperature response to large tropical volcanic eruption?

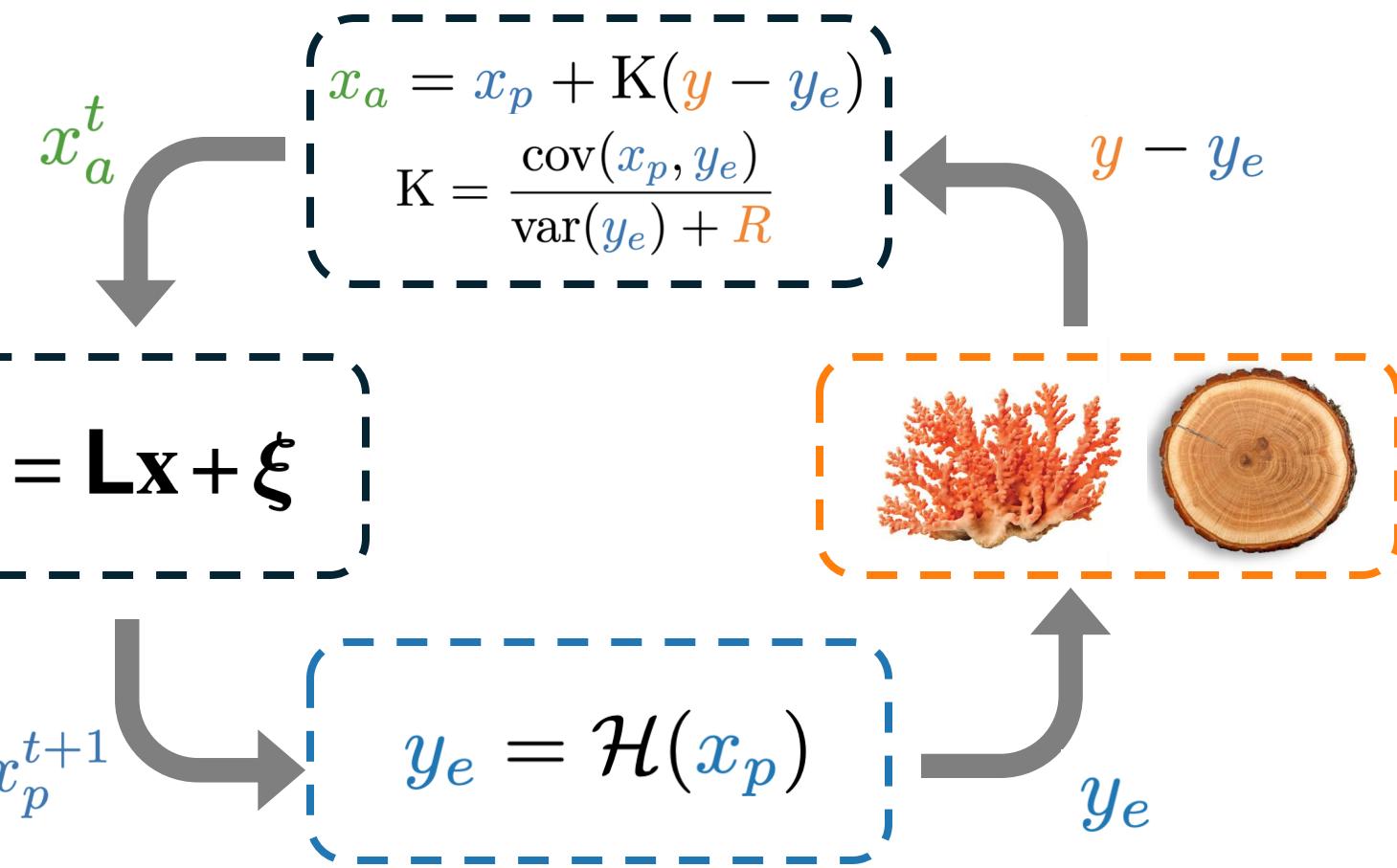
Global Climate Model



$$\frac{\partial \tilde{X}}{\partial t} = \Phi(\tilde{X})$$



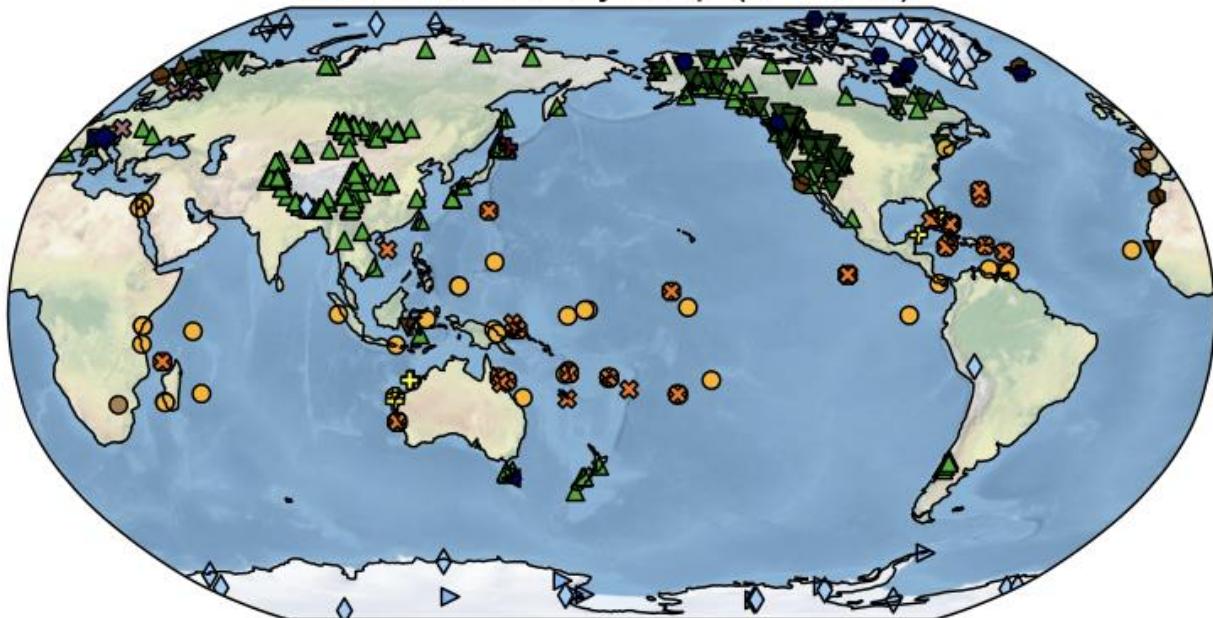
Global Proxy Records



Method

Proxy System Model

Available Proxy Map (n = 521)



- ▲ tree.TRW (n=297)
- ▼ tree.MXD (n=61)
- speleothem.d18O (n=3)
- ▲ marine.diatom (n=1)
- marine.d18O (n=1)
- marine.alkenone (n=4)
- ▼ marine.MgCa (n=3)
- lake.varve_thickness (n=7)
- ◀ lake.reflectance (n=1)
- ▶ lake.midge (n=1)
- ◆ lake.chironomid (n=1)
- ▼ lake.accumulation (n=1)
- ▷ ice.dD (n=7)
- ◊ ice.d18O (n=30)
- + hybrid (n=1)
- * documents (n=3)
- coral.d18O (n=62)
- + coral.calc (n=7)
- ✗ coral.SrCa (n=29)
- bivalve.d18O (n=1)

$$y_e = \mathcal{H}(x_p)$$

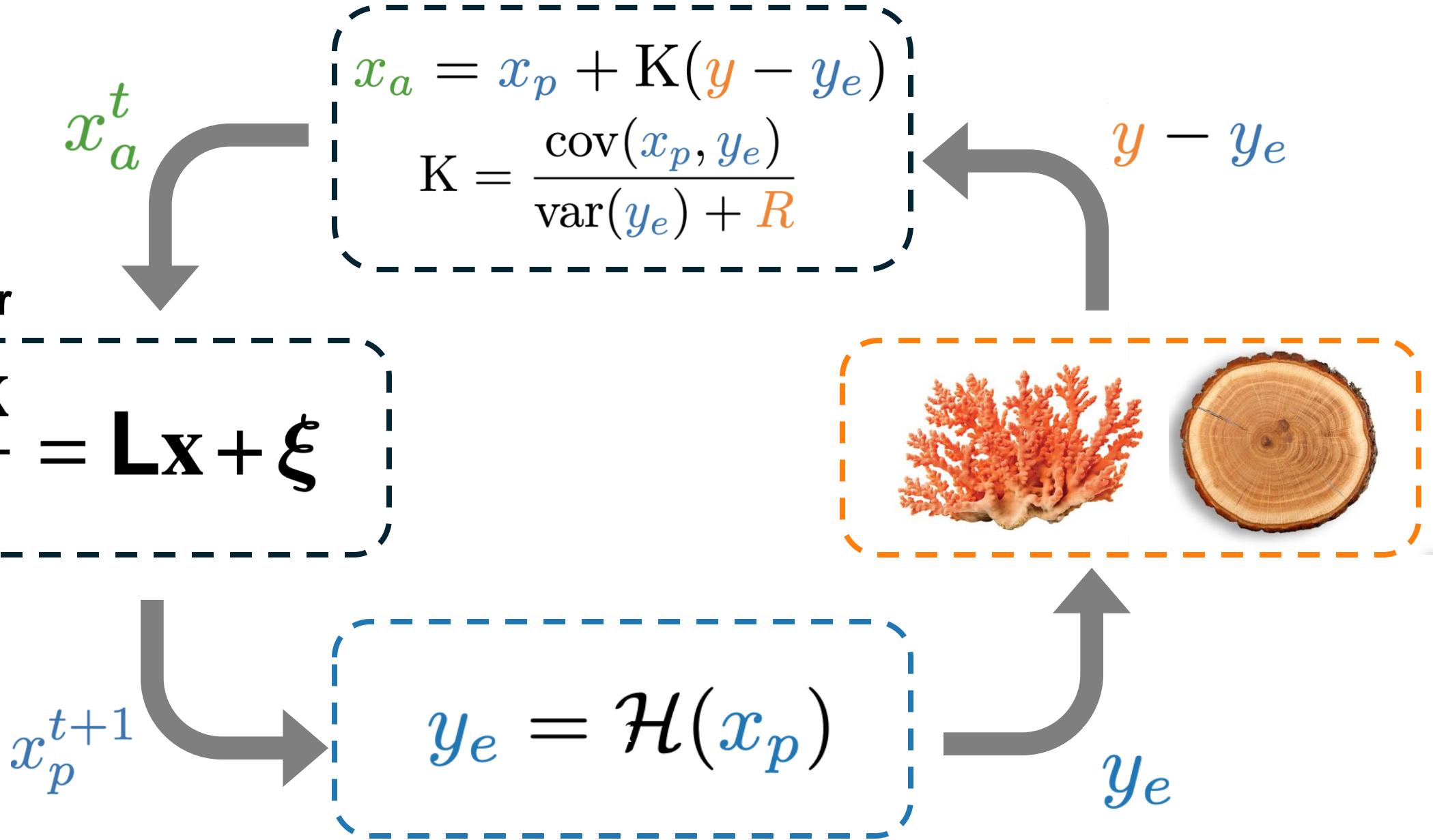


$\delta^{18}O$

SST

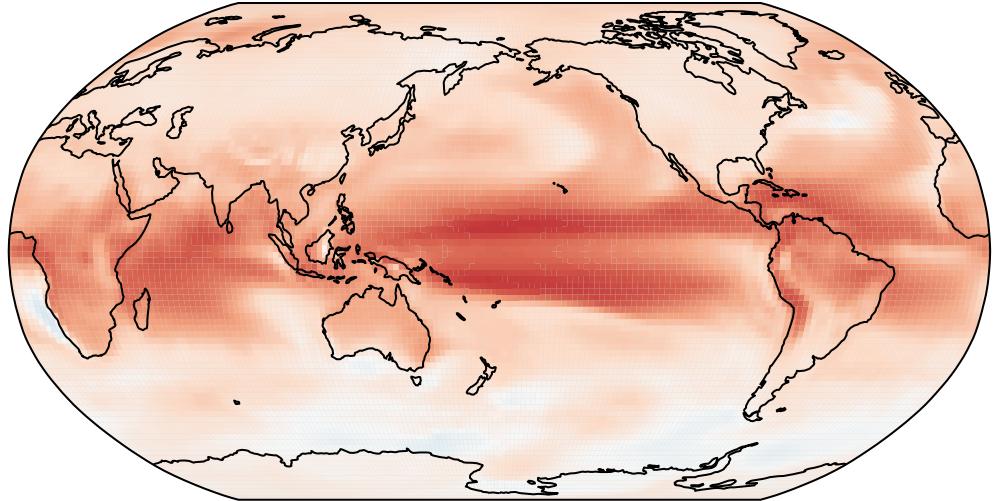
Method Summary – LMR Seasonal Framework

Climate
Model
Emulator

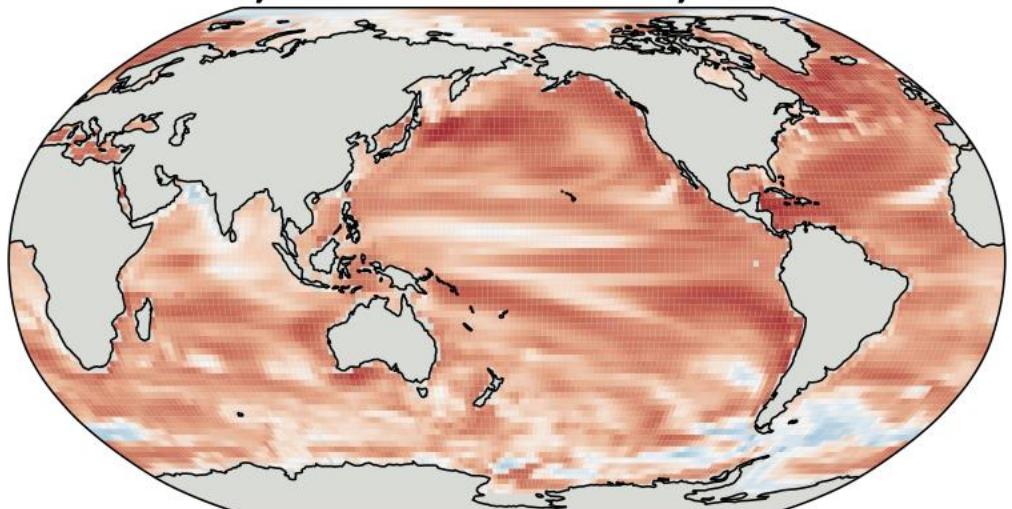


Why Coupled?

