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

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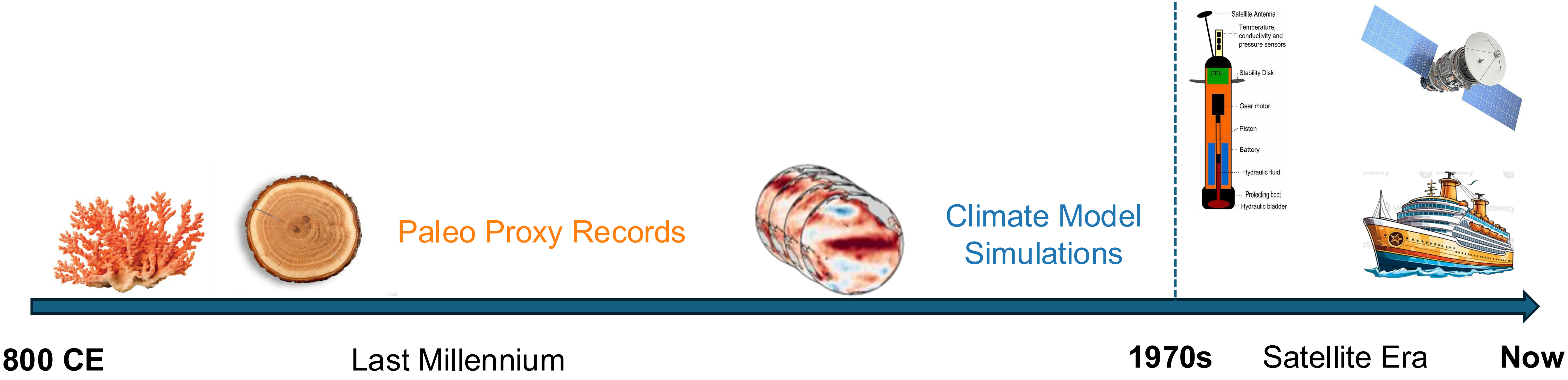
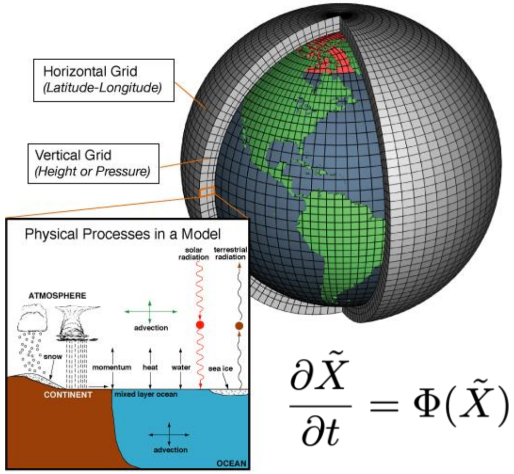
Motivation



- 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

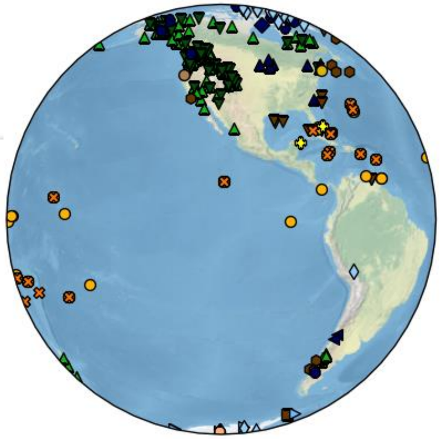


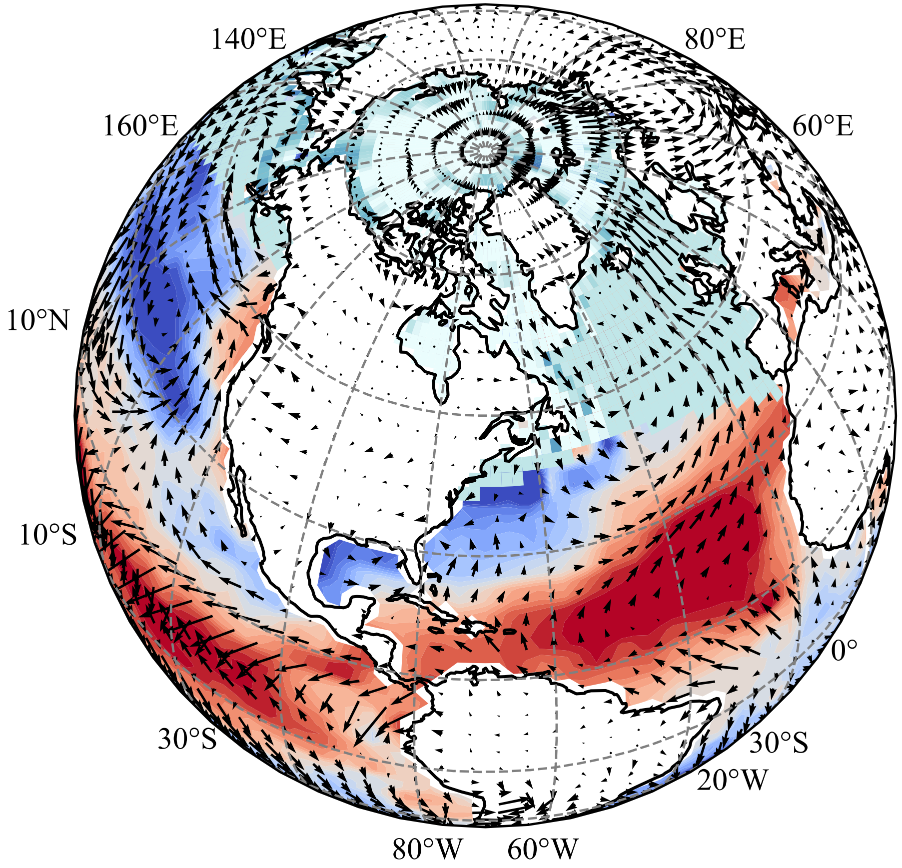
$$\frac{\partial \tilde{X}}{\partial t} = \Phi(\tilde{X})$$

Global Proxy Records

Tree rings

Corals





- ❑DJF
- ❑MAM
- ❑JJA
- ❑SON

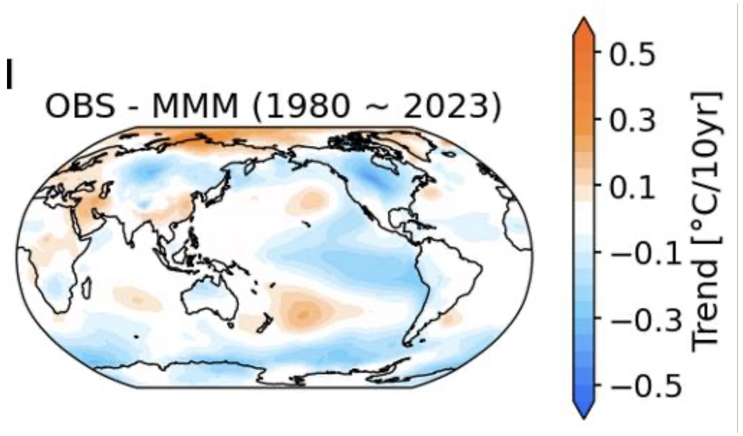
- ➢ Atmosphere, Sea-ice and Ocean coupled
- ➢ Spatially Gridded
- ➢ **1st** Seasonal Temporal Resolution

Reanalysis over the Last Millennium

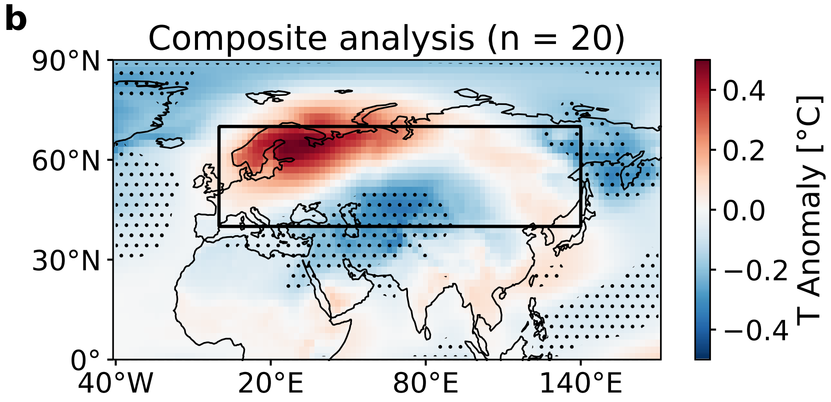
Applications

➢Climate condition over the Last Millennium, Medieval Climate Anomaly (Warm), Little Ice Age (Cold).

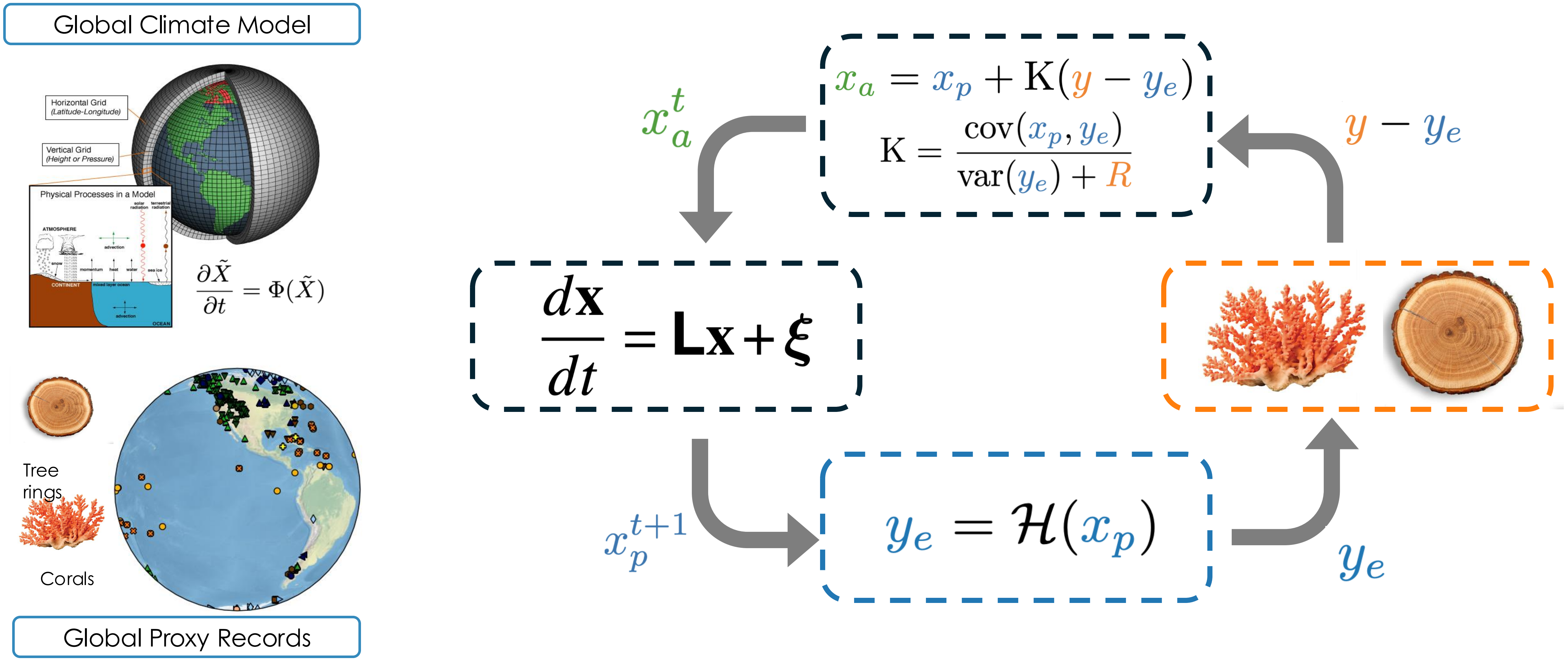
➢Greenland's Vikings' history



➢Recent temperature trend difference between climate models and observations.

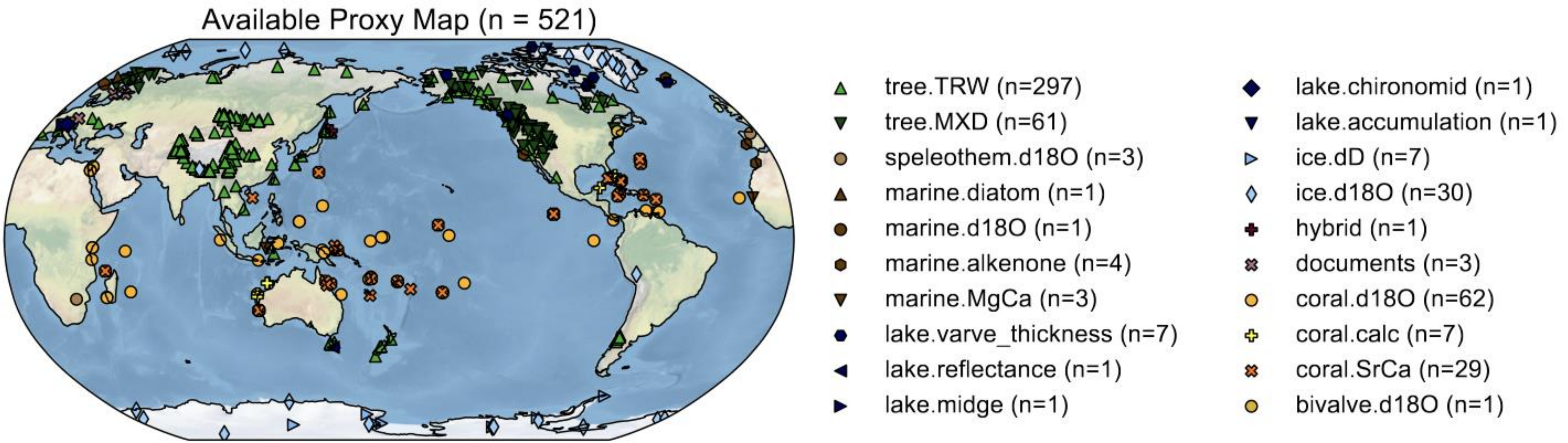


➢How does the Eurasian temperature response to large tropical volcanic eruption?


Global Climate Model
Horizontal Grid (Latitude-Longitude)
Vertical Grid (Height or Pressure)
Physical Processes in a Model
ATMOSPHERE
advection
CONTINENT
mixed layer ocean
OCEAN
$\frac{\partial \tilde{X}}{\partial t} = \Phi(\tilde{X})$
Tree rings
Corals
Global Proxy Records
$x_a = x_p + \mathrm{K}(y - y_e)$
$\mathrm{K} = \frac{\mathrm{cov}(x_p, y_e)}{\mathrm{var}(y_e) + R}$
x_a^t
$y - y_e$
$\frac{d\mathbf{x}}{dt} = \mathbf{L}\mathbf{x} + \boldsymbol{\xi}$
x_p^{t+1}
$y_e = \mathcal{H}(x_p)$
y_e

Method

Proxy System Model

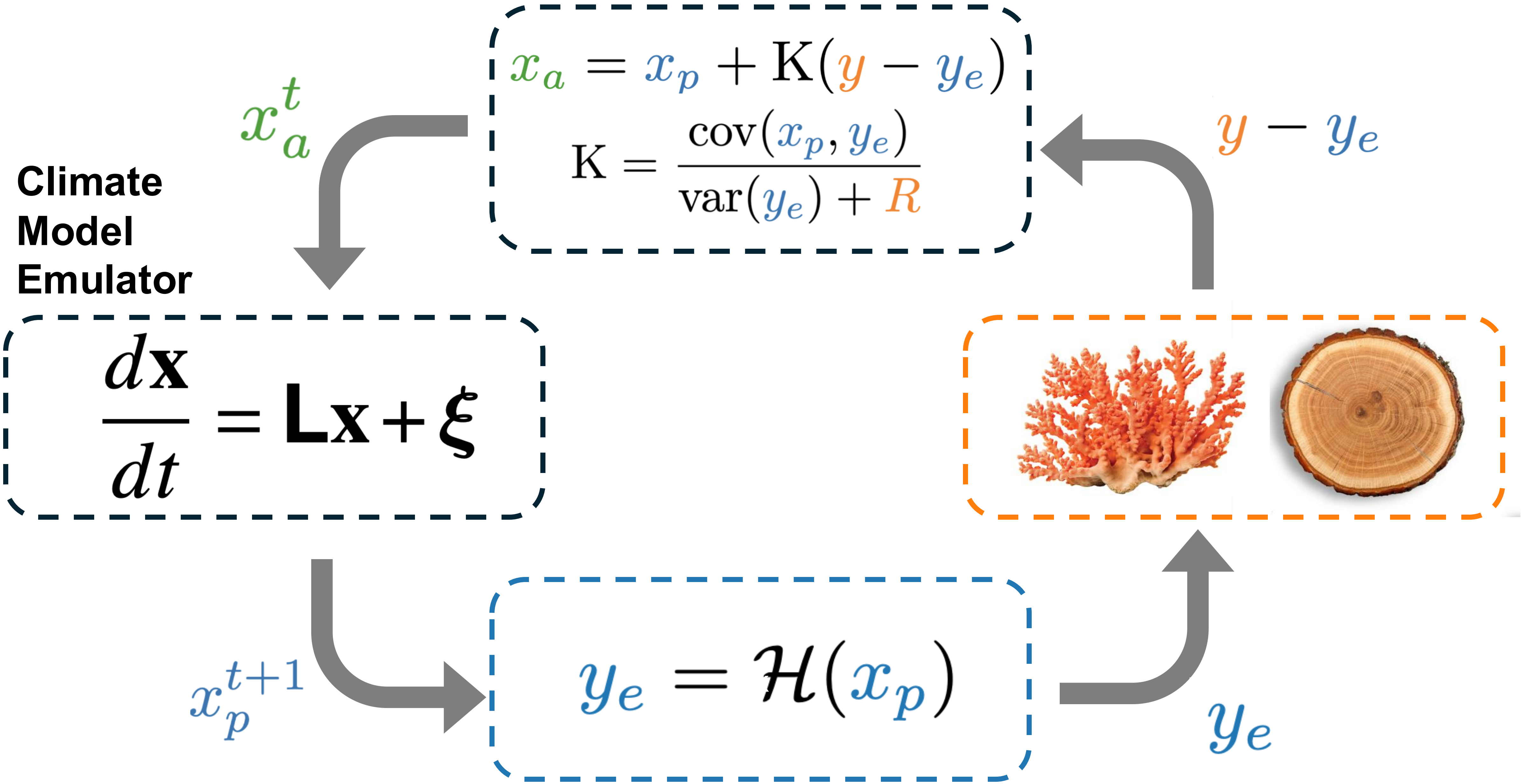


$$y_e = \mathcal{H}(x_p)$$

$\delta^{18}O$

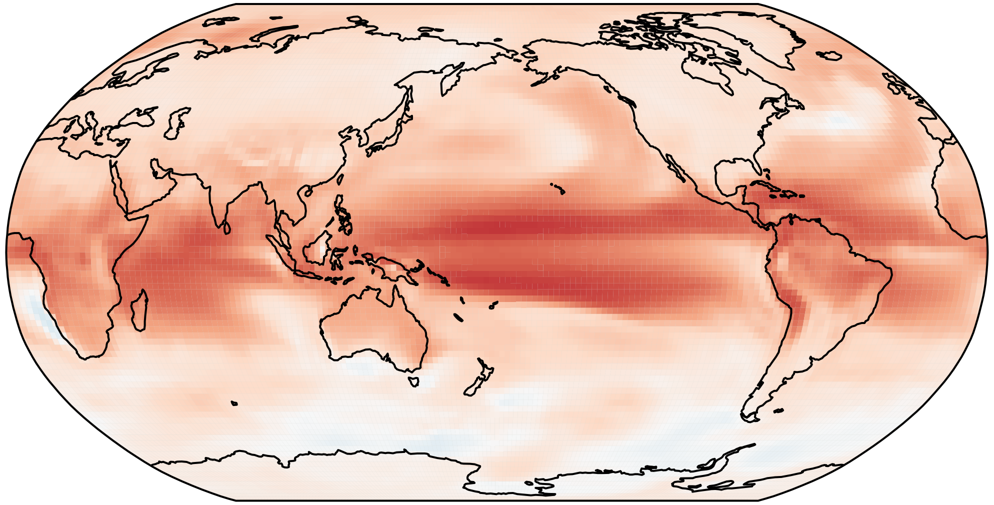
SST

Method Summary – LMR Seasonal Framework

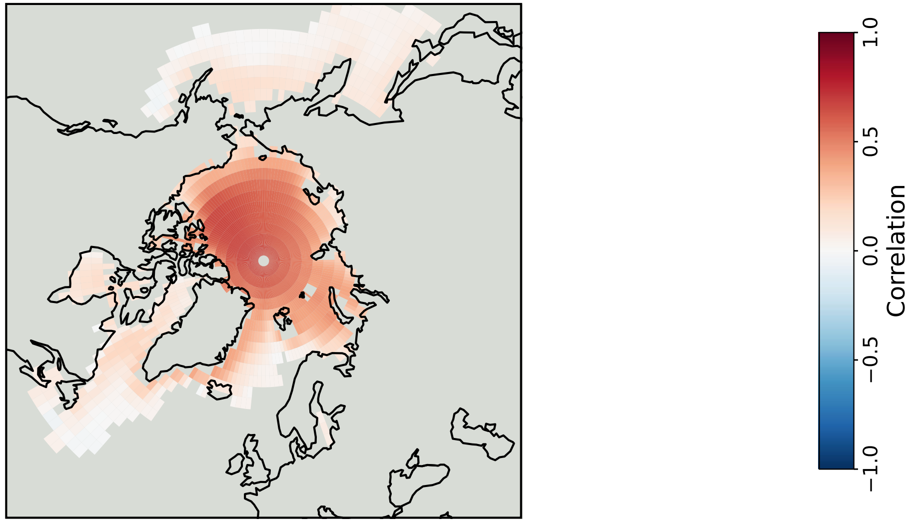


Why Coupled?

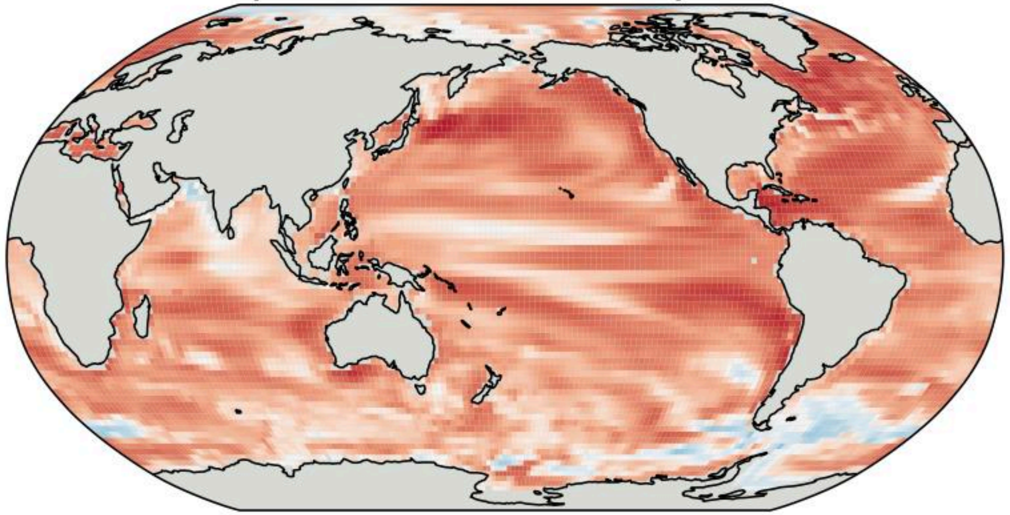
a. TAS; lead = 12 month; corr = 0.23



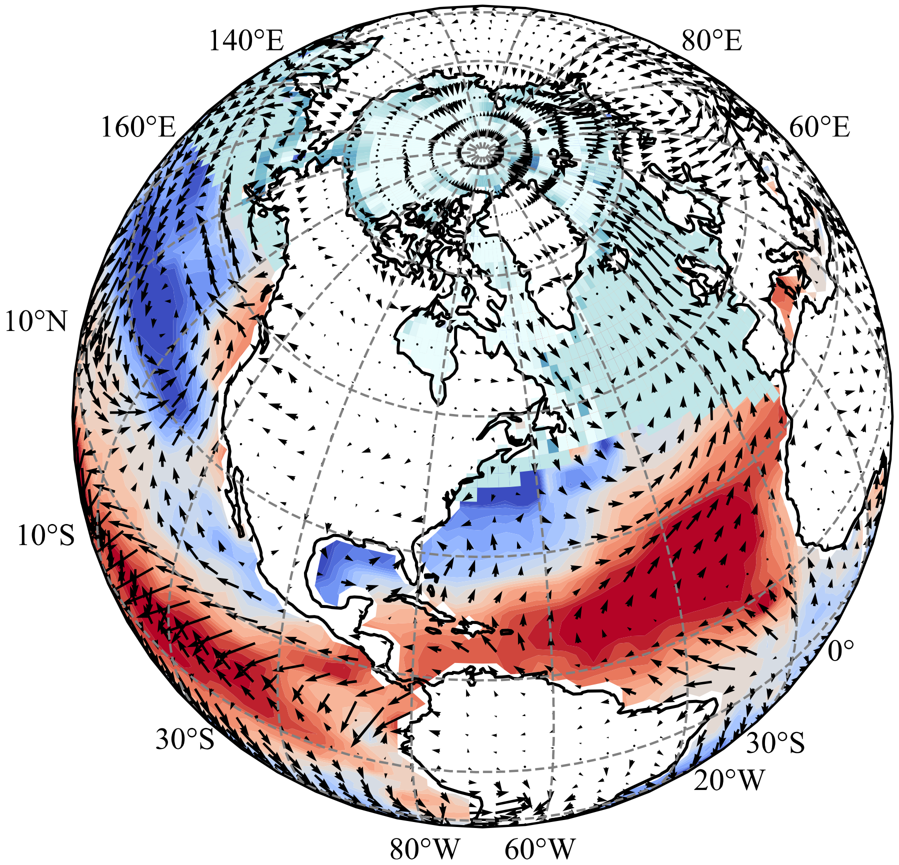
e. SIT; lead = 12 month; corr = 0.39



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

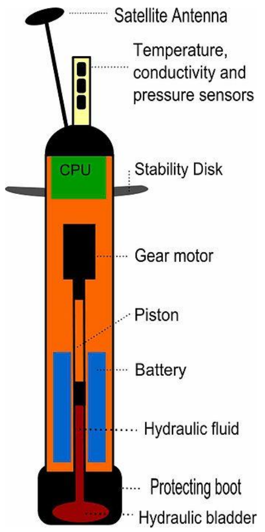


- Ocean Heat Content (OHC) and Sea Ice Thickness (SIT) high predictability
- Reconstruct Oceanic and sea-ice variabilities
- **1st** Sea Ice Volume reconstructions over the last millennium