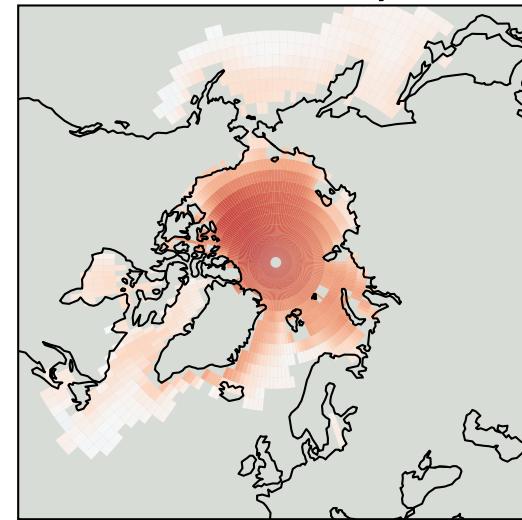
a. TAS; lead = 12 month; corr = 0.23



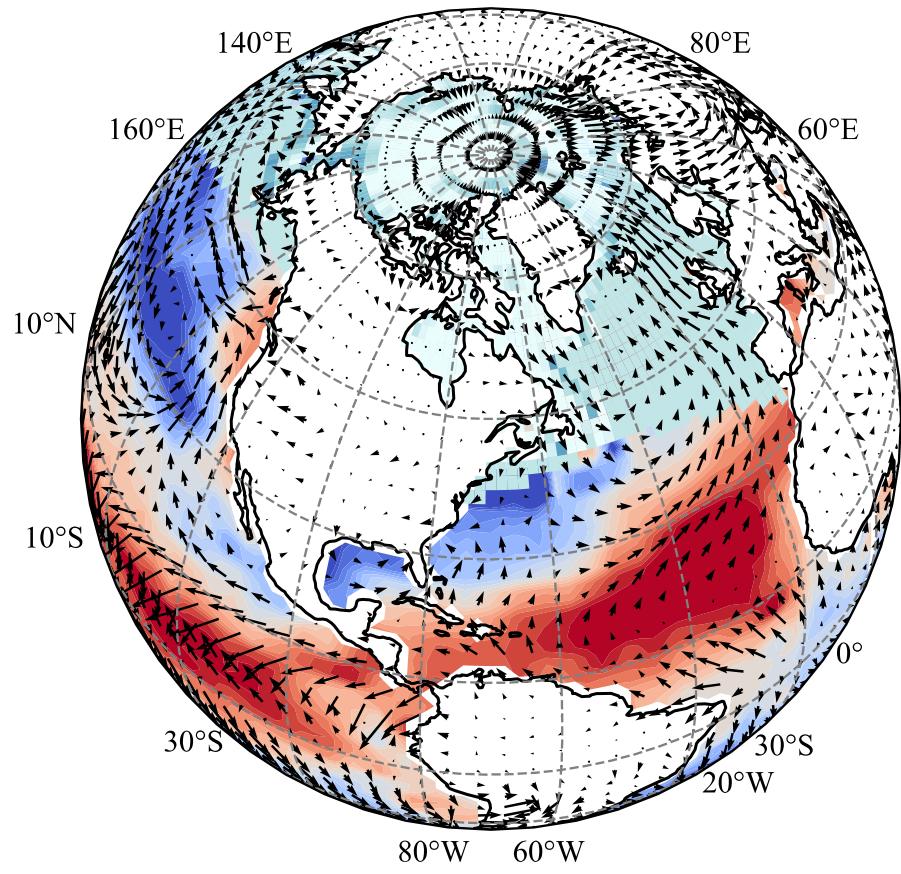
c. OHC300; lead = 12 month; corr = 0.35



e. SIT; lead = 12 month; corr = 0.39



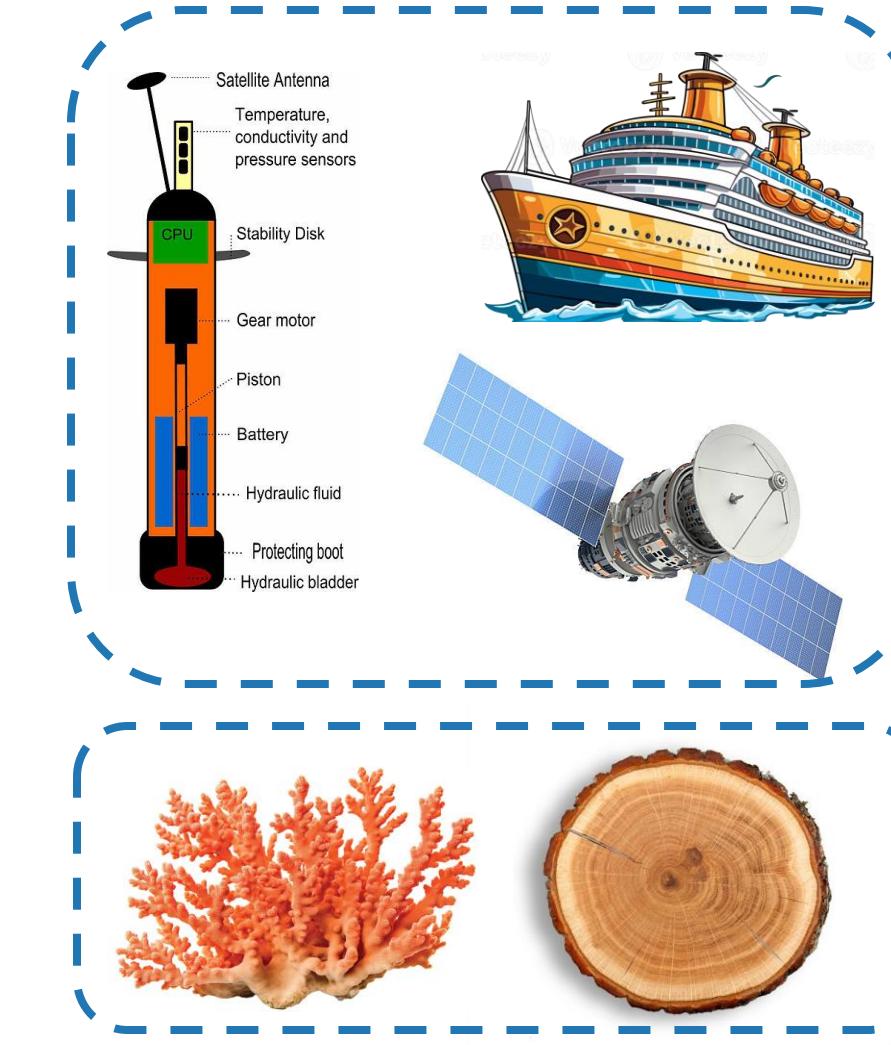
- Ocean Heat Content (OHC) and Sea Ice Thickness (SIT) high predictability
- Reconstruct Oceanic and sea-ice variabilities
- **1st** Sea Ice Volume reconstructions over the last millennium



Reconstruction

VS

VS



Verification

Instrumental Verification

- Compare reconstruction with instrumental dataset (reanalysis, satellite).
- Compare with other Last Millennium DA reconstructions:

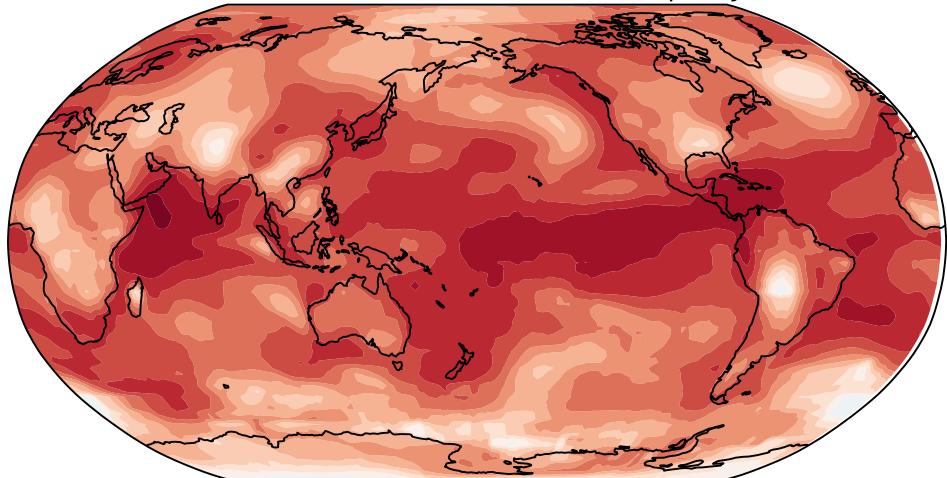
TABLE 1. Summary of Data Assimilation Products over the Last Millennium

Name	PDA Method	$N_{\text{proxy}}^{\text{1}}$	Time Resolution	Reference
PHYDA	Offline	2978	(Sub)Annual ²	Steiger et al. (2018)
LMR v2	Offline	2250	Annual	Tardif et al. (2019)
LMR Online	Online	545	Annual	Perkins and Hakim (2021)
LMR Seasonal	Online	521	Seasonal ³	this study

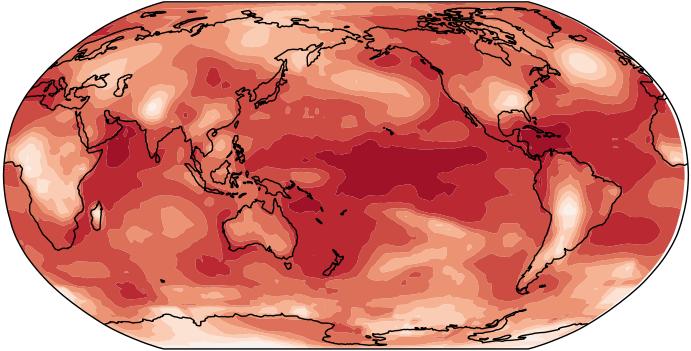
Annual Mean Temperature

Reconstructed **Annual Mean Temperature** vs.
HadCRUT5 (1880 ~ 2000)

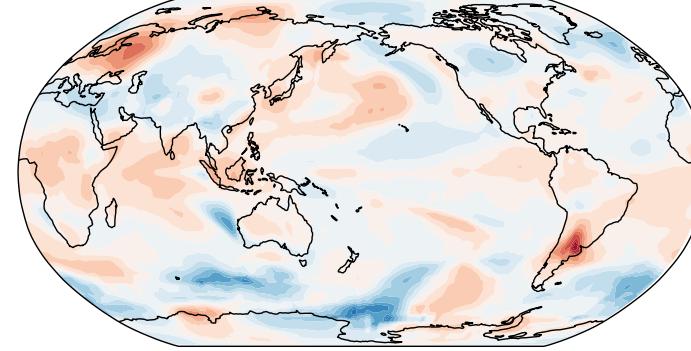
a LMR Seasonal (mean = 0.54, $N_{proxy} = 521$)



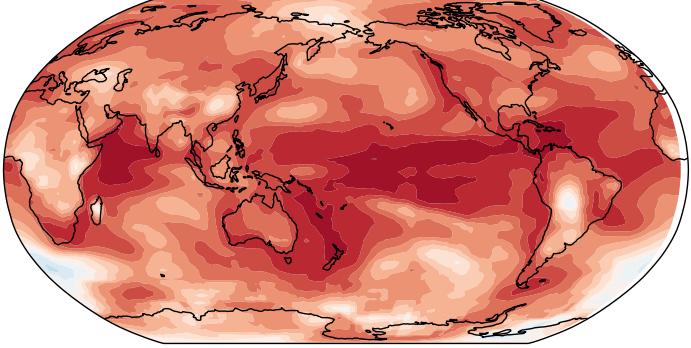
b LMRv2 (mean = 0.53, $N_{proxy} = 2250$)



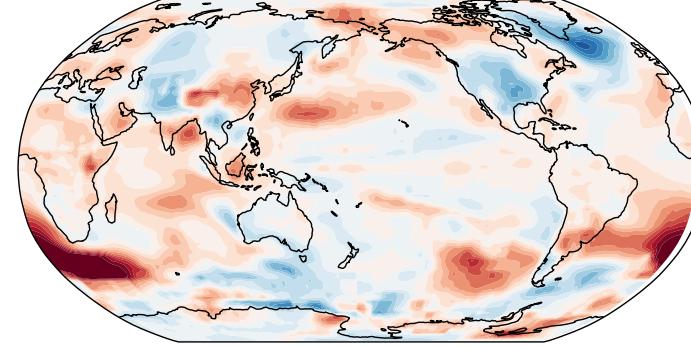
e LMR Seasonal - LMRv2 (mean = 0.01)



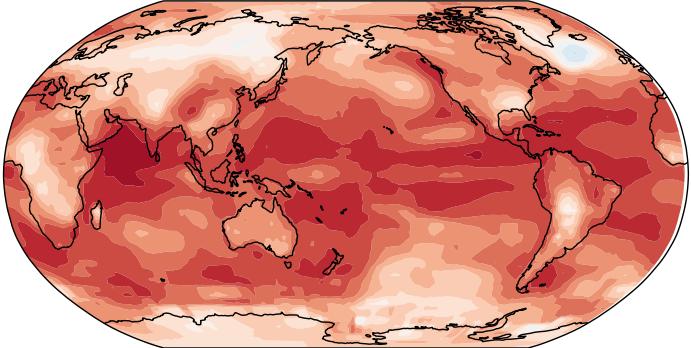
c PHYDA (mean = 0.50, $N_{proxy} = 2978$)



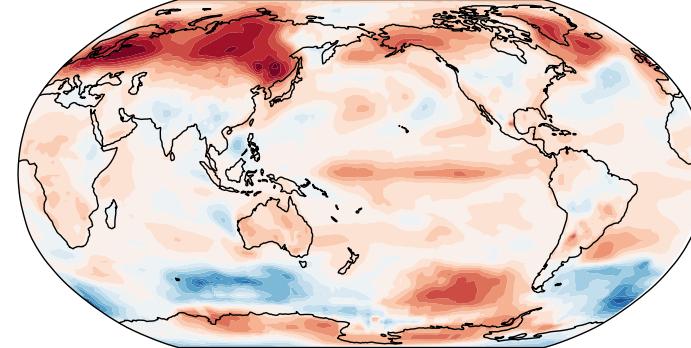
f LMR Seasonal - PHYDA (mean = 0.04)



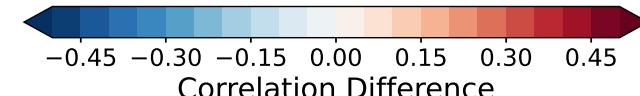
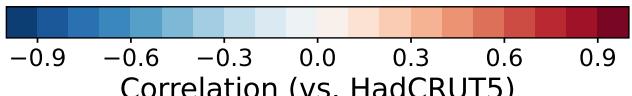
d LMR Online (mean = 0.47, $N_{proxy} = 545$)



g LMR Seasonal - LMR Online (mean = 0.07)