Reconstruction

VS



VS

Verification

Instrumental Verification

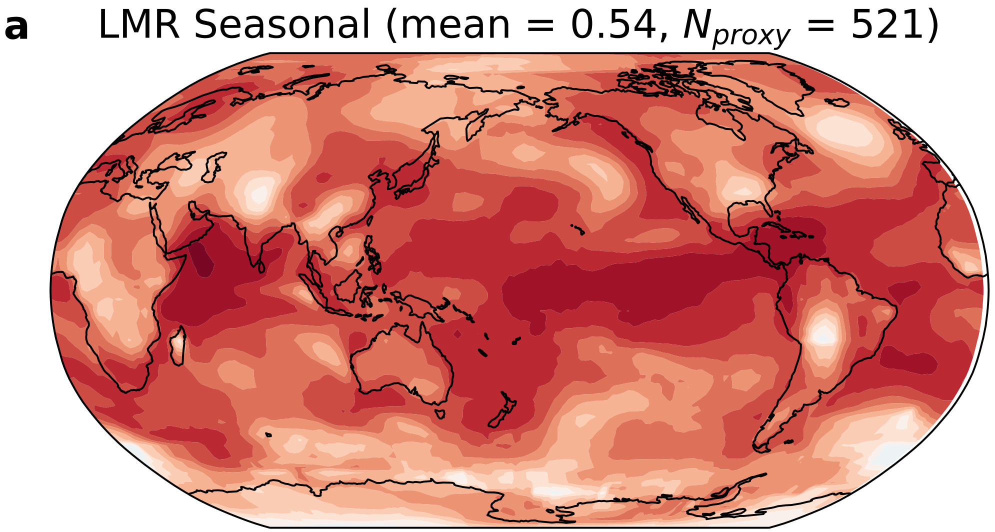
- Compare reconstruction with instrumental dataset (reanalysis, satellite).
- Compare with other Last Millennium DA reconstructions:

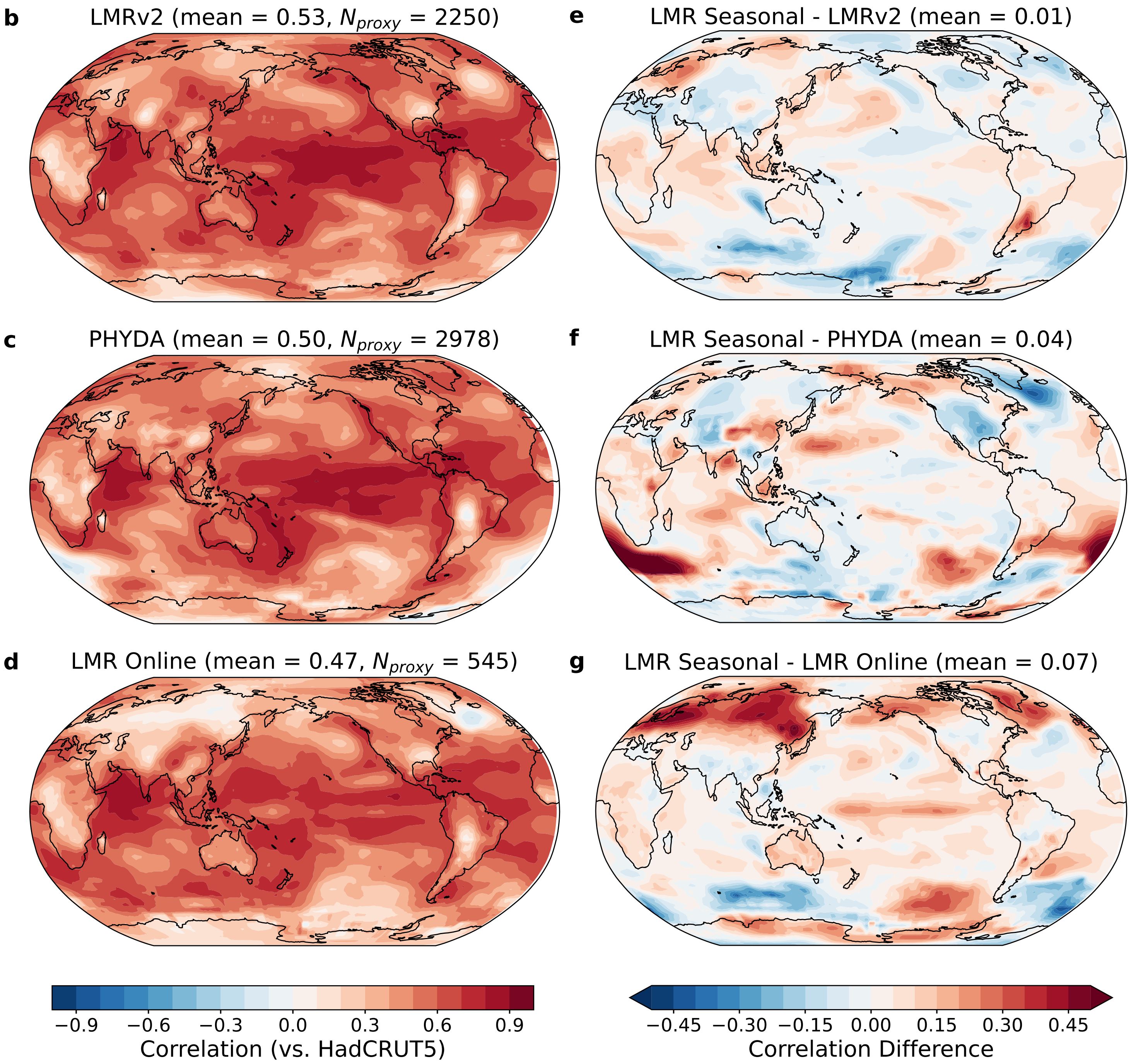
TABLE 1. Summary of Data Assimilation Products over the Last Millennium

Name	PDA Method	N_{proxy} [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

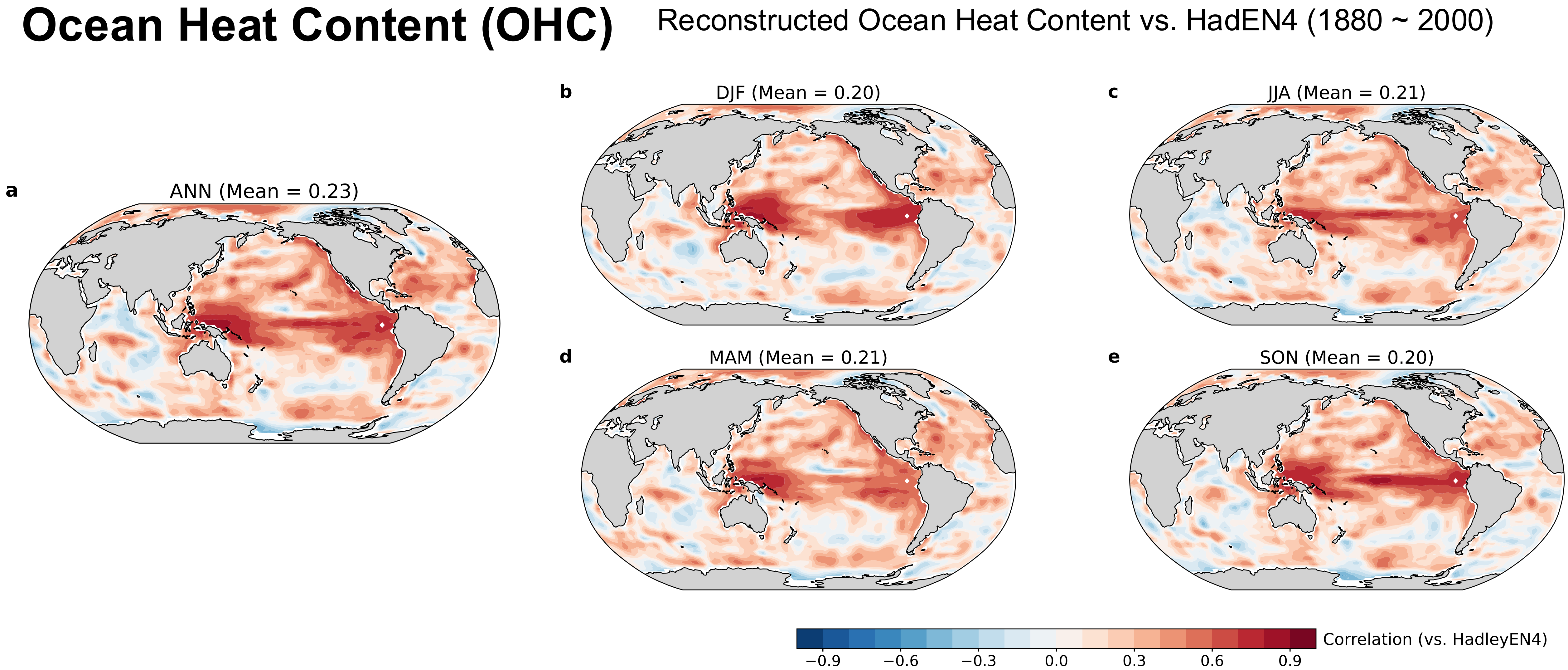
Reconstructed **Annual Mean Temperature** vs. HadCRUT5 (1880 ~ 2000)





- ➢ Achieve the highest correlation skill, while using fewer proxies

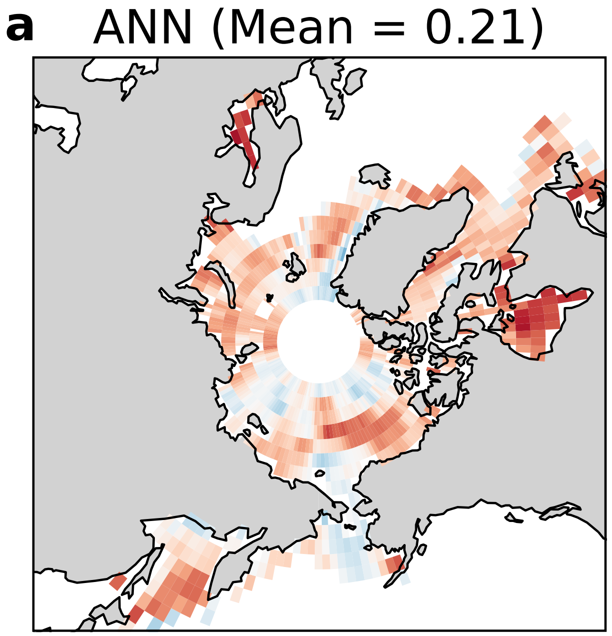
Ocean Heat Content (OHC)