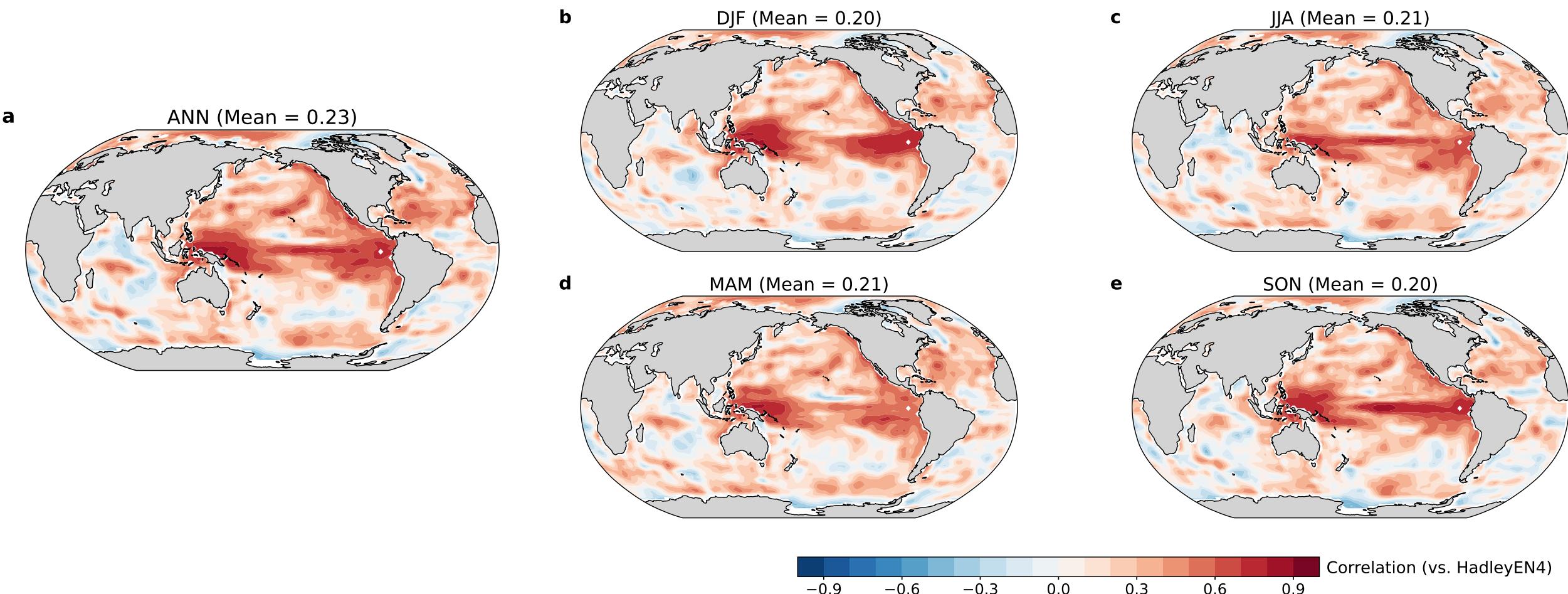


- Achieve the highest correlation skill, while using fewer proxies



Ocean Heat Content (OHC)

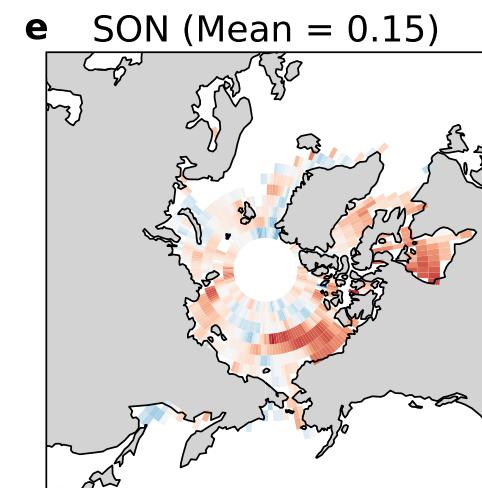
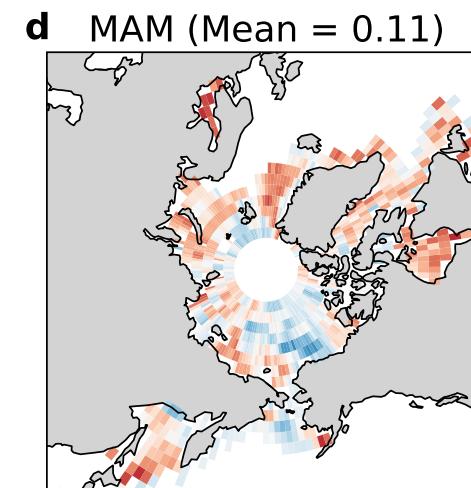
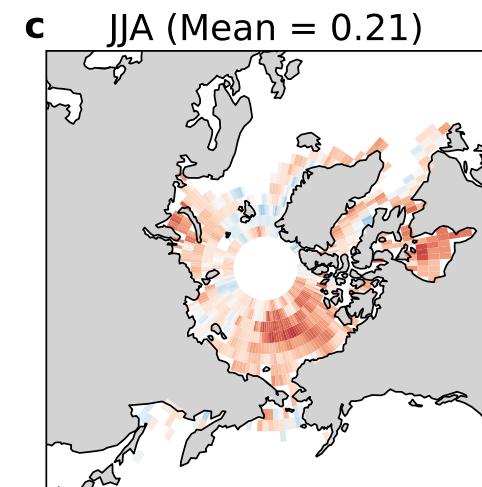
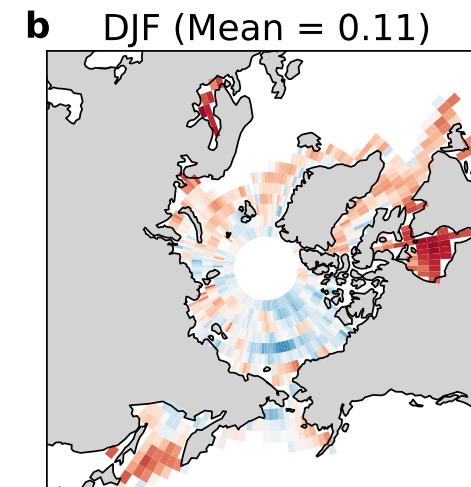
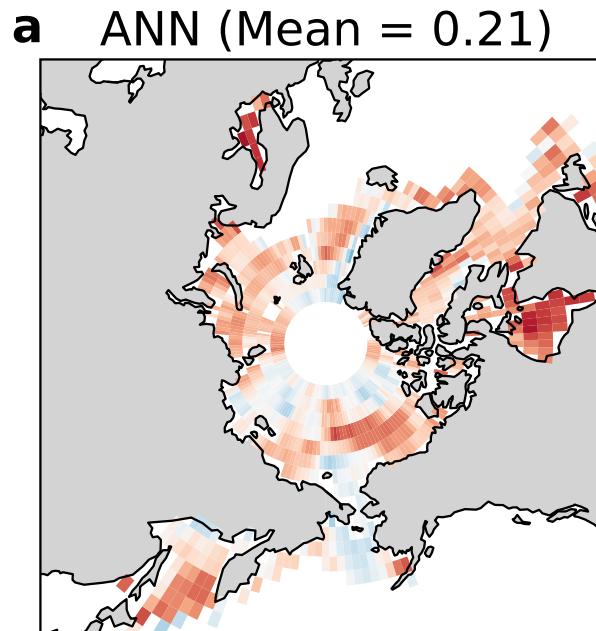
Reconstructed Ocean Heat Content vs. HadEN4 (1880 ~ 2000)



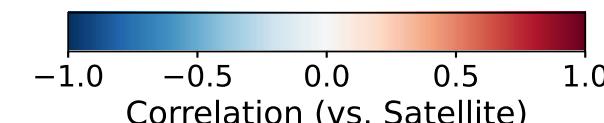
- Without direct observations on OHC.
- Skill is highest in the tropical Pacific, the eastern North Pacific, and northern Atlantic Ocean regions.

Sea Ice Concentration (SIC)

Reconstructed SIC vs. satellite observation (Fetterer et al. 2017)



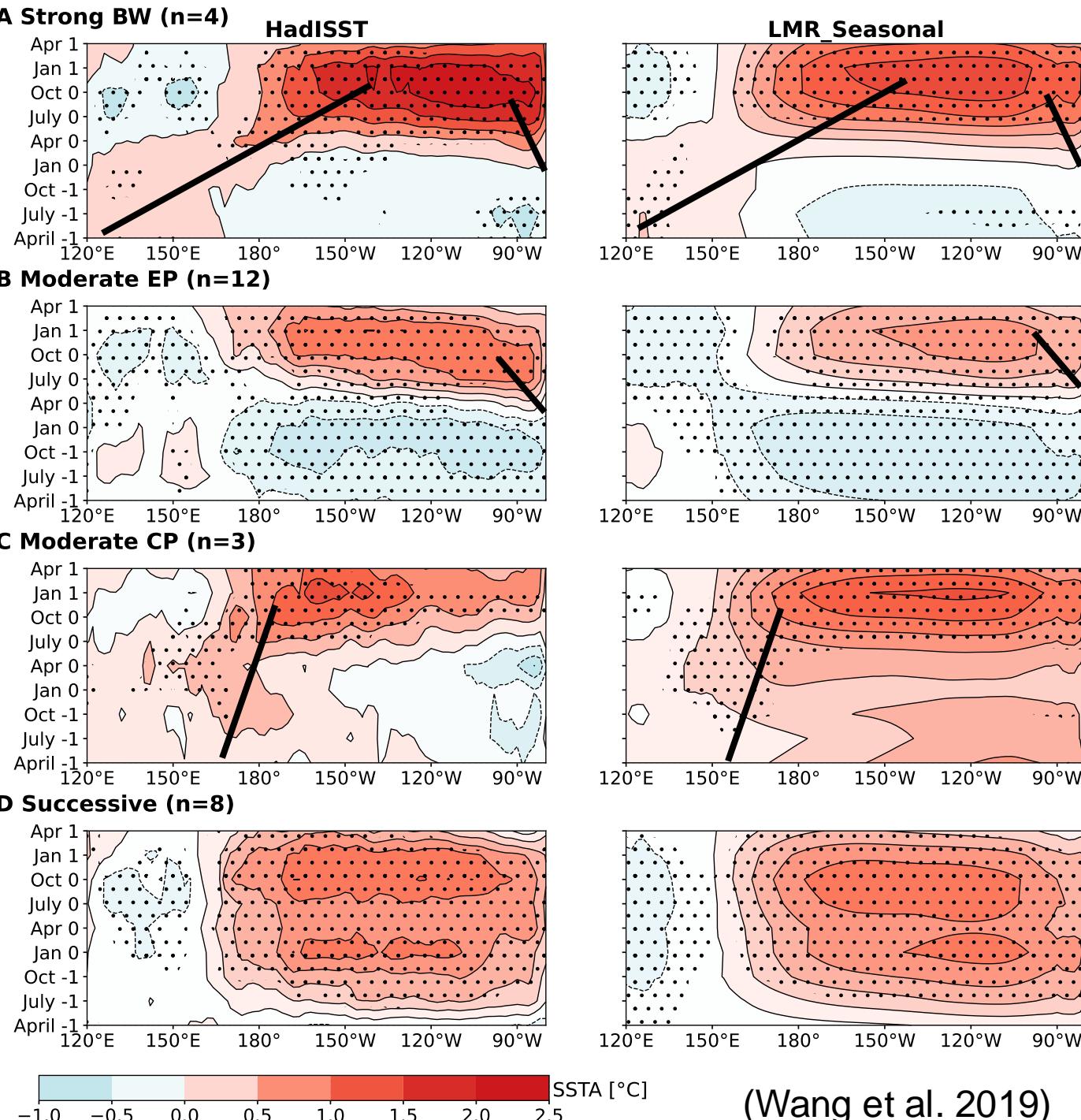
- Without direct observations on SIC.
- Skill is highest in Hudson Bay, and near sea-ice edges, especially around Greenland and the Barents Sea.



El Niño Evolution

Reconstructed El Niño evolution vs. HadISST
(1900 ~ 2000)

- LMR Seasonal successfully captures most of the seasonal evolution of four El Niño classes
- El Niño Evolution over the last millennium?



(Wang et al. 2019)

Independent Proxy Verification

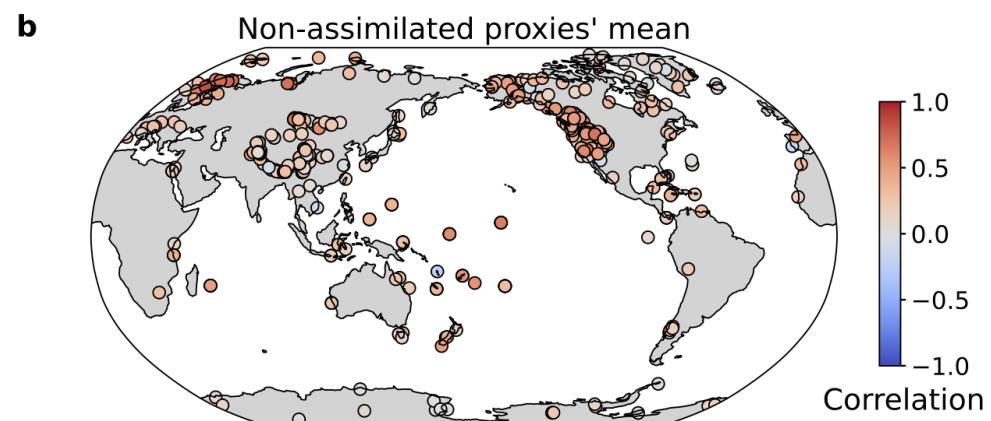
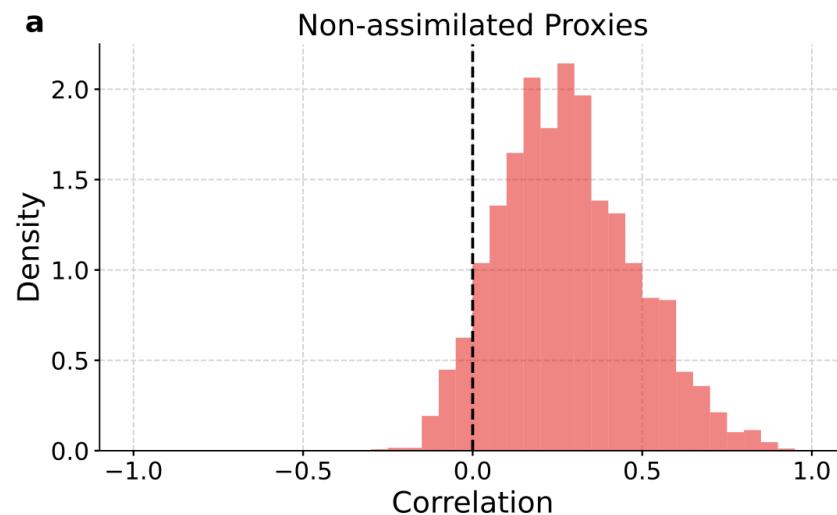
Assimilate 75% Proxies

Randomly Drop 25% Proxies

X25 times

$$y_e = \mathcal{H}(x_a)$$

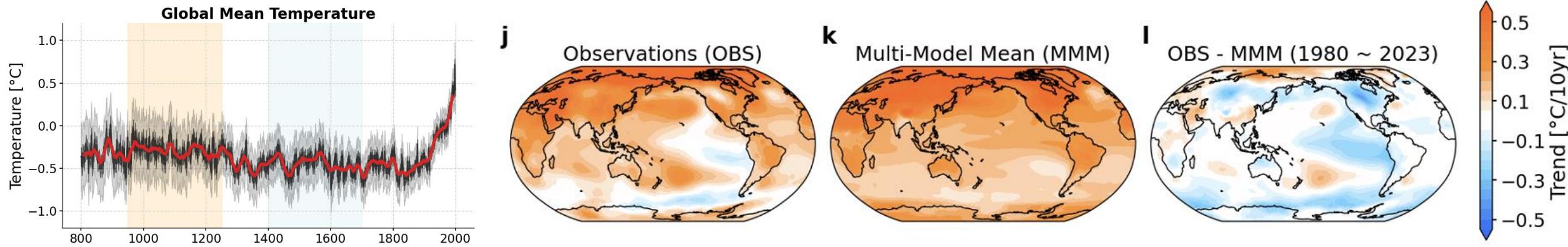
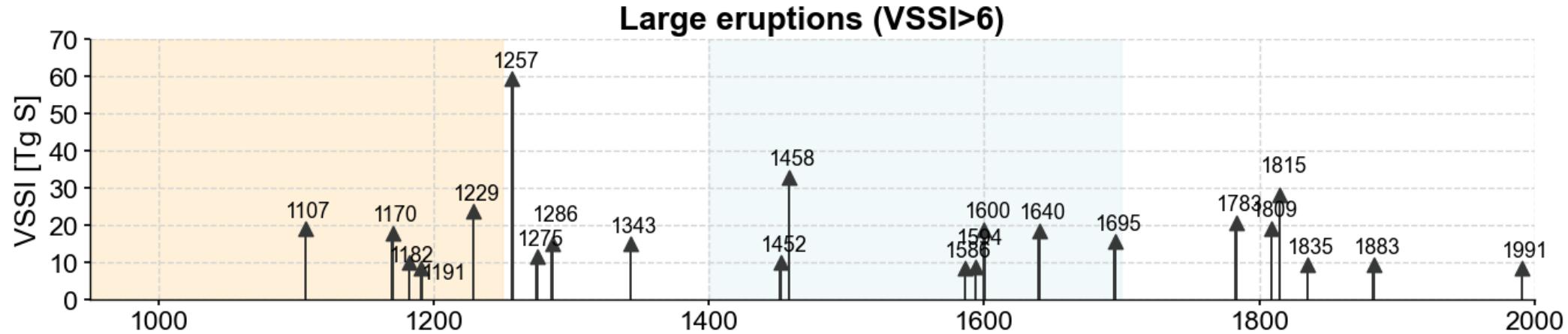
$$\text{corr}(y_e, y)$$



- Verification against independent proxy records shows that reconstruction skill is robust throughout the last millennium.