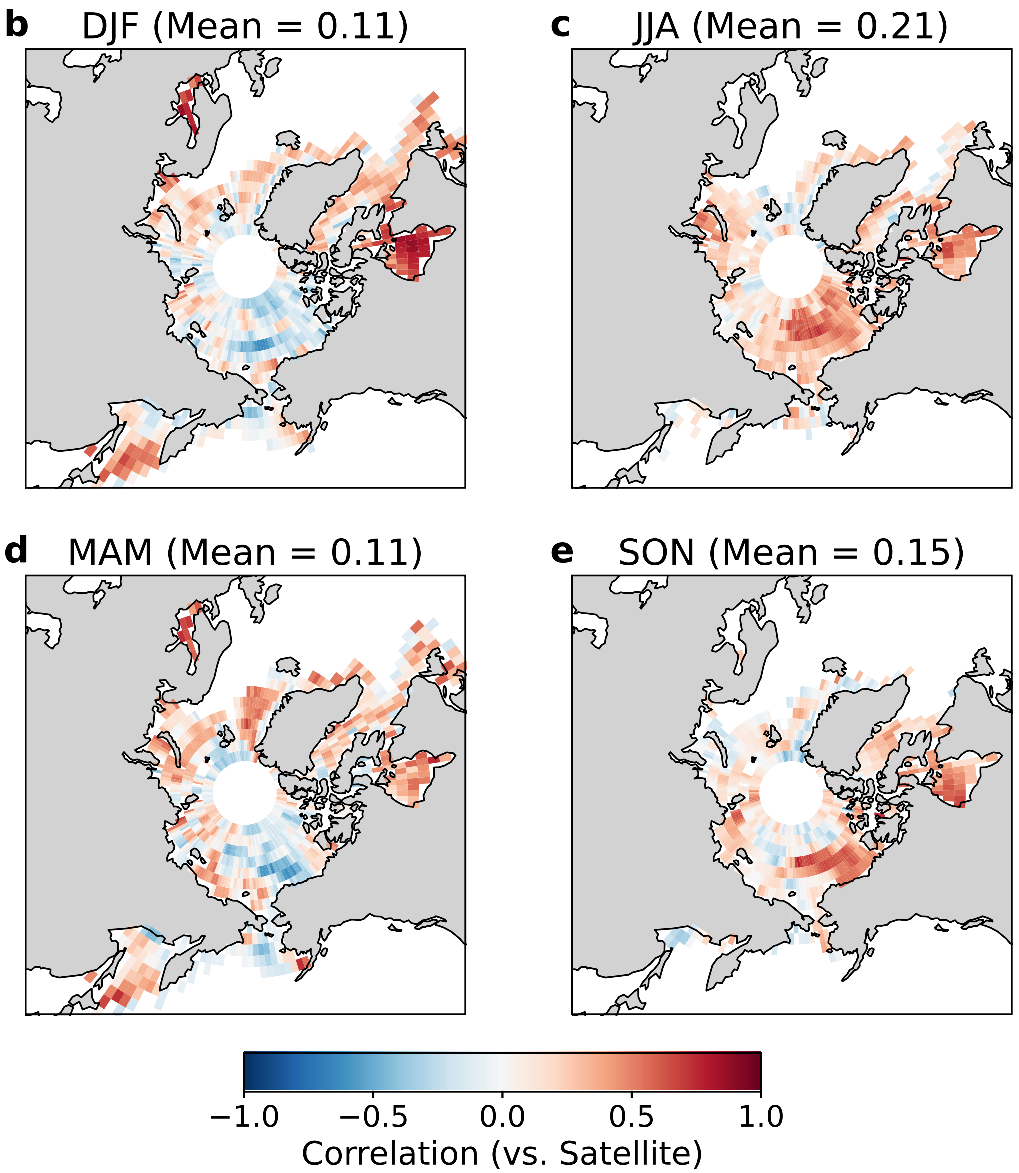


- Without direct observations on OHC.
- Skill is highest in the tropical Pacific, the eastern North Pacific, and northern Atlantic Ocean regions.

Sea Ice Concentration (SIC)

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



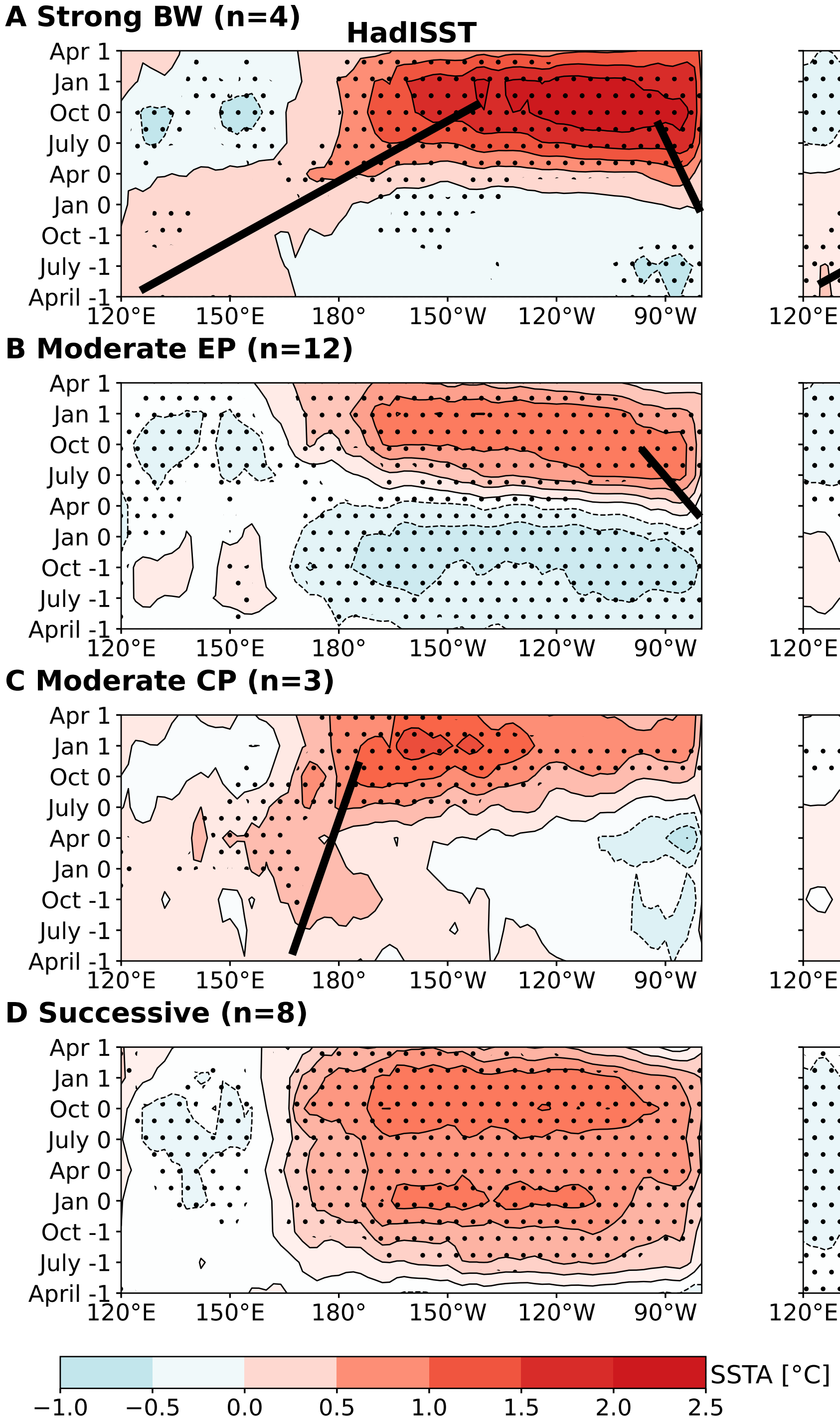


- Without direct observations on SIC.
- Skill is highest in Hudson Bay, and near sea-ice edges, especially around Greenland and the Barents Sea.

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?

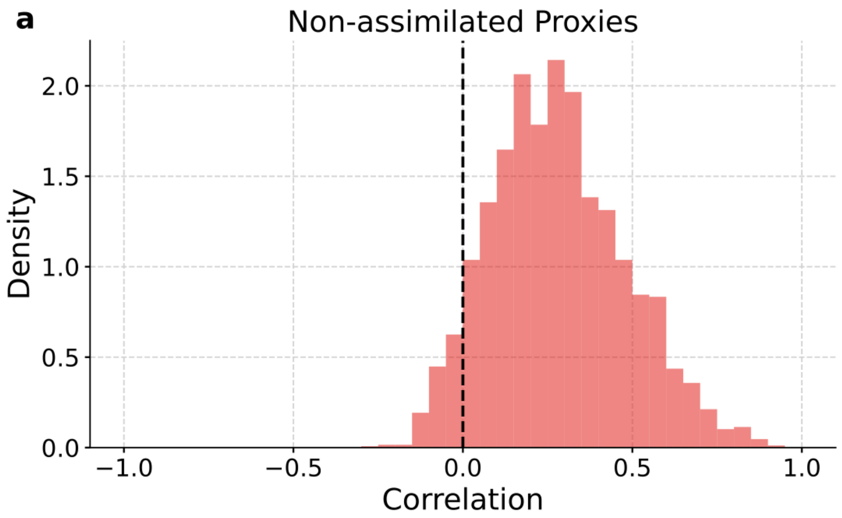


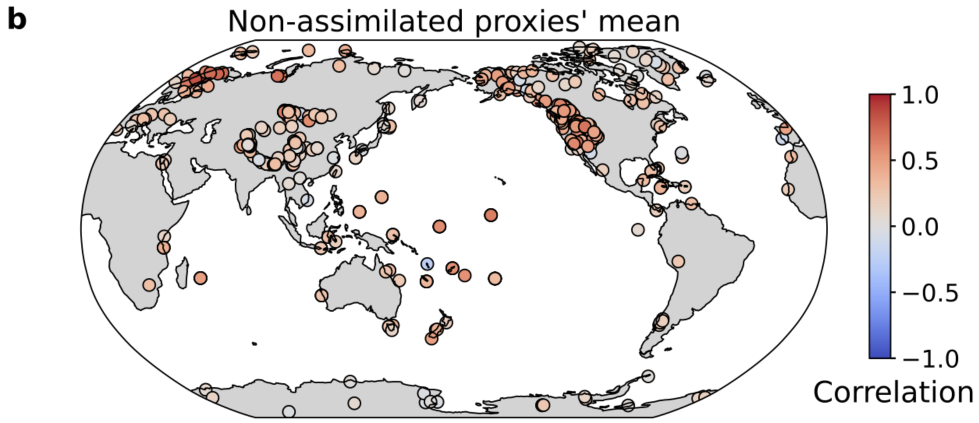
(Wang et al. 2019)

Independent Proxy Verification

Assimilate 75% Proxies | Randomly Drop 25% Proxies

X25 times $y_e = \mathcal{H}(x_a)$ $\mathrm{corr}(y_e, y)$





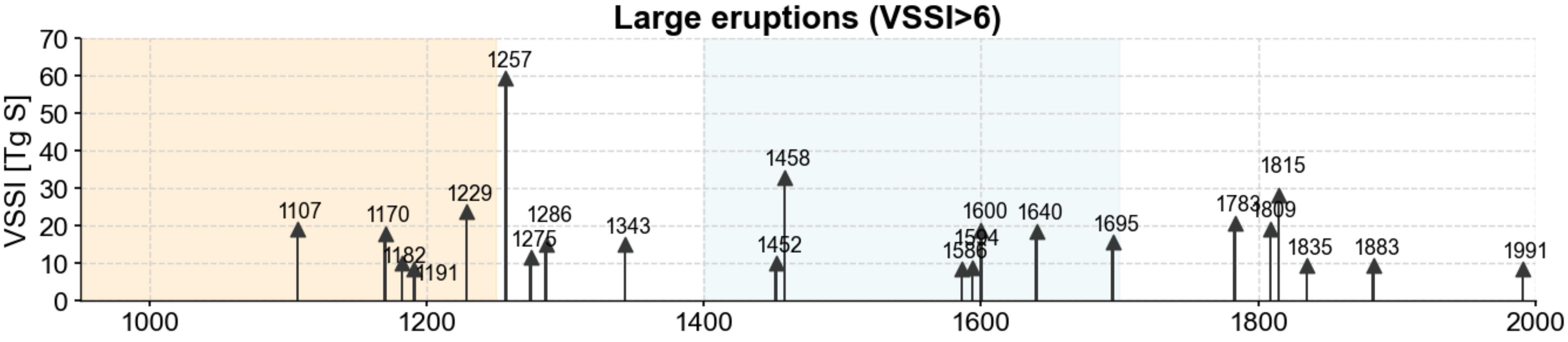
➢Verification against independent proxy records shows that reconstruction skill is robust throughout the last millennium.