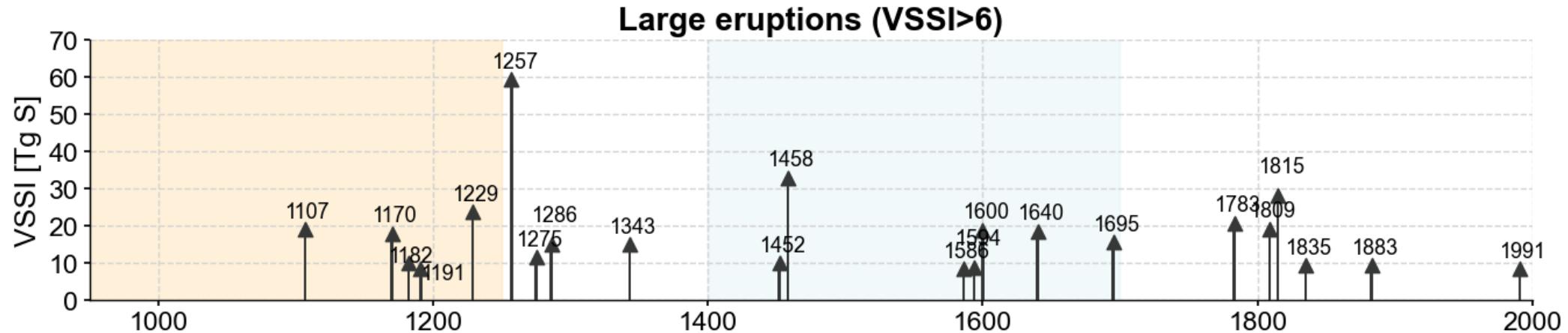
Verification Summary

- Instrumental verification (1880 ~ 2000):
 - LMR Seasonal achieves the highest correlation skill using fewer proxies in surface temperature.
 - Reconstructed ocean and sea-ice variables also have high correlation with instrumental and satellite datasets.
 - El Niño evolution is consistent with observation.
- Independent Verification (800 ~ 2000):
 - Independent proxy records show that reconstruction skill is robust throughout the last millennium.



Applications

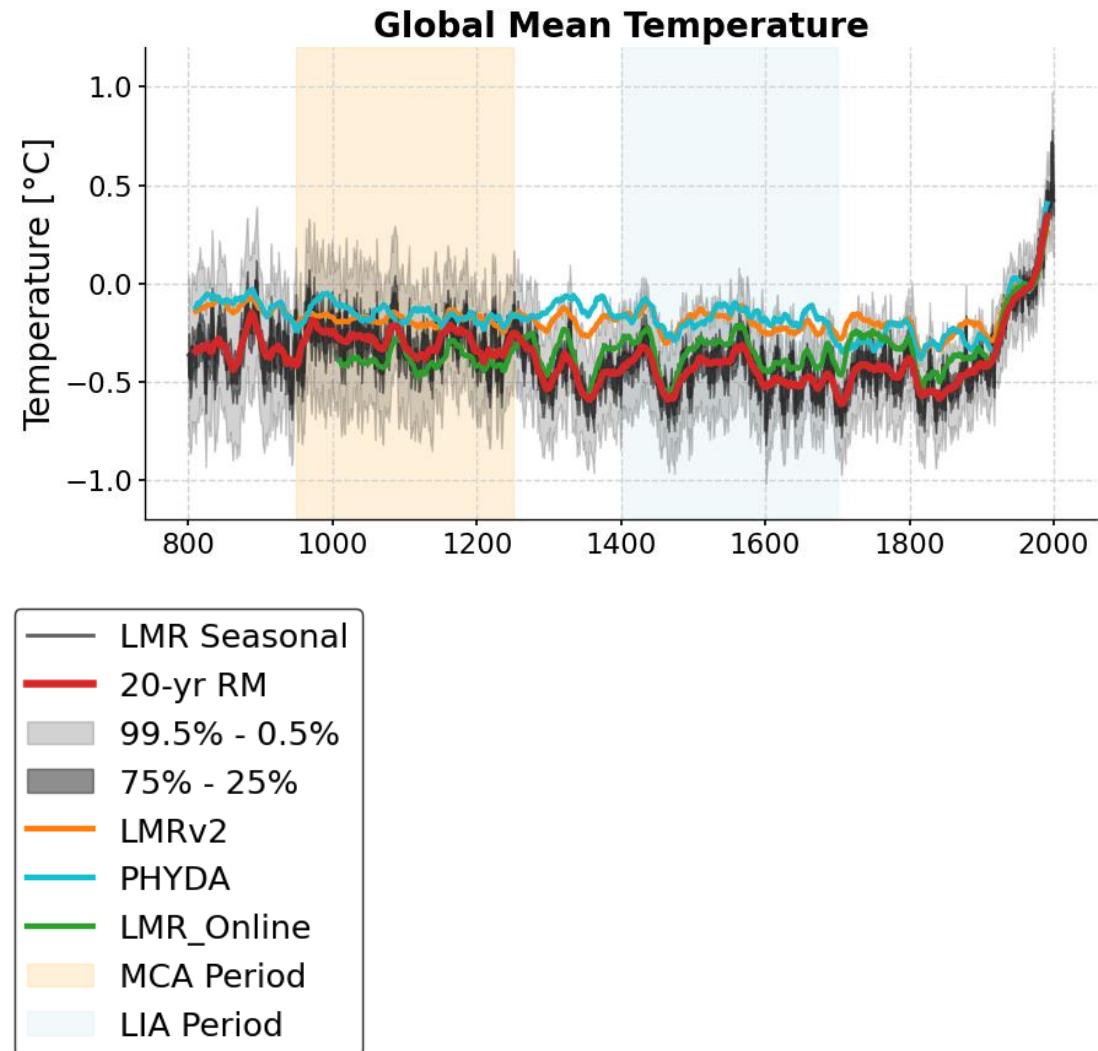
Last Millennium Climate



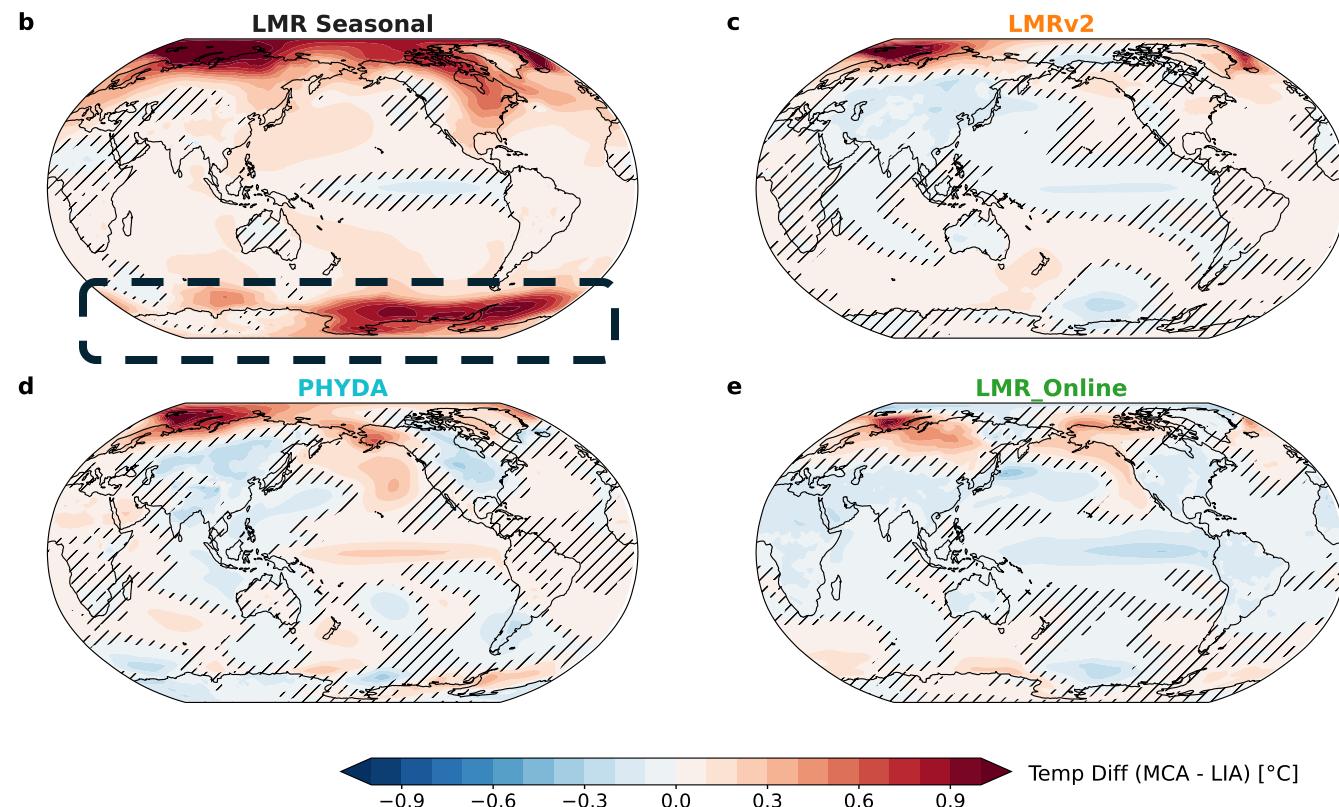
VSSI: volcanic stratospheric sulfur injection (**Teragram**)

- Cool the Earth's climate by releasing particles (Sulfur) into the stratosphere that reflect sunlight back into space.
- Medieval Climate Anomaly (MCA) – Warm, 950CE~1250CE
- Little Ice Age (LIA) – Cold, 1400CE~1700CE

MCA and LIA

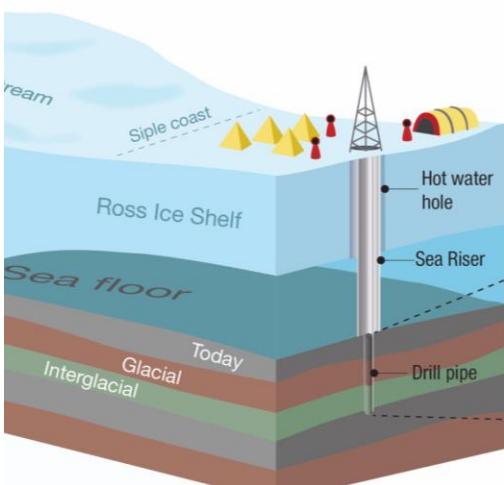


Pattern Difference (MCA - LIA):

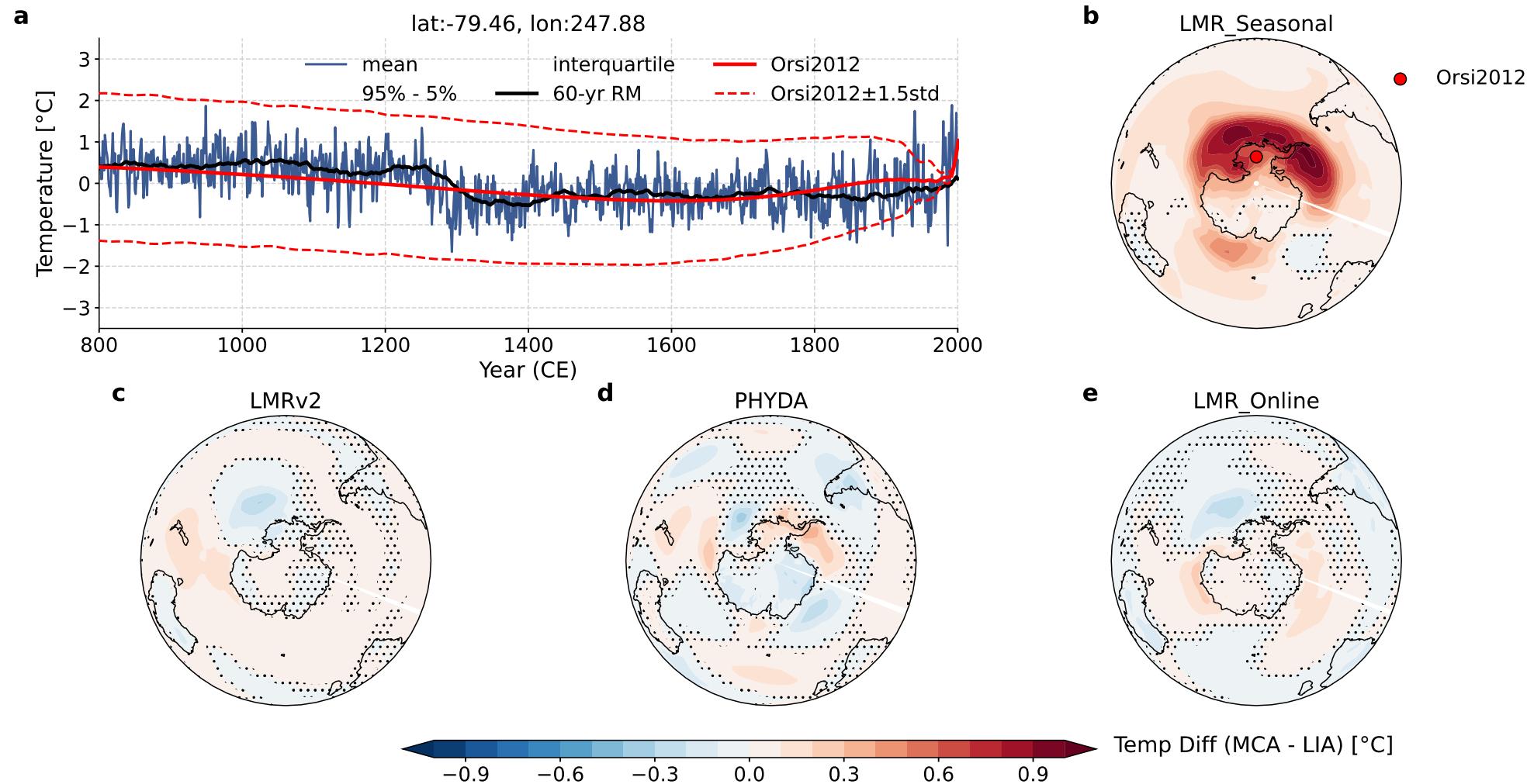


➤ LMR Seasonal reconstructs the global MCA-LIA difference.

MCA and LIA: Borehole Verification

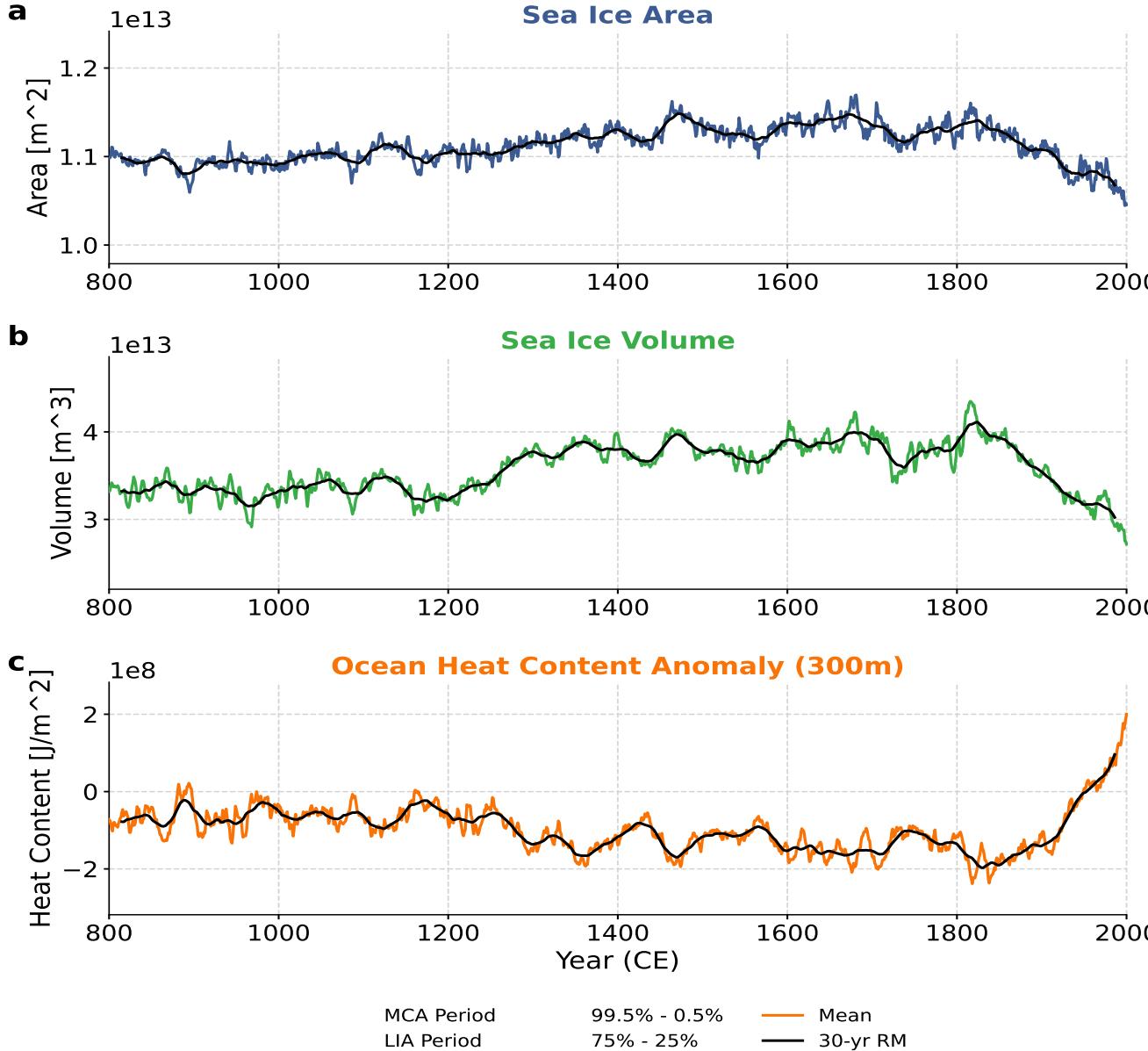


Borehole



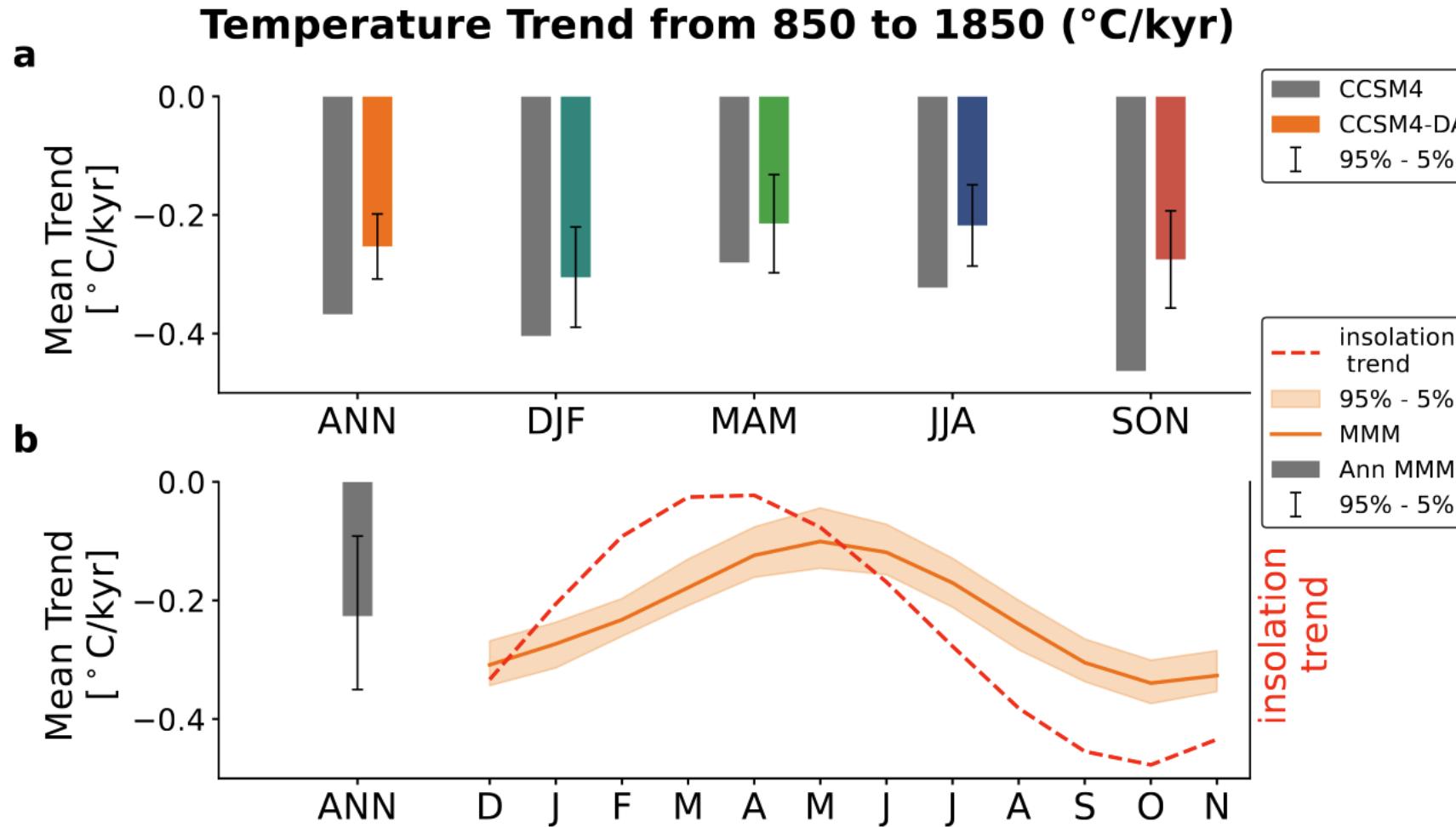
➤ LMR Seasonal is consistent with the western Antarctica borehole.

Last Millennium Climate



➤ MCA and LIA difference can also be seen in other variables.

Last Millennium Temperature Trend



➤ Seasonal
Temperature is
consistent with
orbital forcing.

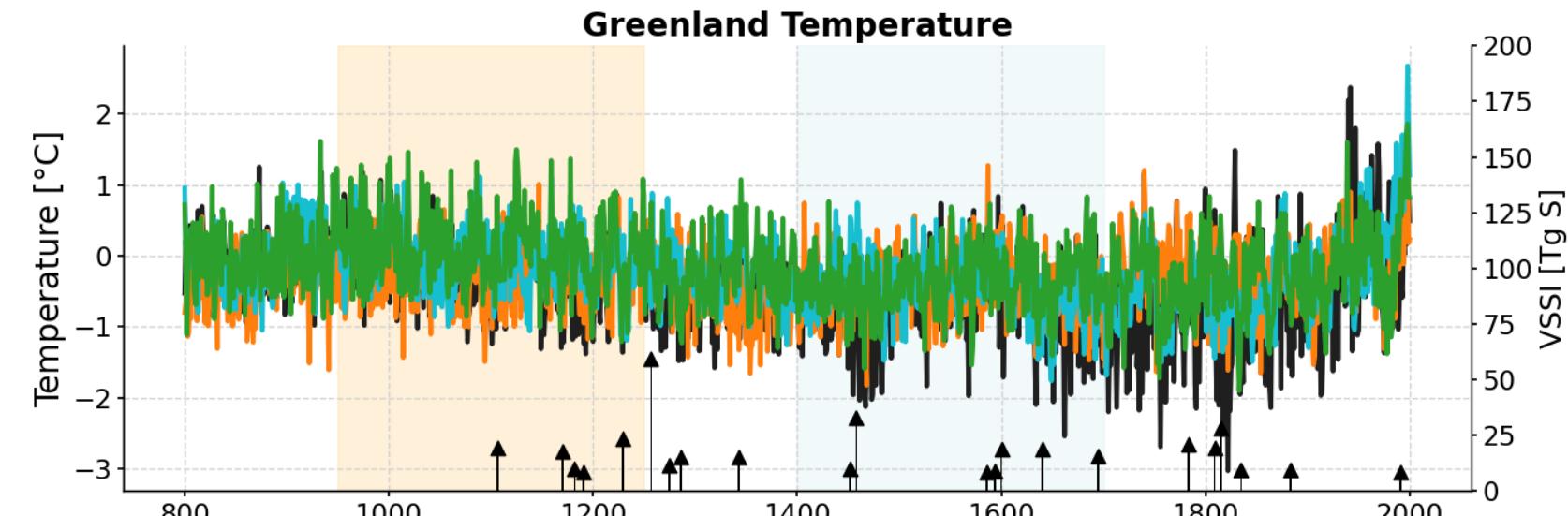
Vikings' History

- Vikings occupied Greenland from 985 CE to the mid-15th century.
- Vikings moved from Iceland to Greenland.
- Vikings disappeared in 15th centuries.

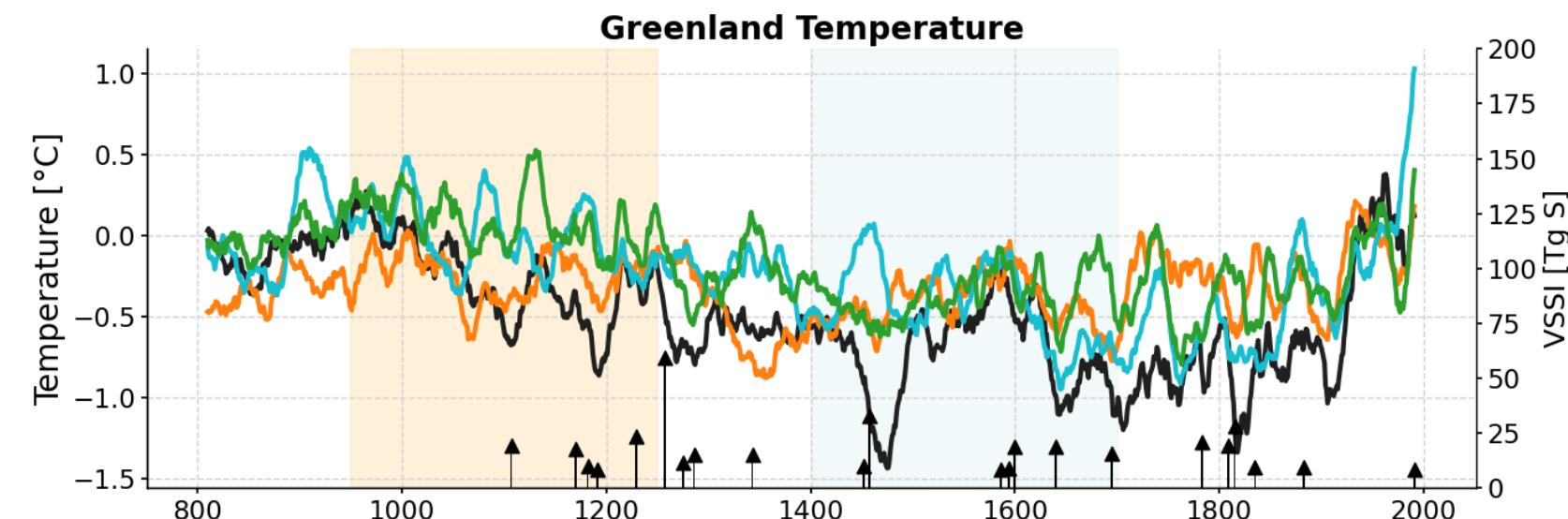
Could we find some climate signal?