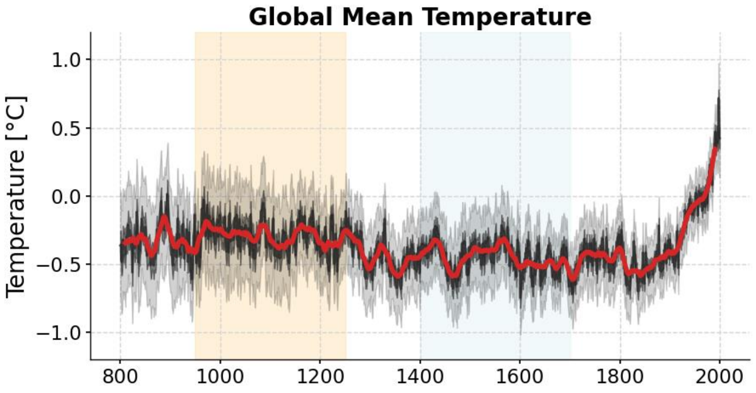
(Hakim et al. 2016)

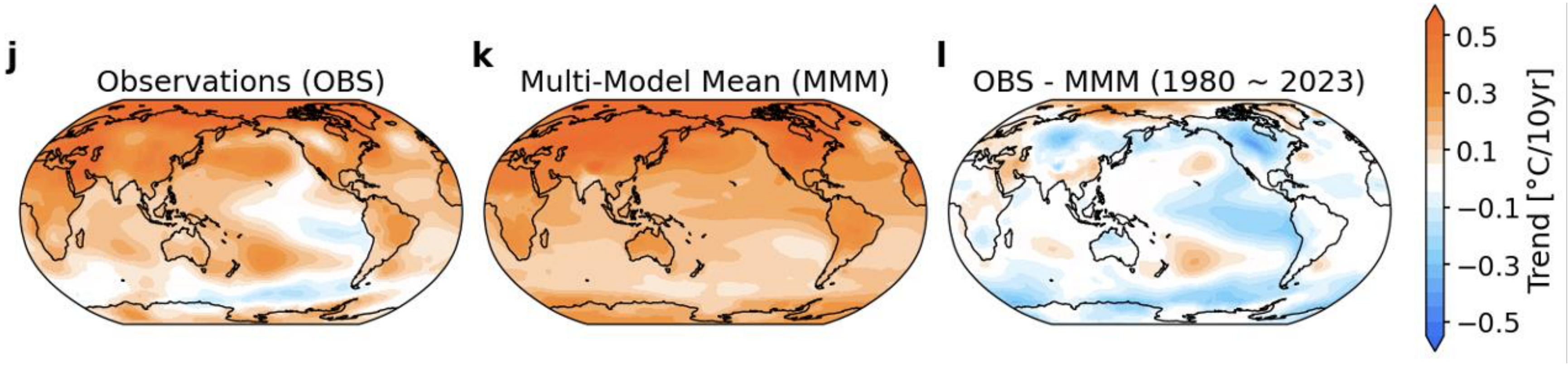
Verification Summary

- 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.

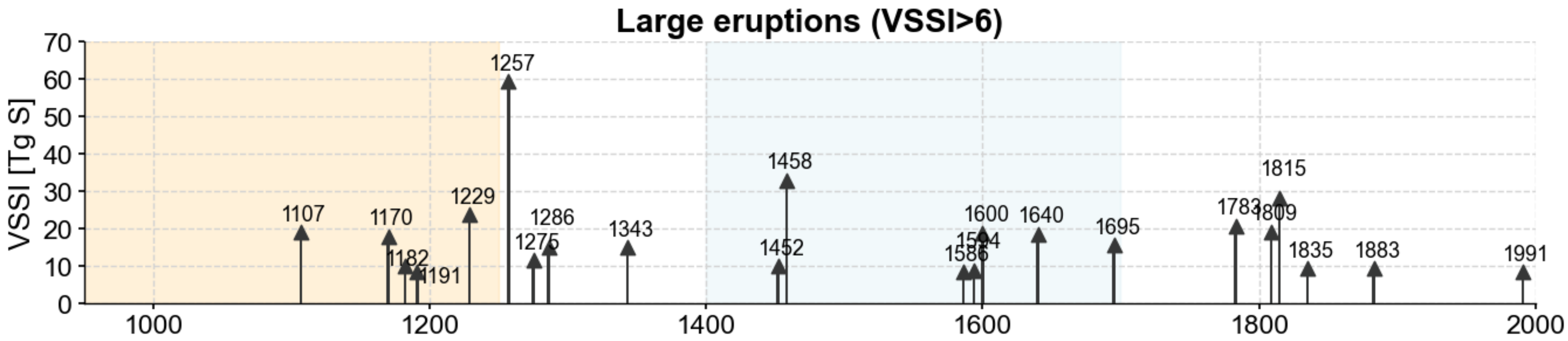






Applications

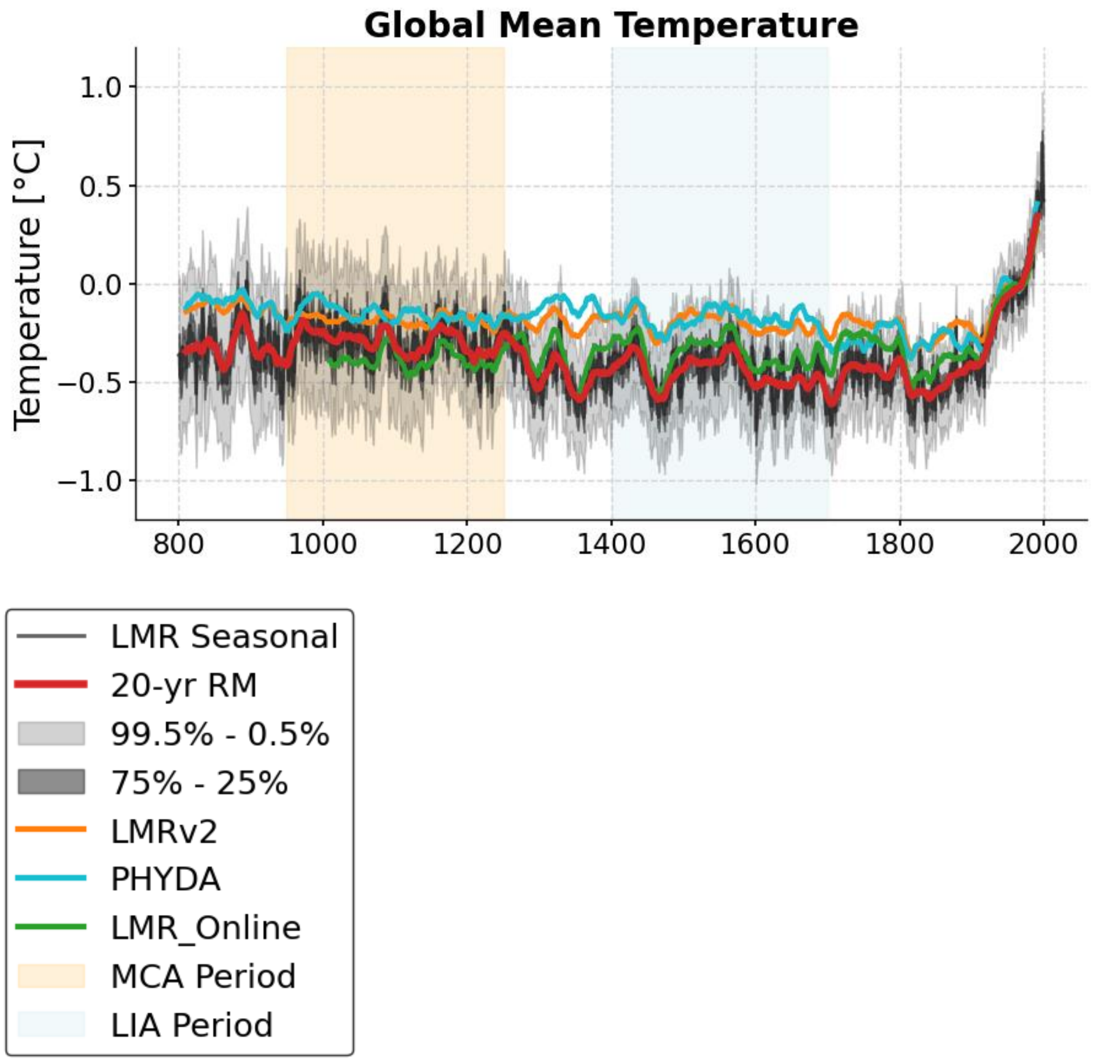
Last Millennium Climate



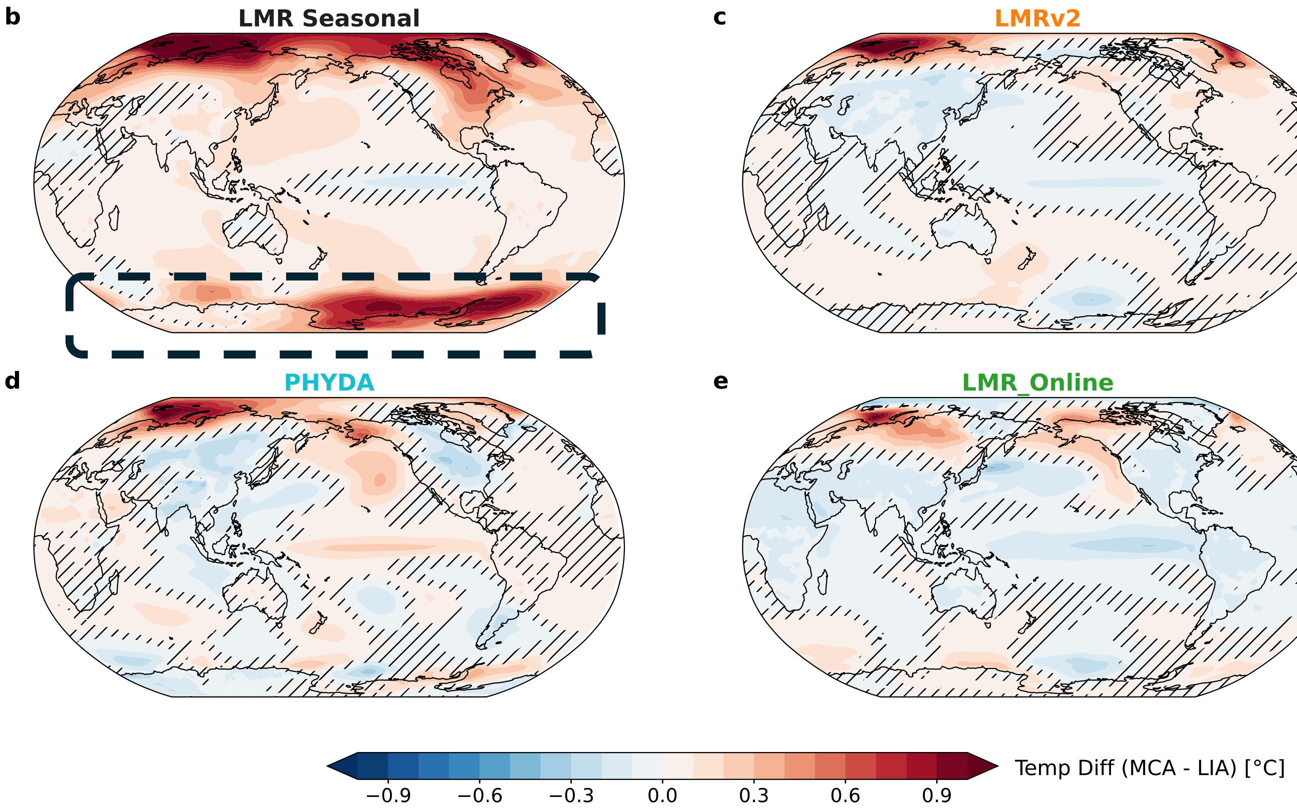
VSSI: volcanic stratospheric sulfur injection (**Teragram**)

- 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

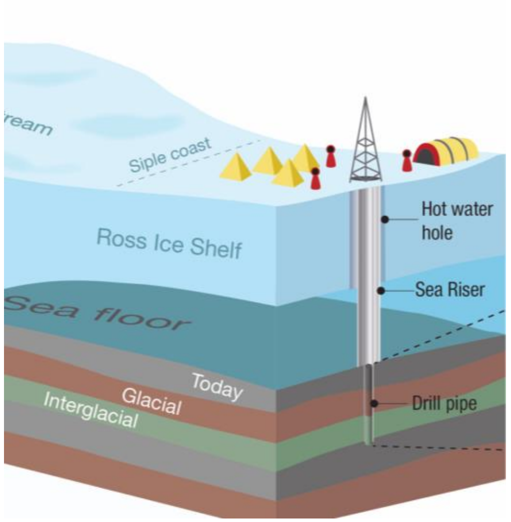


Pattern Difference (MCA - LIA):