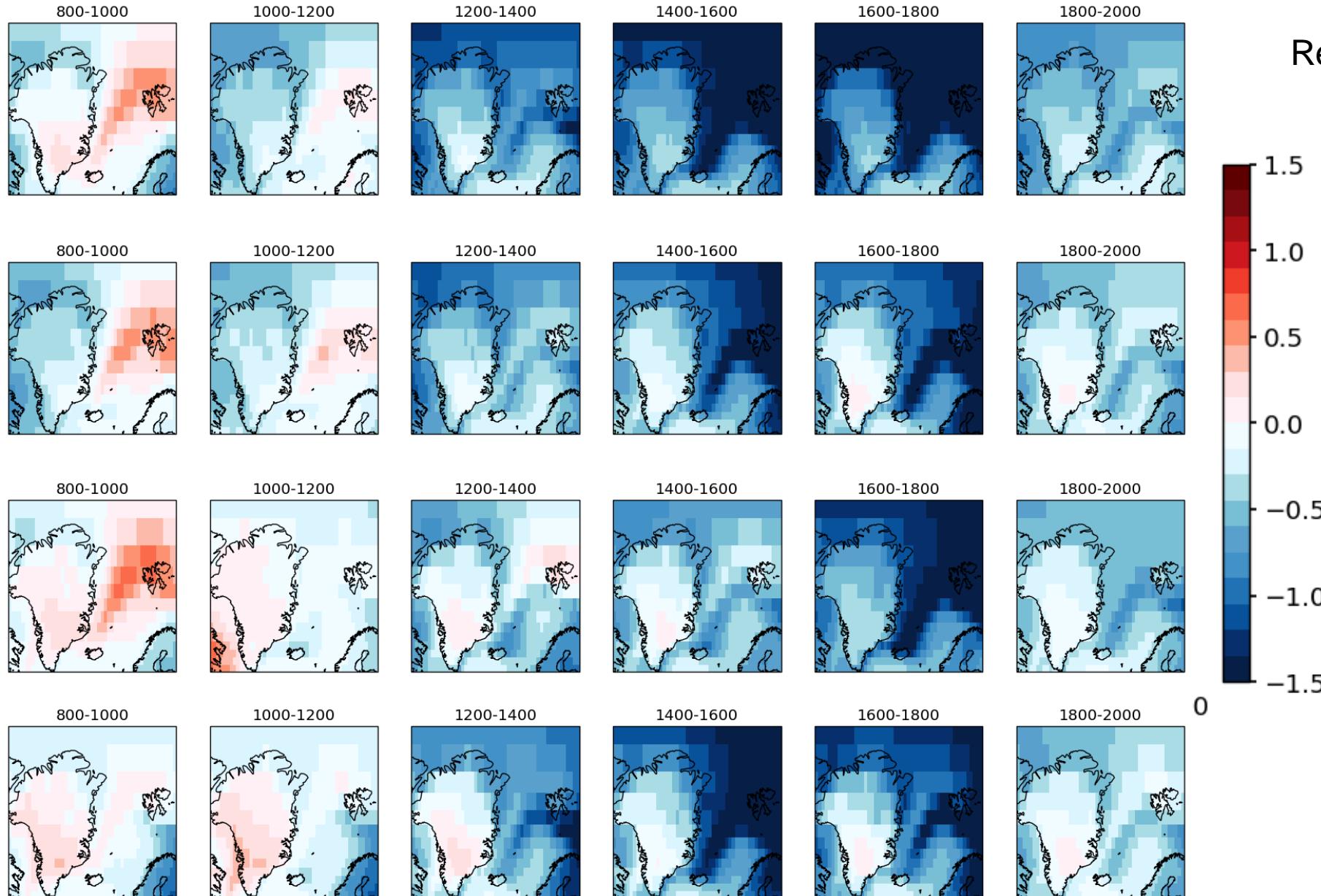
Seasonal Mean Temperature



20 years Running Mean

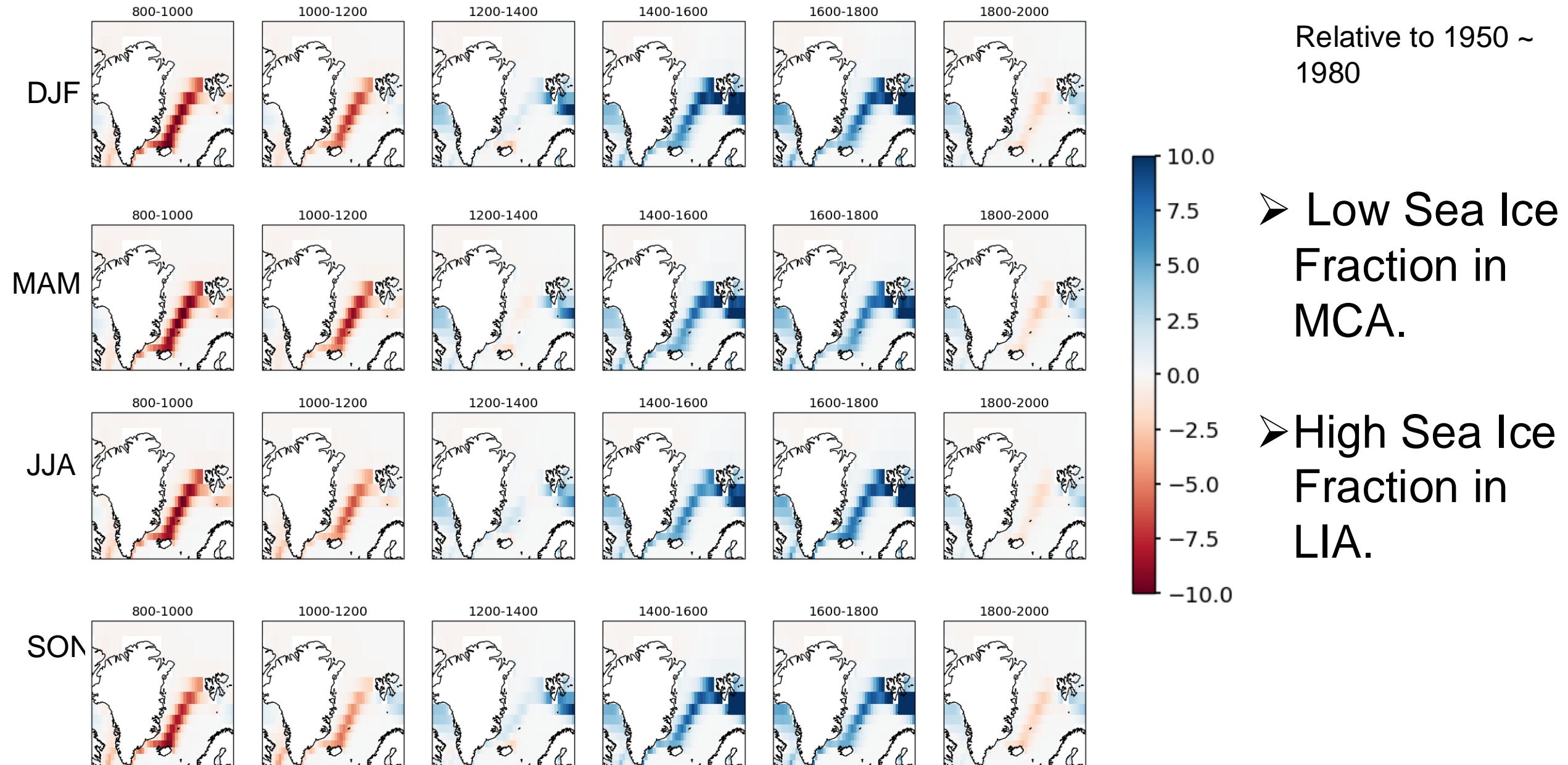


Seasonal Mean Temperature (K)

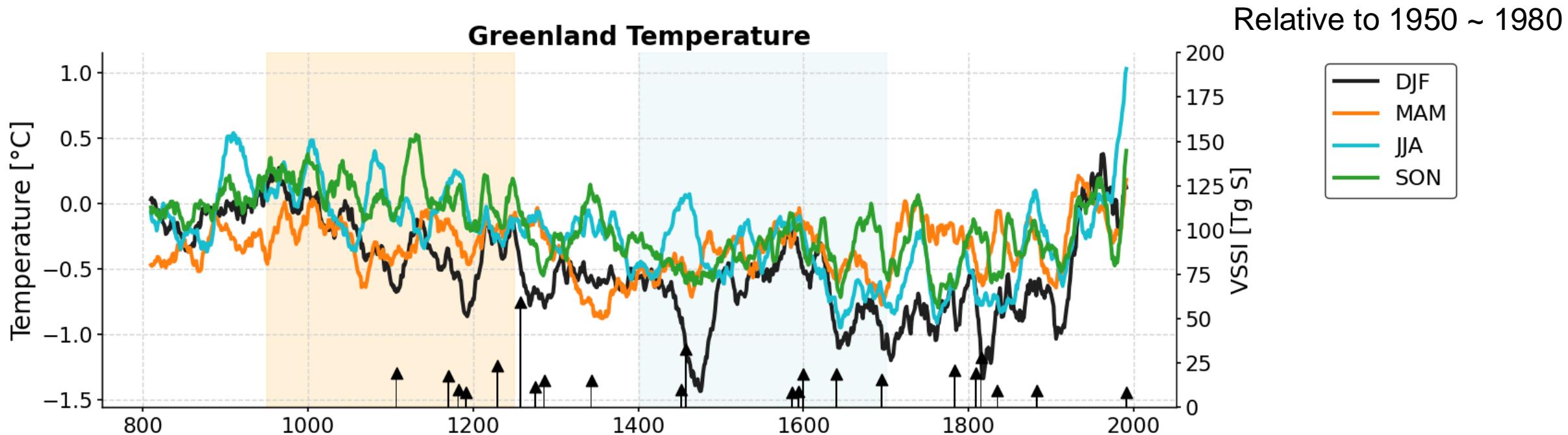


- High JJA Temperature in MCA.
- Low Temperature in LIA.

Seasonal Mean Sea Ice Friction



Vikings' Summary



- High MCA Temperature and low Sea Ice Fraction -> Vikings from Ice land to Greenland.
- Low LIA DJF Temperature -> Vikings' disappearing.

Eurasia response to large tropical volcanic eruption

1) volcanic aerosols from a low-latitude eruption—being longwave absorbers—produce significant warming in the tropical lower stratosphere; 2) through thermal wind balance, the tropical stratospheric warming results in a strengthening of the winter stratospheric polar vortex; and 3) this strengthening causes a positive phase of the North Atlantic Oscillation (NAO), which in turn induces downstream warm surface temperature anomalies over Eurasia. (e.g., Graft et al. 1993)

Climate model simulation of winter warming and summer cooling following the 1991 Mount Pinatubo volcanic eruption

I Kirchner, GL Stenchikov, HF Graf, A Robock, JC Antuña

Journal of Geophysical Research: Atmospheres, 1999 • Wiley Online Library

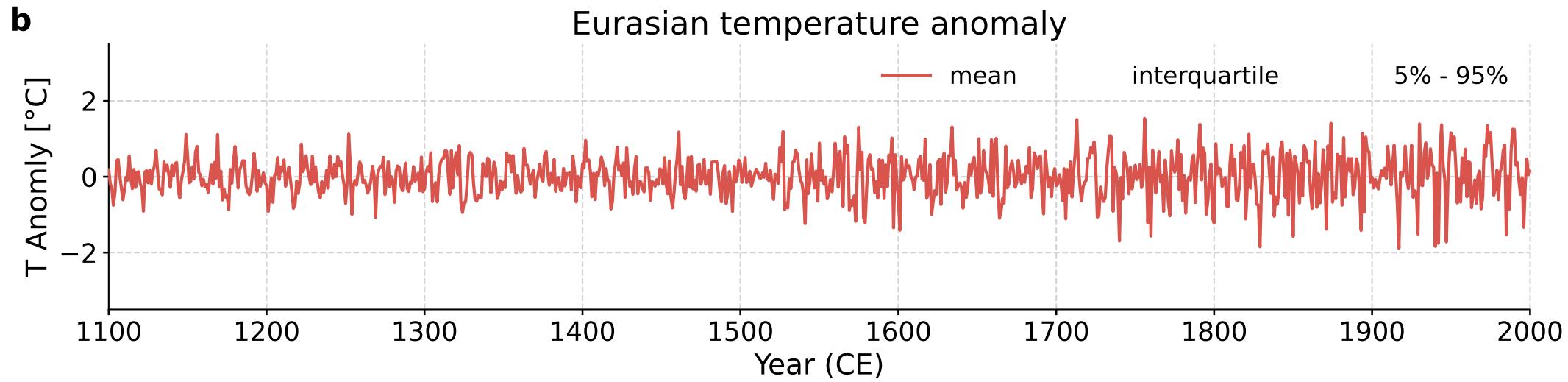
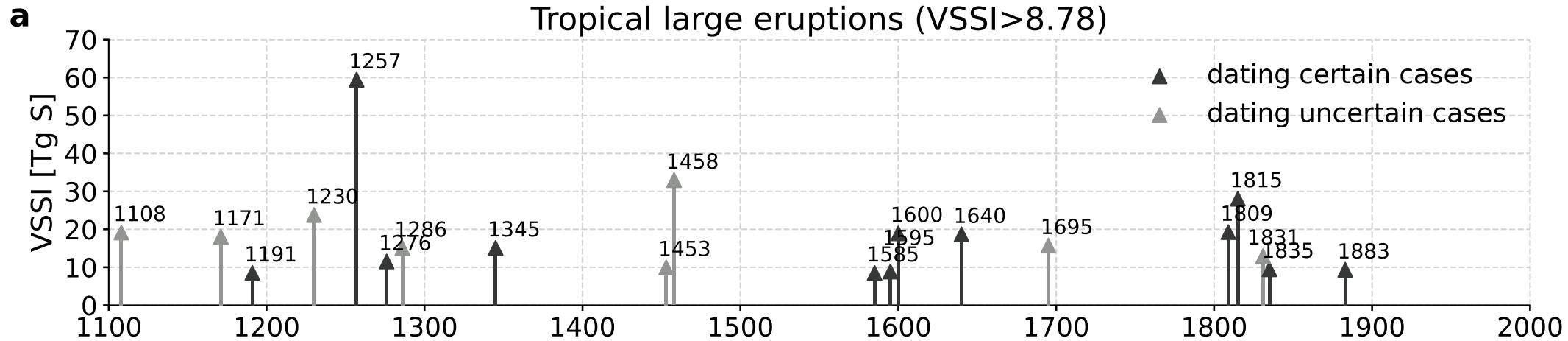
We simulate climate change for the 2-year period following the eruption of Mount Pinatubo in the Philippines on June 15, 1991, with the ECHAM4 general circulation model (GCM). The model was forced by realistic aerosol spatial-time distributions and spectral radiative characteristics calculated using Stratospheric Aerosol and Gas Experiment II extinctions and Upper Atmosphere Research Satellite-retrieved effective radii. We calculate statistical ensembles of GCM simulations with and without volcanic aerosols for 2 years after the

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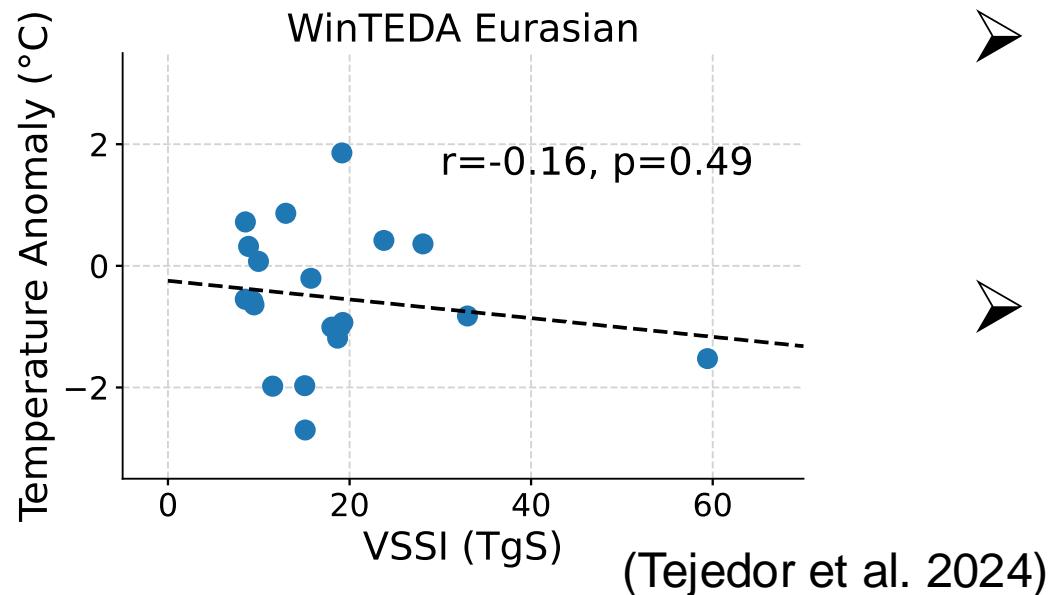
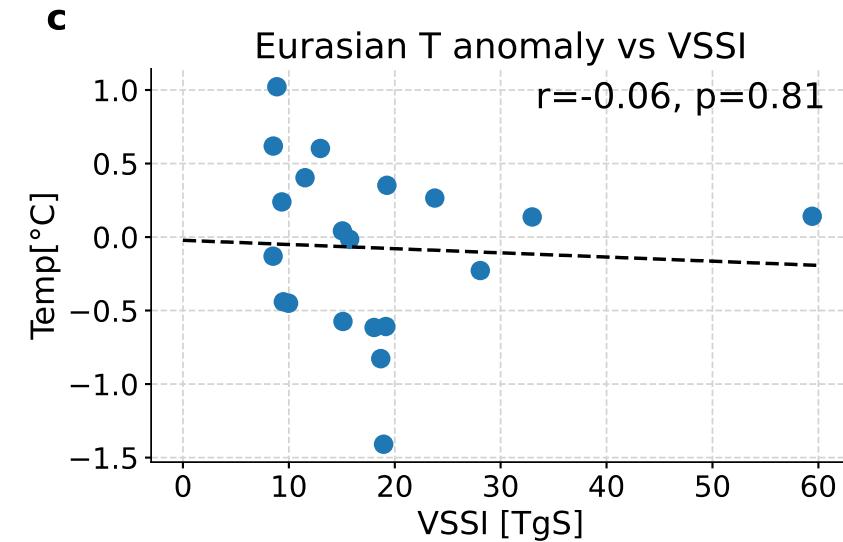
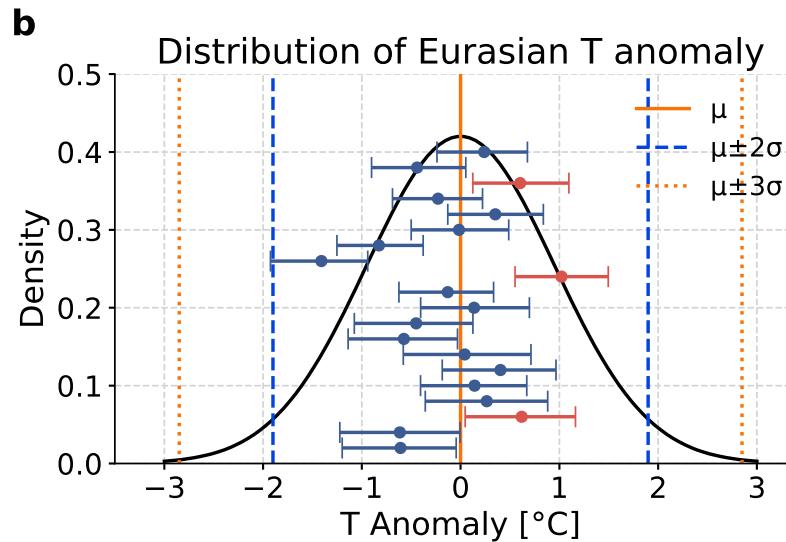
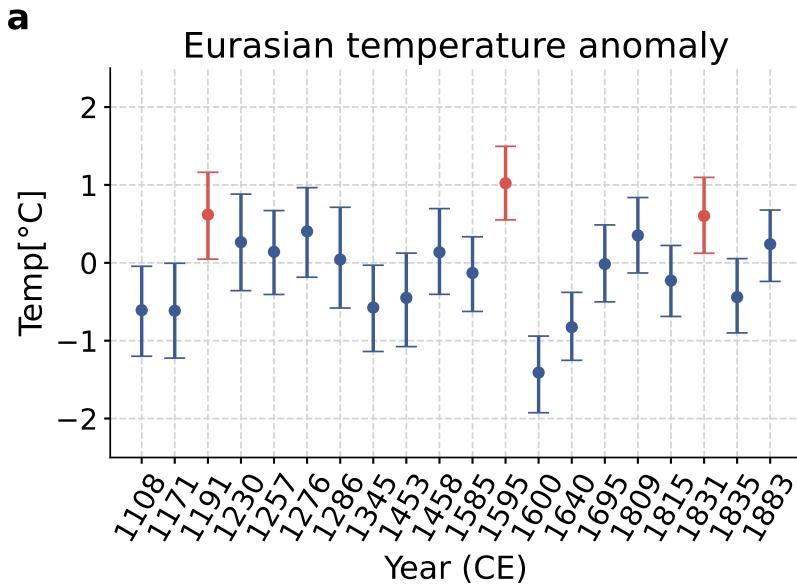
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Low latitude Volcanic Eruption can lead to DJF Eurasia Warming.
True or not True?

Volcanic Eruption and Winter Eurasia

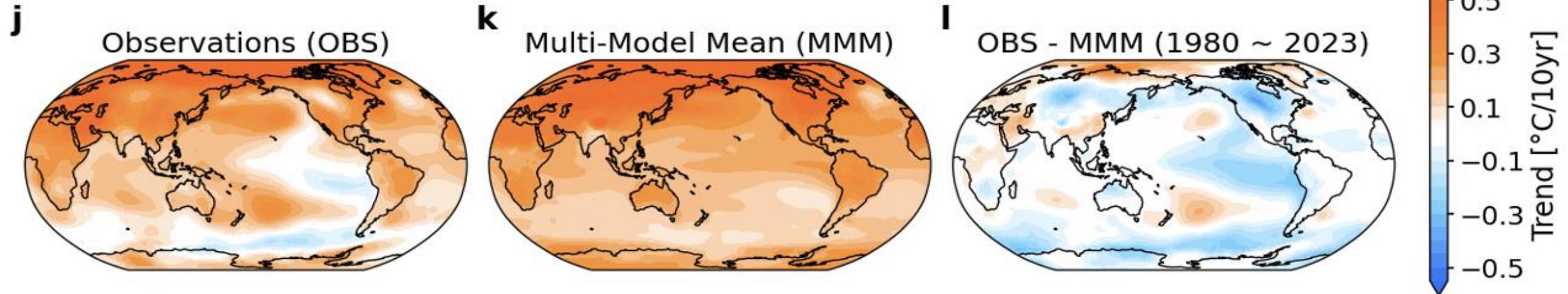


Volcanic Eruption and Winter Eurasia

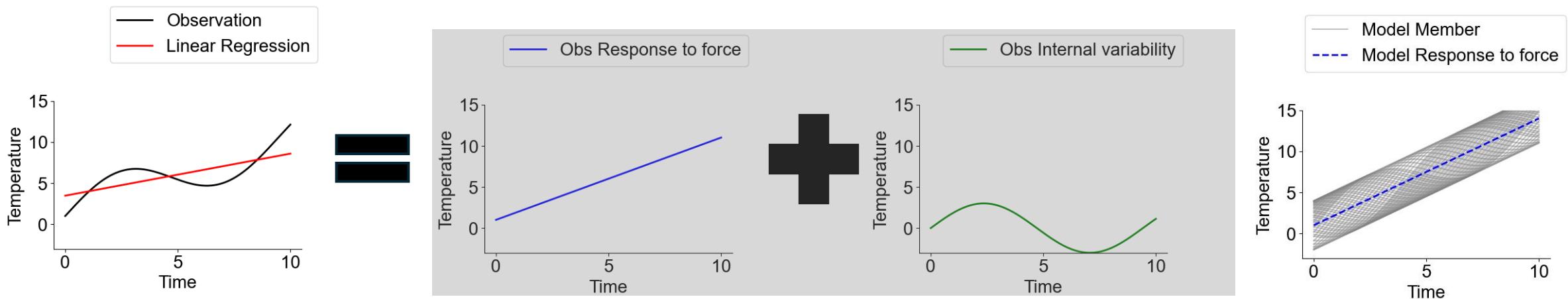


- No significant warming or cooling after volcanic eruption.
- Internal variability may overwhelm any forced volcanic response.

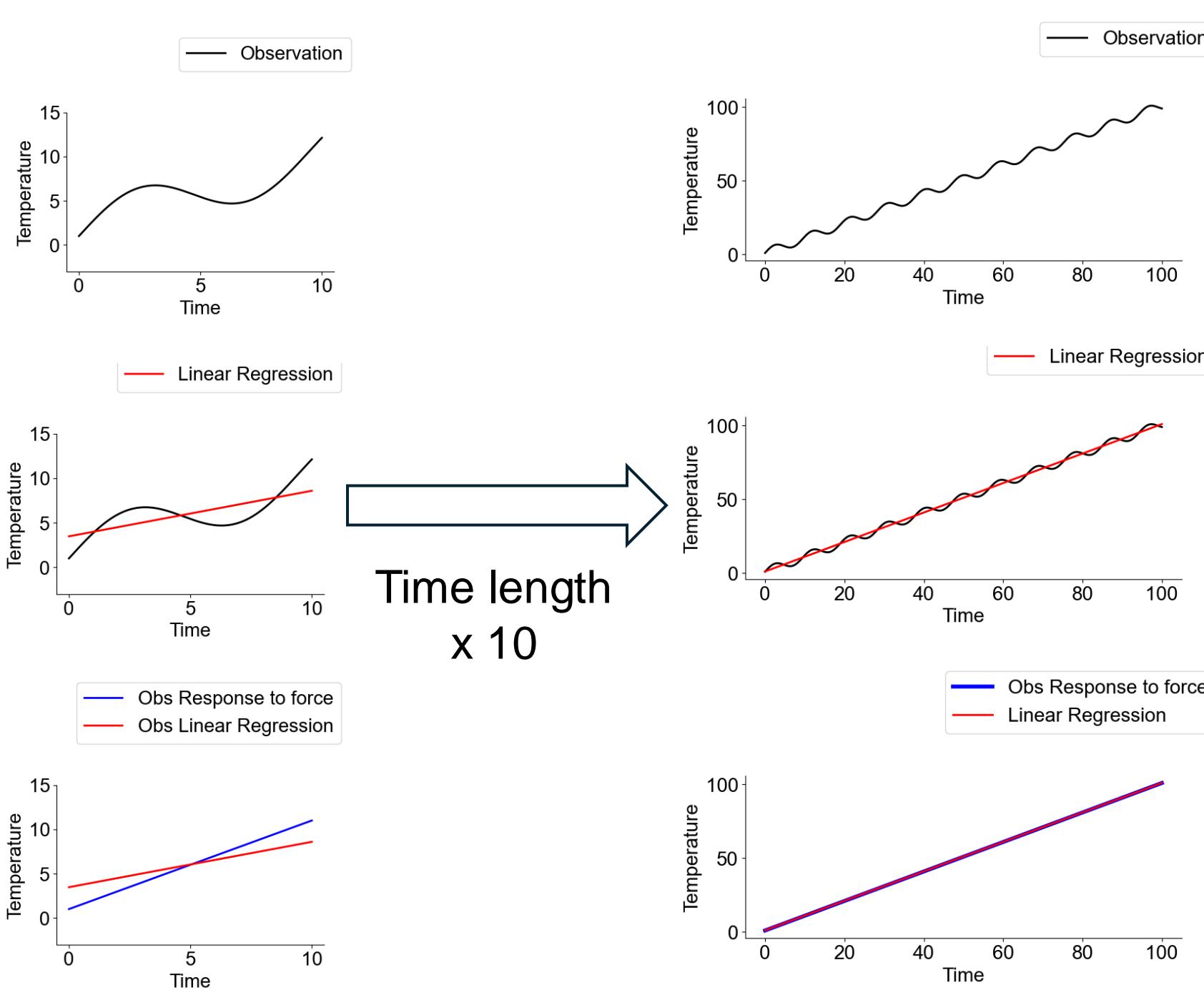
Discrepancy in Temperature trend difference



What is the discrepancy?



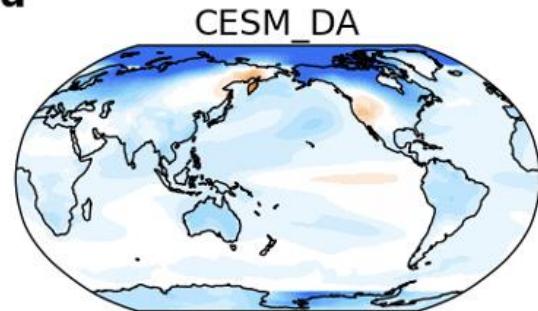
OBS – MMM = Internal Variability (Sweeney et al. 2024) + Model error response to extra forcing



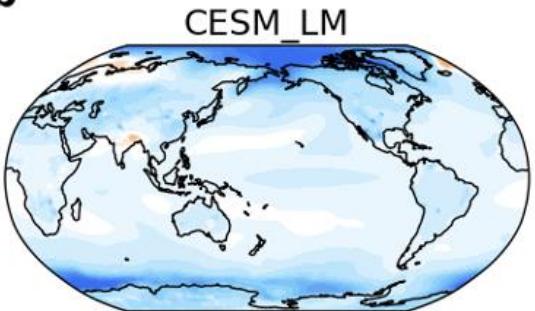
Longer observation makes the linear regression result closer to the response to extra forcing.