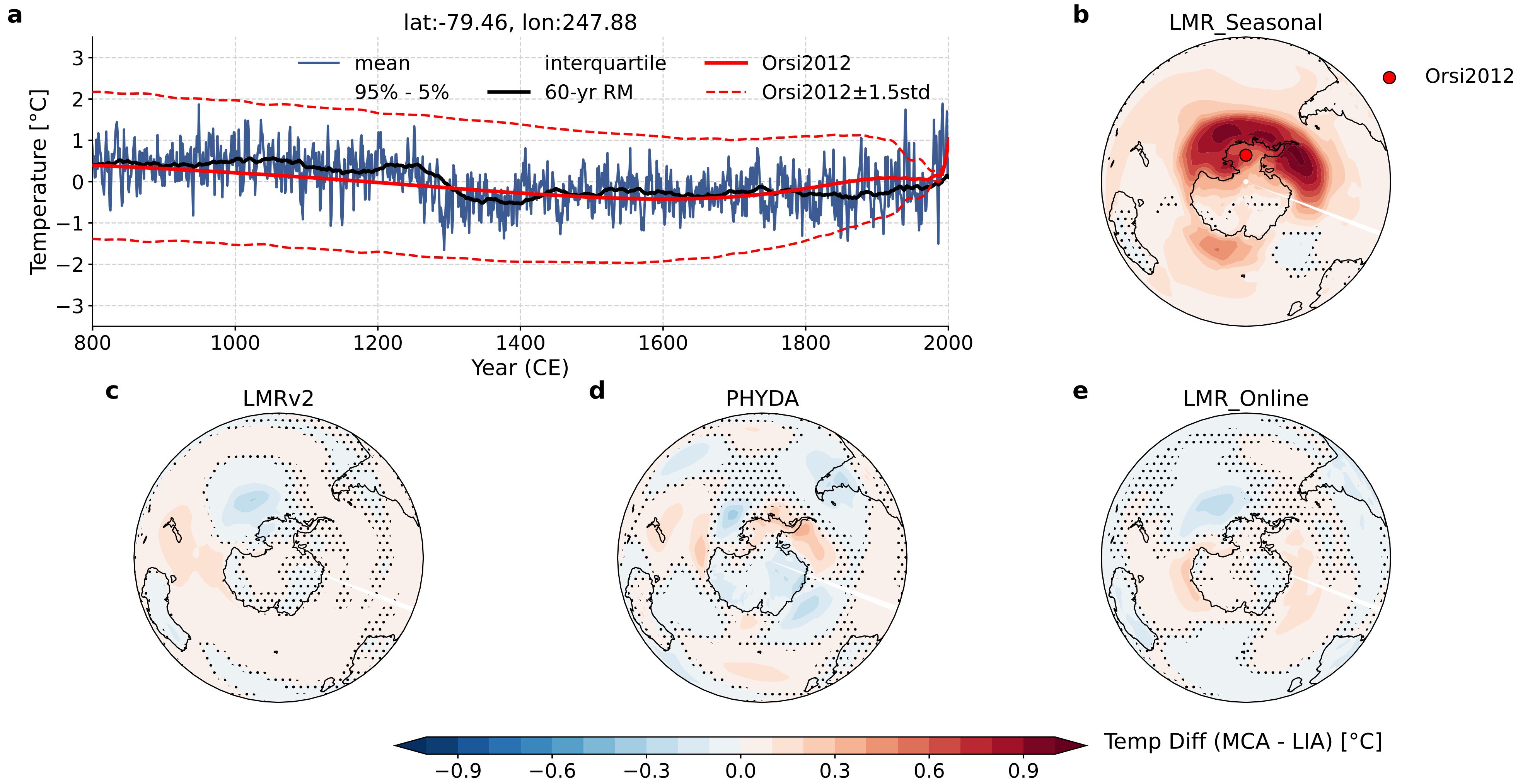


➢ LMR Seasonal reconstructs the global MCA-LIA difference.

MCA and LIA: Borehole Verification

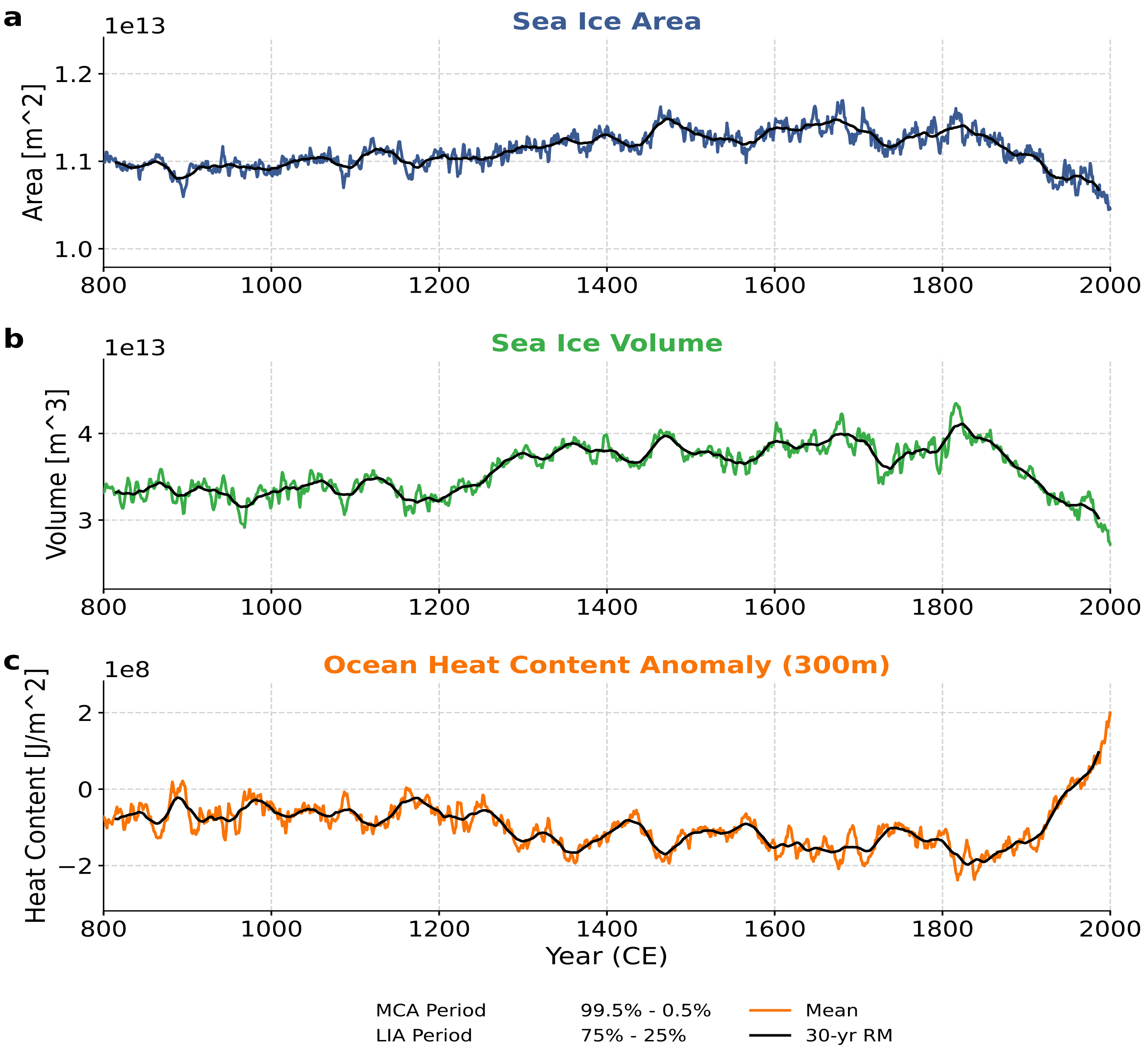


Borehole



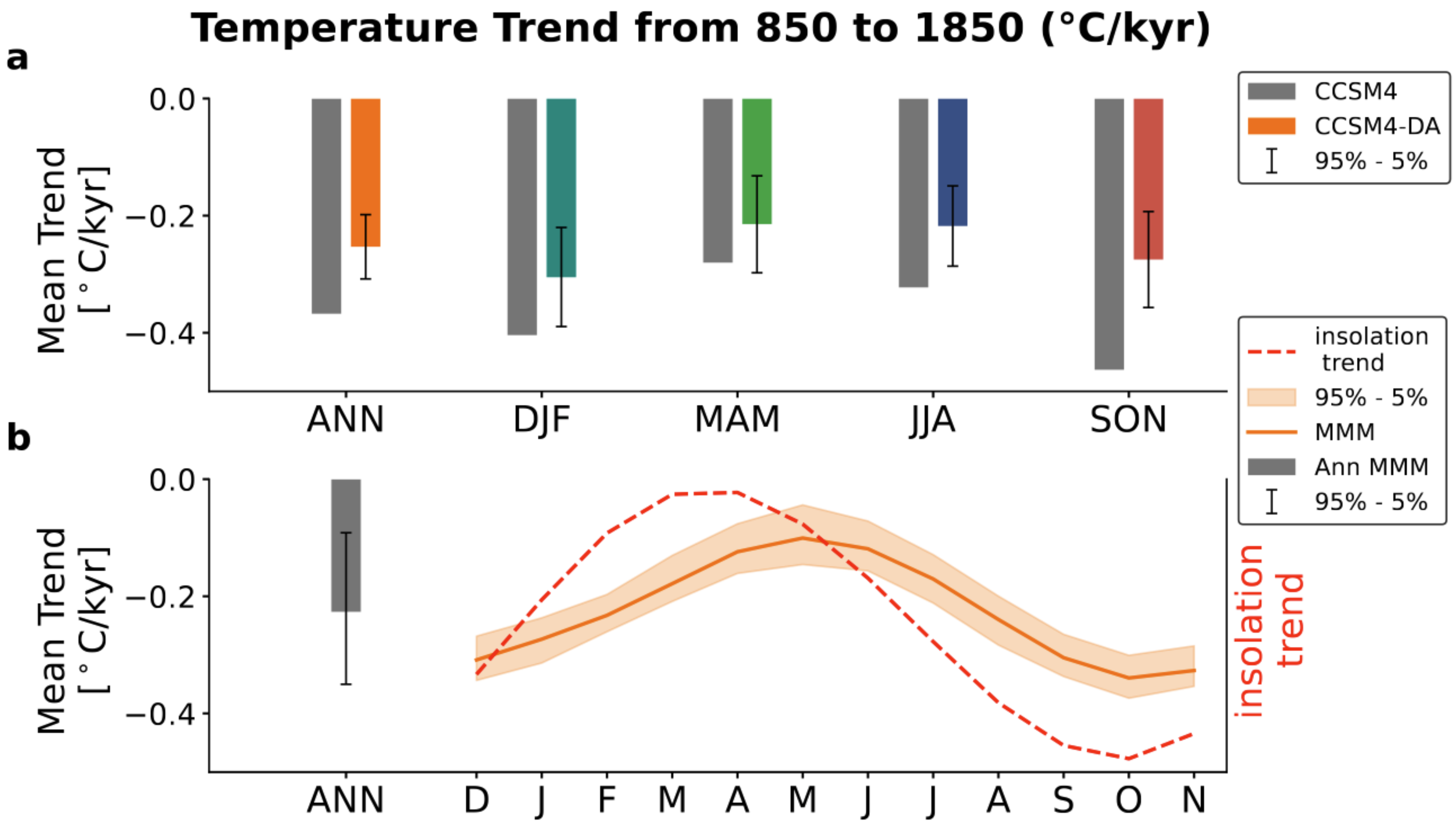
➢ LMR Seasonal is consistent with the western Antarctica borehole.

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.