Model Error

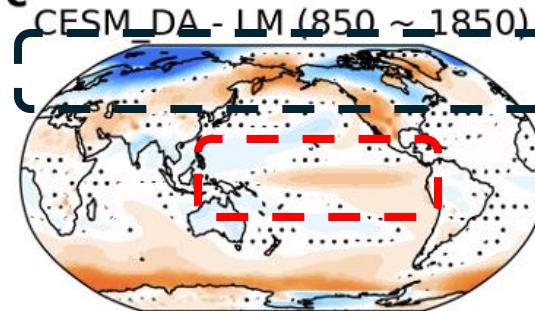
a



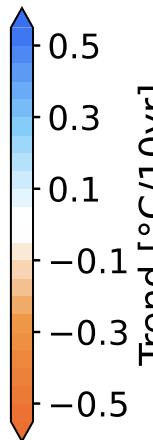
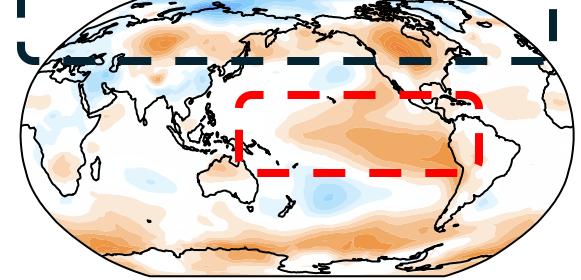
b



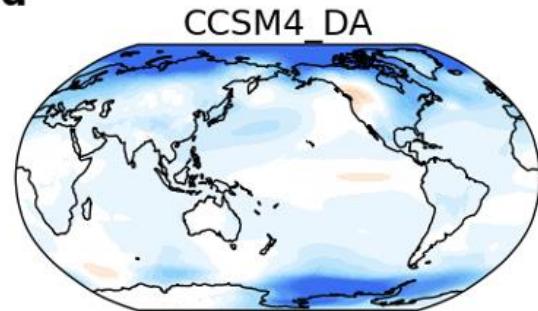
c



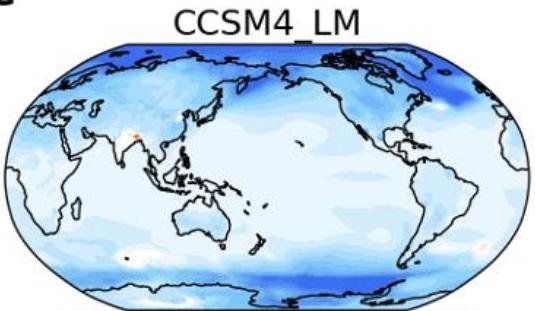
OBS - MMM (1980 ~ 2023)



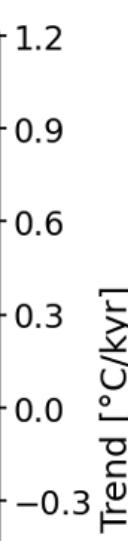
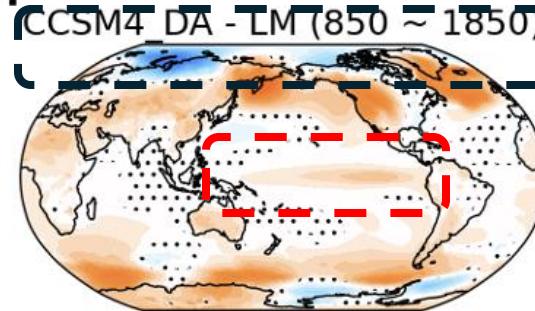
d



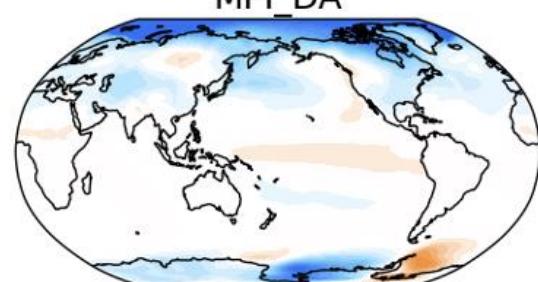
e



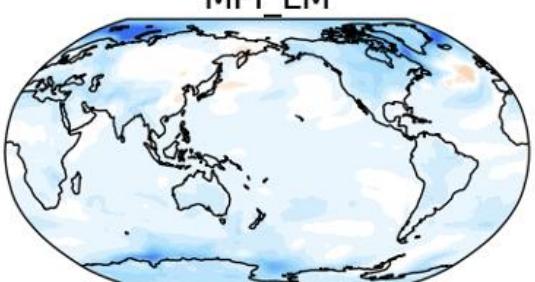
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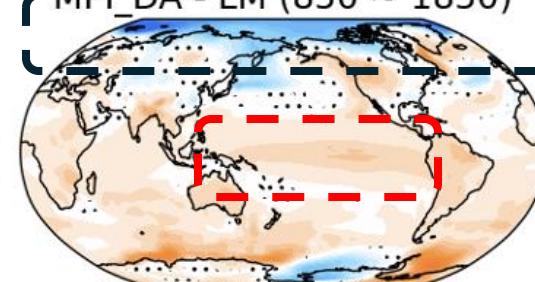
g



h



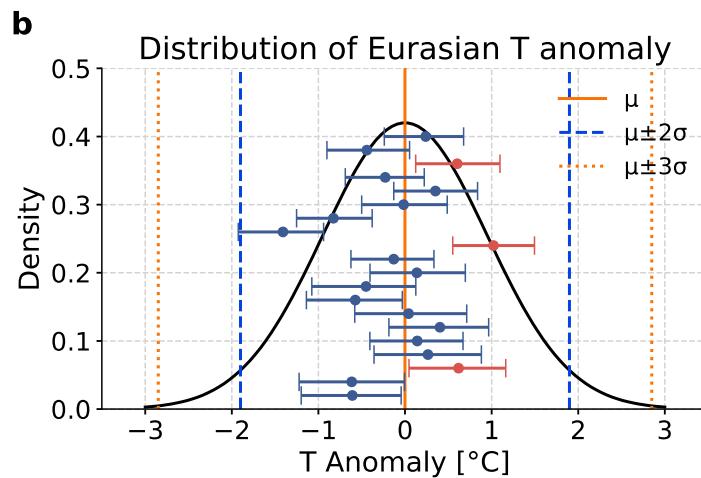
i



Model error
response to extra
forcing
contributes to the
the discrepancy.

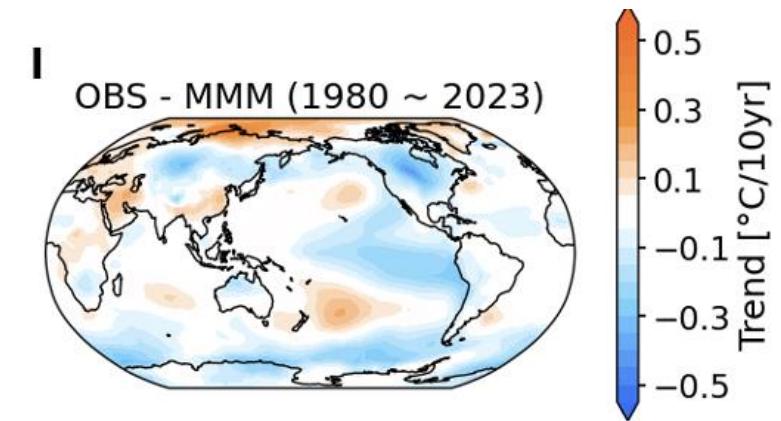
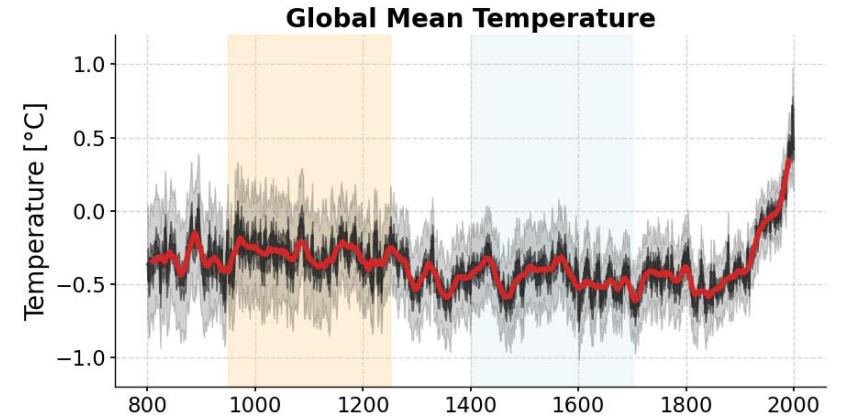
Application Summary

- LMR Seasonal can successfully reconstruct MCA and LIA.

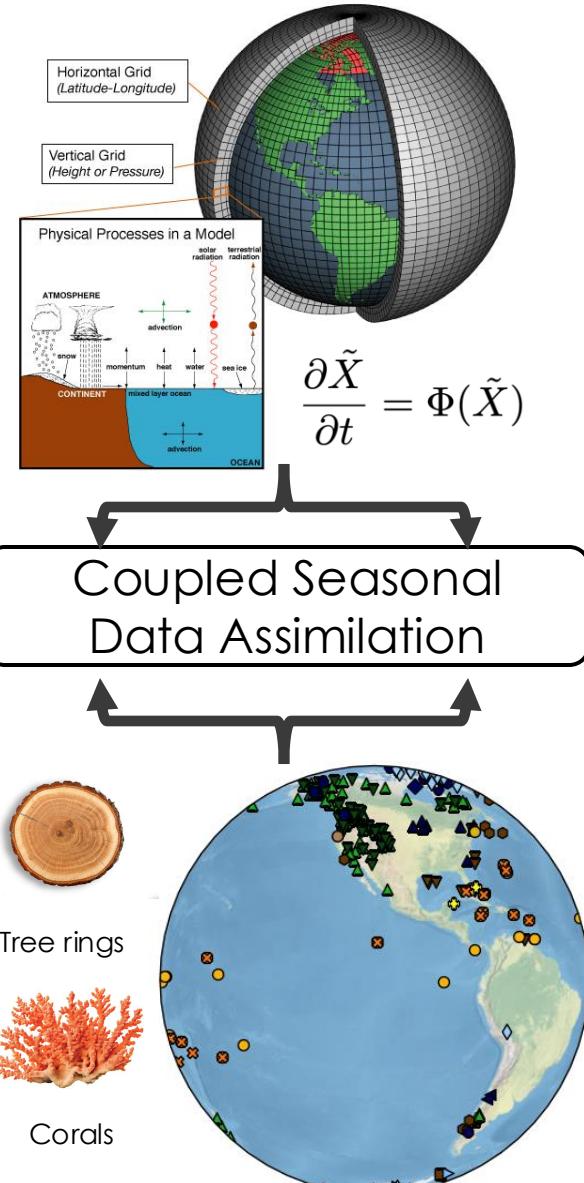


- Internal variability overwhelmed the Eurasia forced response to volcanic eruption .

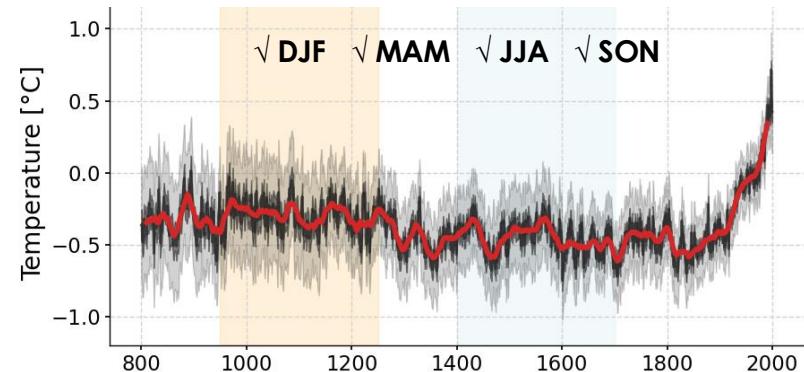
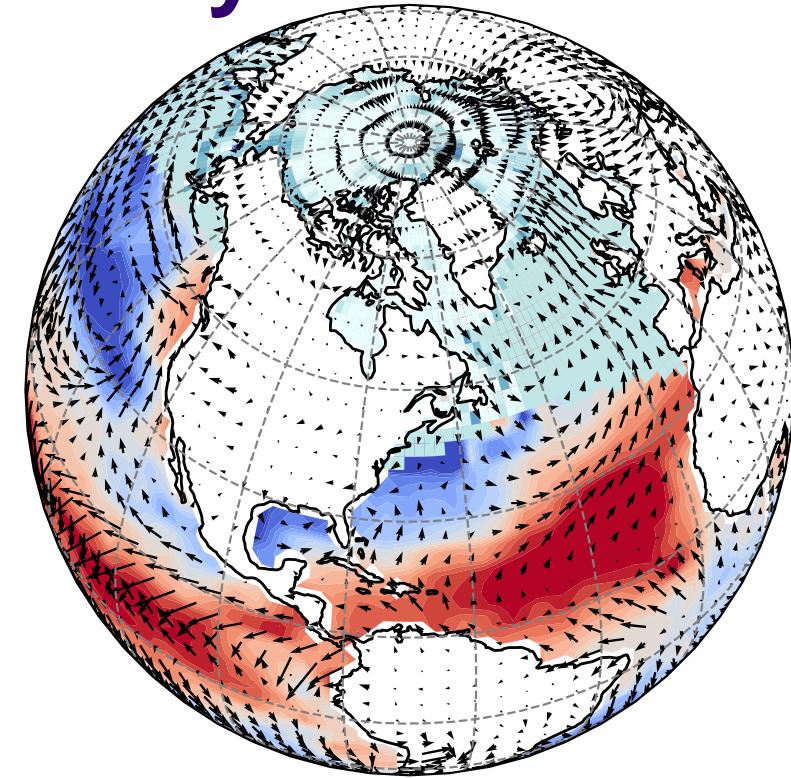
- Recent temperature trend difference can be attributed to CMIP model bias response to extra forcing.



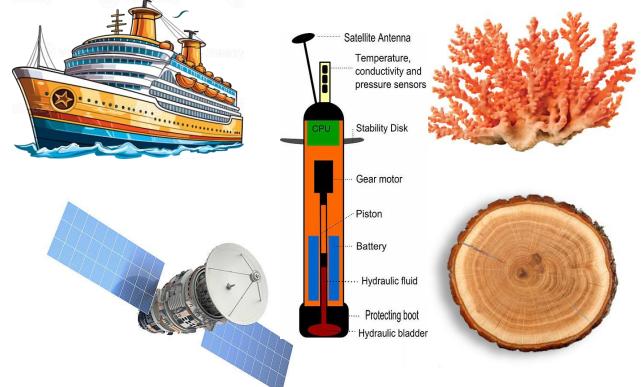
Global Climate Model



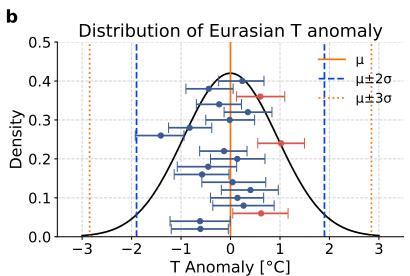
Last Millennium Reanalysis Seasonal



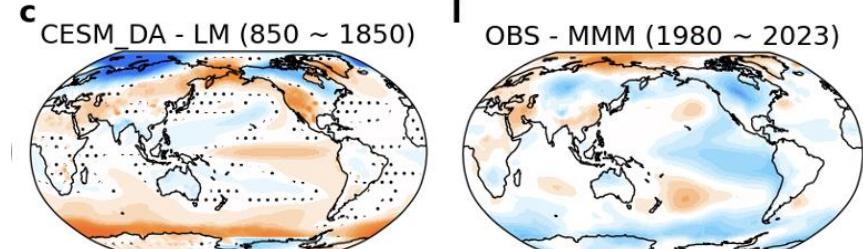
Instrumental and Proxy Verification



Eurasia and volcanic eruption



Temperature trend difference



Publications

- **LMR Seasonal:** First seasonal resolution reanalysis over the last millennium, accurate, robust.

Meng Zilu, Gregory J. Hakim, and Eric J. Steig. "Coupled Seasonal Data Assimilation of Sea Ice, Ocean, and Atmospheric Dynamics over the Last Millennium." *Journal of Climate* (2025), under review.

Meng Zilu, and Lorenzo M. Polvani. "No evidence for significant warming or cooling in Eurasian winter response to major volcanic eruptions over the last millennium." *Geophysical Research Letters*, under review

Meng Zilu, Gregory J. Hakim, and Eric J. Steig. "Greenland Seasonal Temperature over the Last Millennium." *Geophysical Research Letters* (2025), in prep

- Deep Learning Model can increase the data assimilation accuracy.

Meng Zilu, and Gregory J. Hakim. "Reconstructing the tropical Pacific upper ocean using online data assimilation with a deep learning model." *Journal of Advances in Modeling Earth Systems* 16.11 (2024): e2024MS004422.



Acknowledgements



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Lorenzo Polvani



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