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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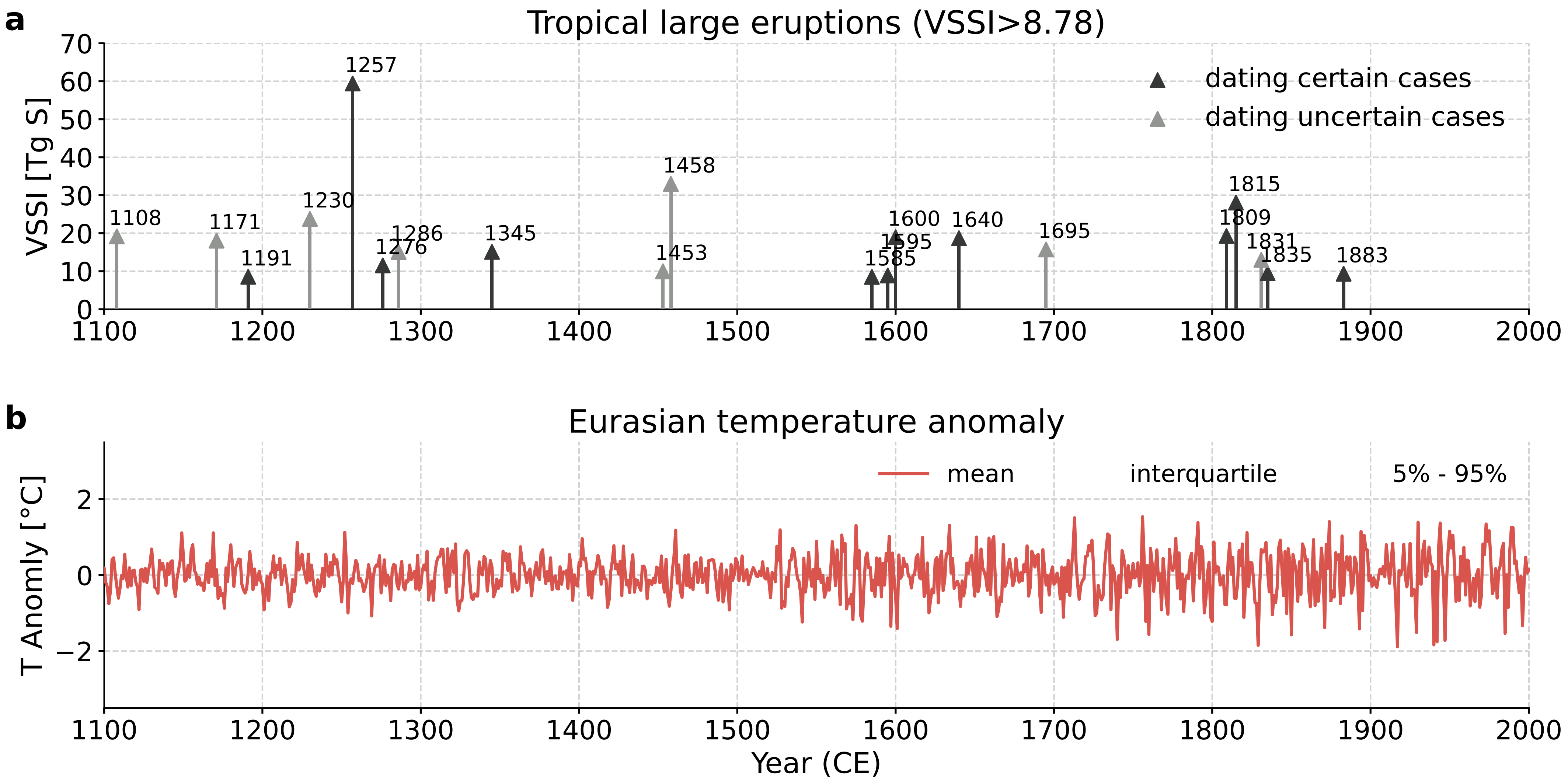
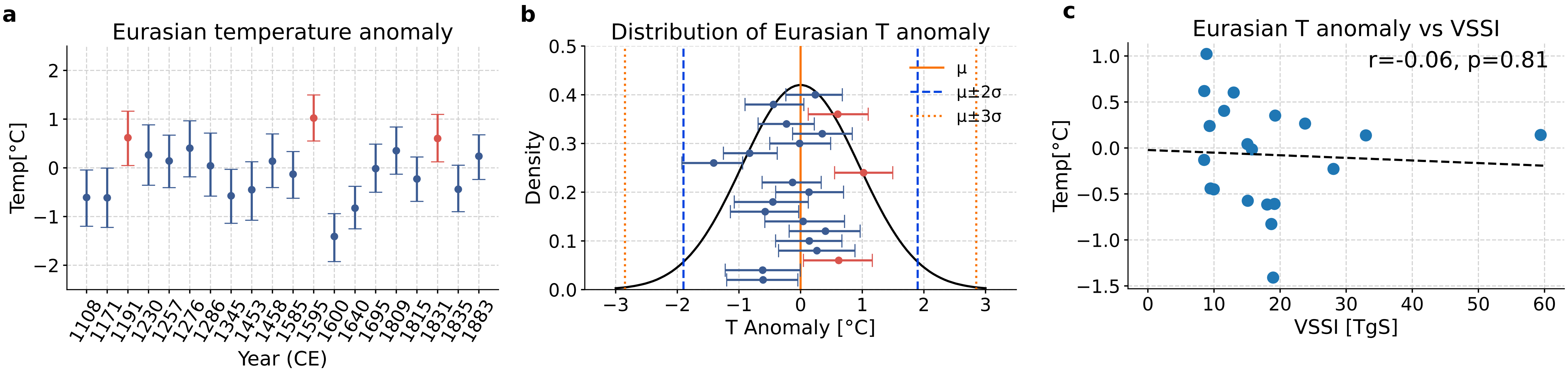
Low latitude Volcanic Eruption can lead to DJF Eurasia Warming.

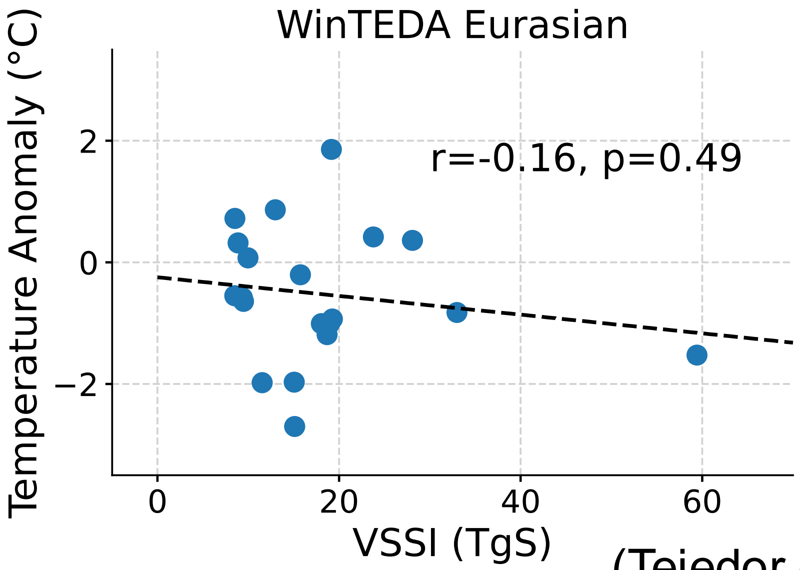
True or not True?

Volcanic Eruption and Winter Eurasia



Volcanic Eruption and Winter Eurasia

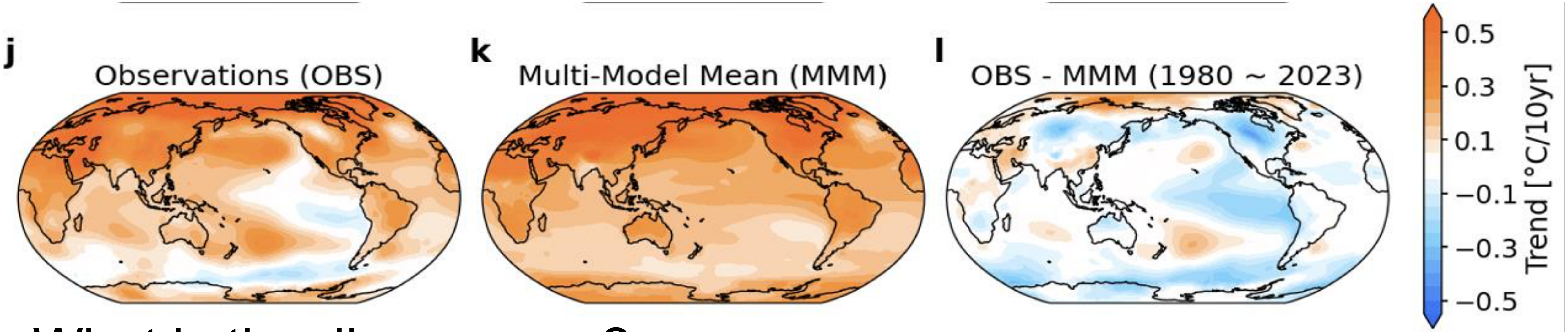




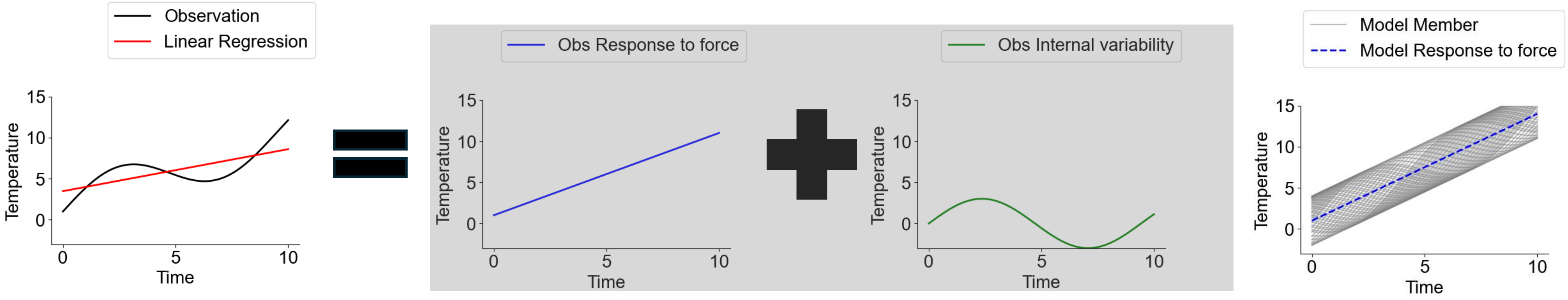
- No significant warming or cooling after volcanic eruption.
- Internal variability may overwhelm any forced volcanic response.

(Tejedor et al. 2024)

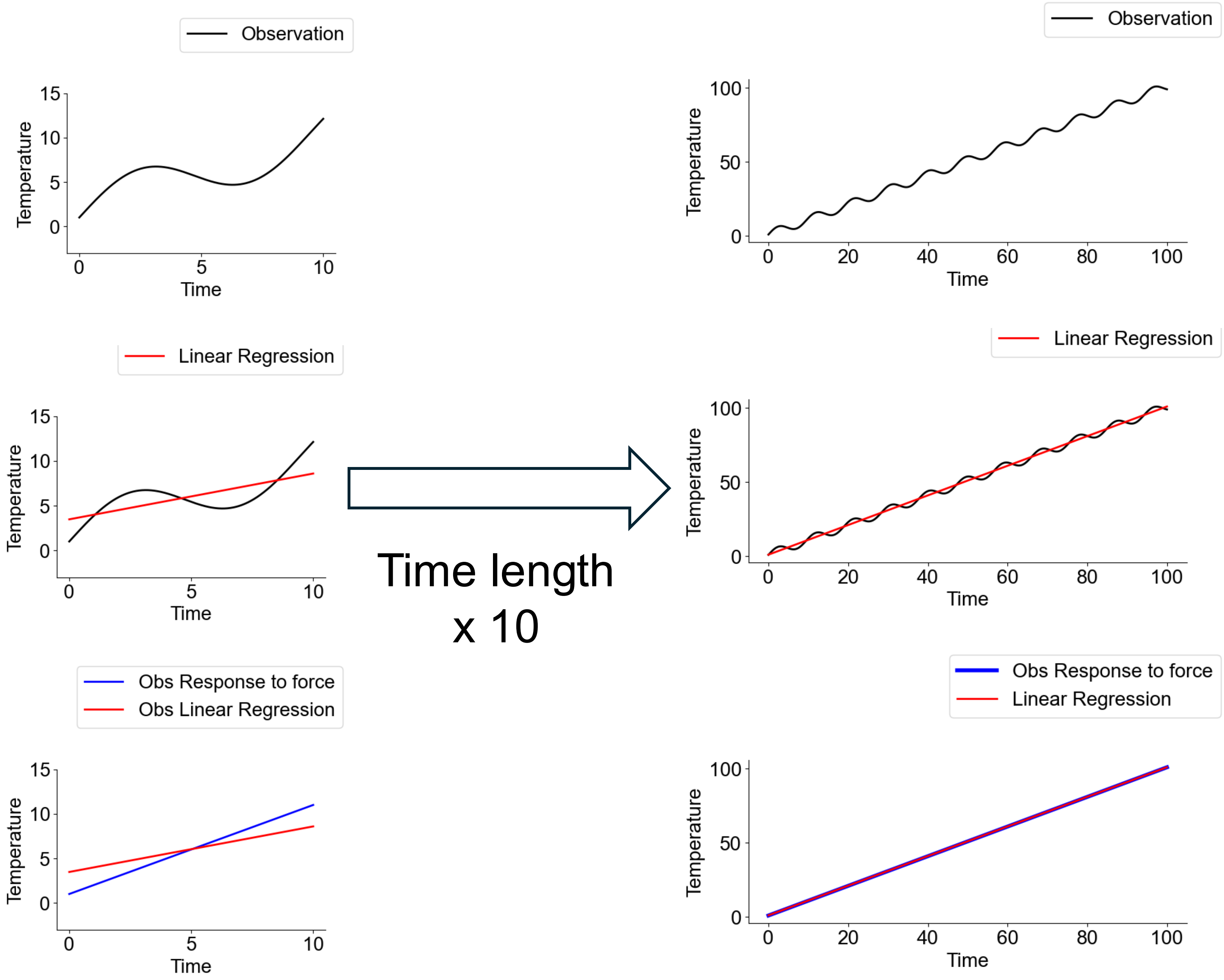
Discrepancy in Temperature trend difference



What is the discrepancy?

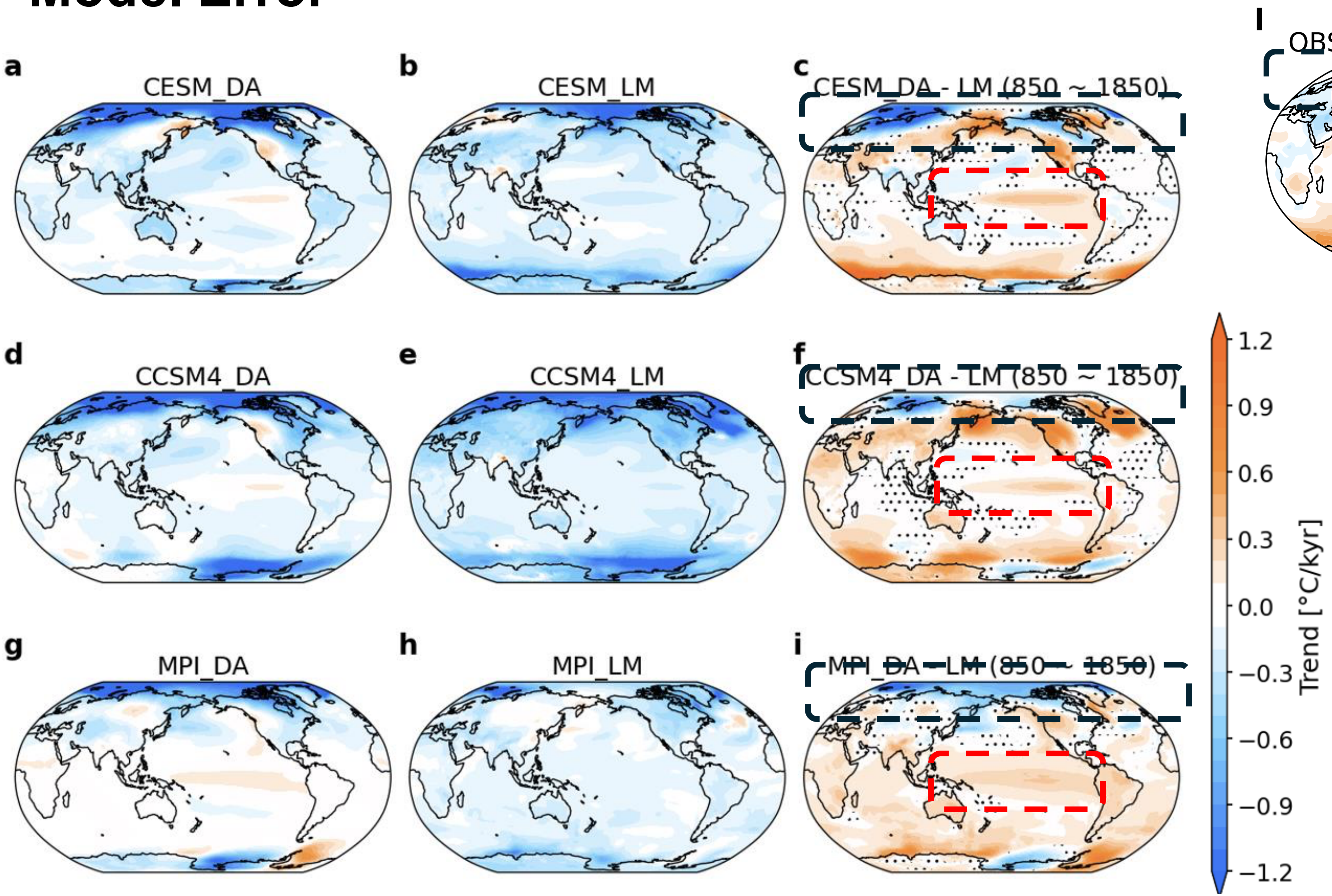


OBS – MMM = Internal Variability (Sweeney et al. 2024) + Model error response to extra forcing



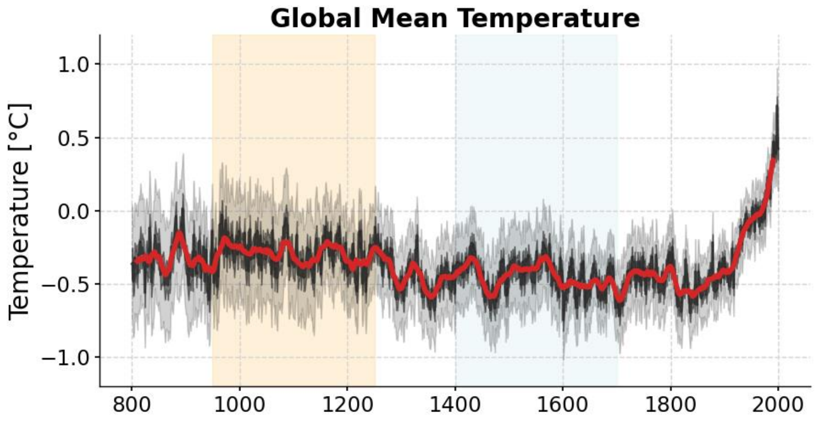
Longer observation makes the linear regression result closer to the response to extra forcing.

Model Error

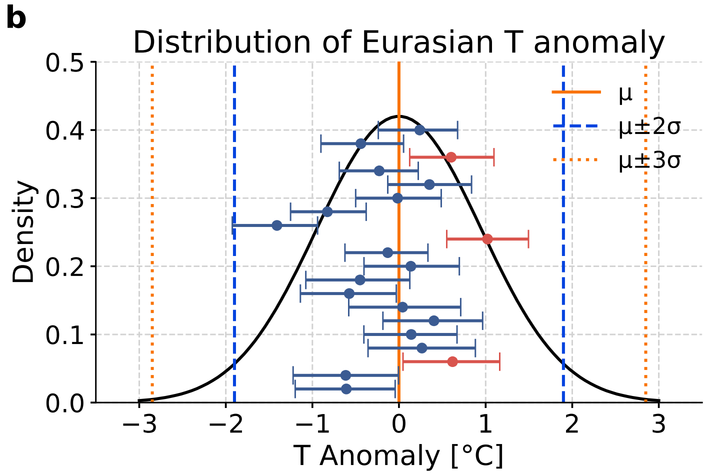


Model error response to extra forcing contributes to the the discrepancy.

Application Summary

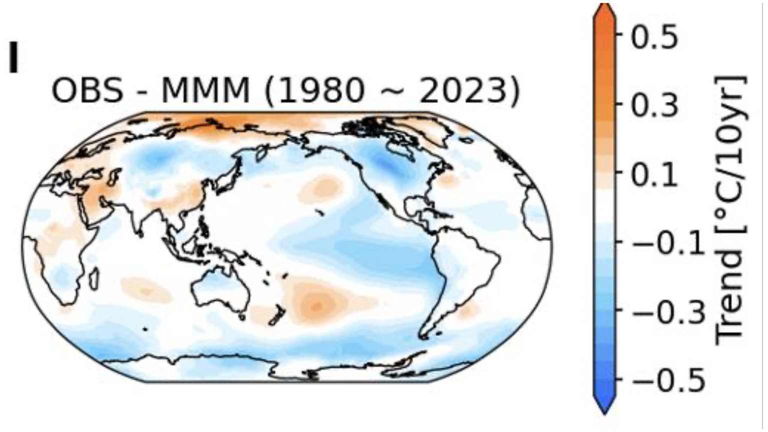


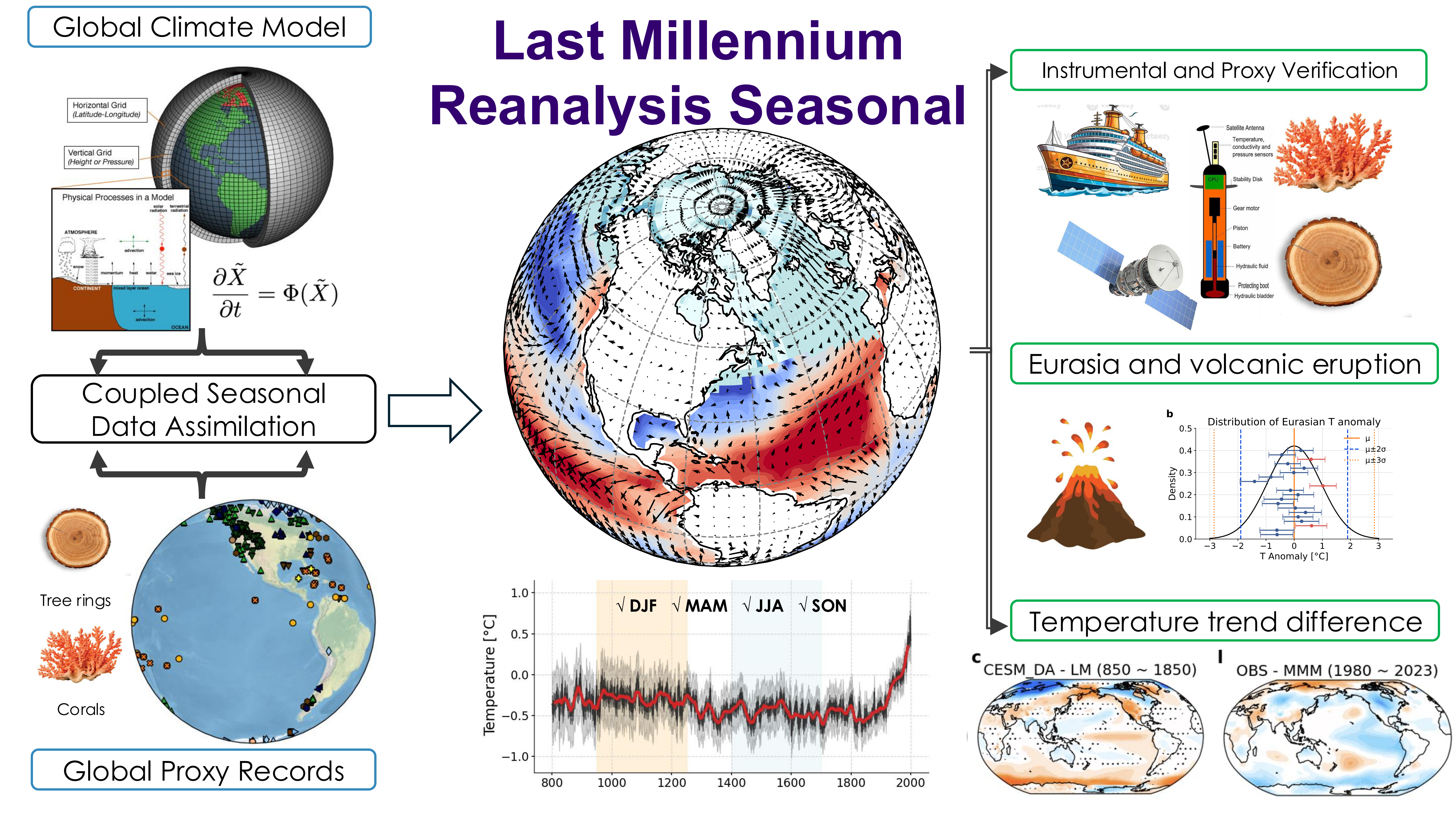
- LMR Seasonal can successfully reconstruct MCA and LIA.



- 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.





Last Millennium Reanalysis Seasonal
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Horizontal Grid (Latitude-Longitude)
Vertical Grid (Height or Pressure)
Physical Processes in a Model
$\frac{\partial \tilde{X}}{\partial t} = \Phi(\tilde{X})$
Coupled Seasonal Data Assimilation
Tree rings
Corals
Global Proxy Records
√ DJF √ MAM √ JJA √ SON
Temperature [°C]
1.0
0.5
0.0
−0.5
−1.0
800 1000 1200 1400 1600 1800 2000
Instrumental and Proxy Verification
Satellite Antenna
Temperature, conductivity and pressure sensors
Stability Disk
Gear motor
Piston
Battery
Hydraulic fluid
Protecting boot
Hydraulic bladder
Eurasia and volcanic eruption
b
Distribution of Eurasian T anomaly
μ
μ±2σ
μ±3σ
Density
T Anomaly [°C]
Temperature trend difference
c
CESM_DA - LM (850 ~ 1850)
OBS - MMM (1980 ~ 2023)

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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