4th ICTP Summer School on Theory, Mechanisms and Hierarchical Modeling of Climate Dynamics: Atlantic Variability and Tropical Basin Interactions, Trieste, Italy, 7 August 2023

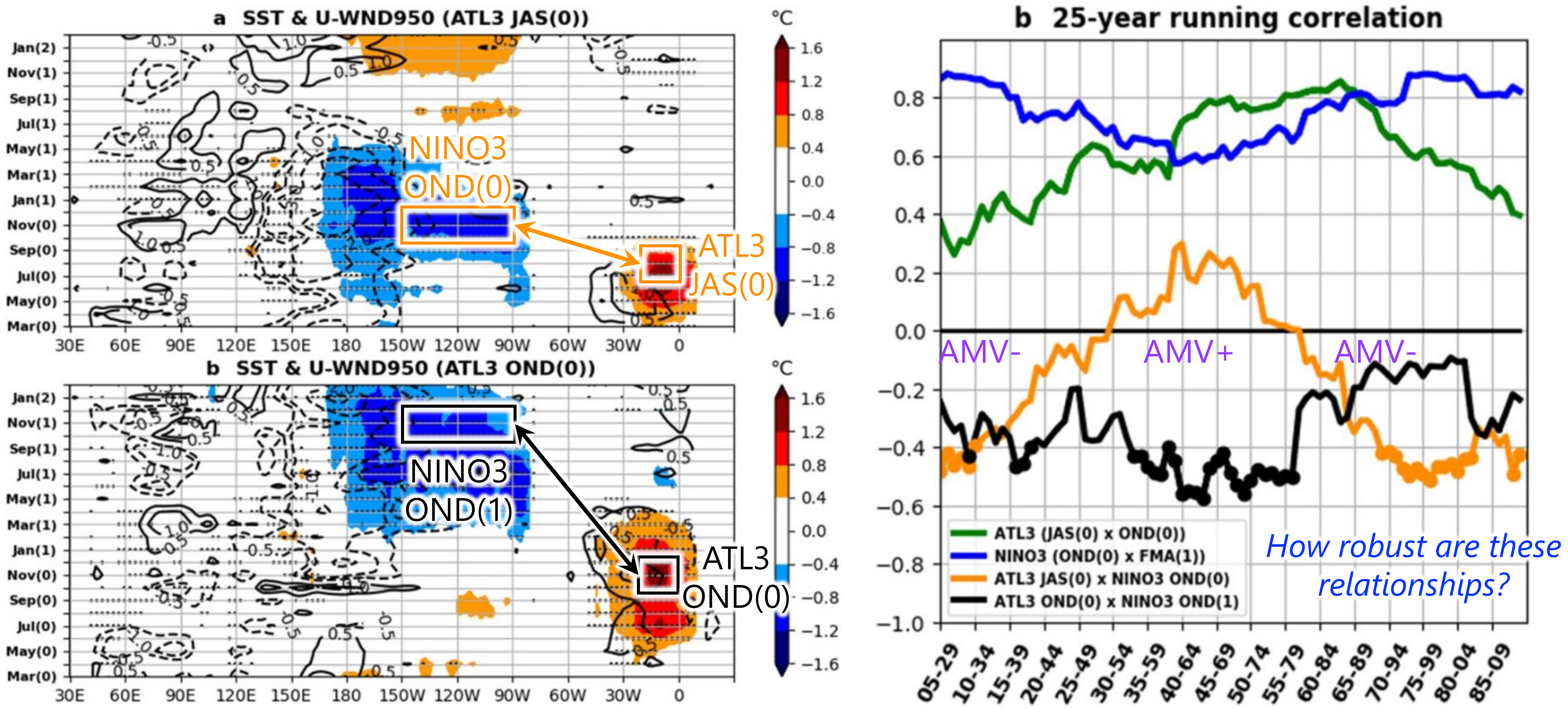
How can we use paleoclimate proxy records to advance our understanding of AMV and TBI?

Yuko M. Okumura

University of Texas at Austin Institute for Geophysics

Observational records are too short, and models are imperfect….

Multidecadal modulation of Atlantic Nino-ENSO linkages

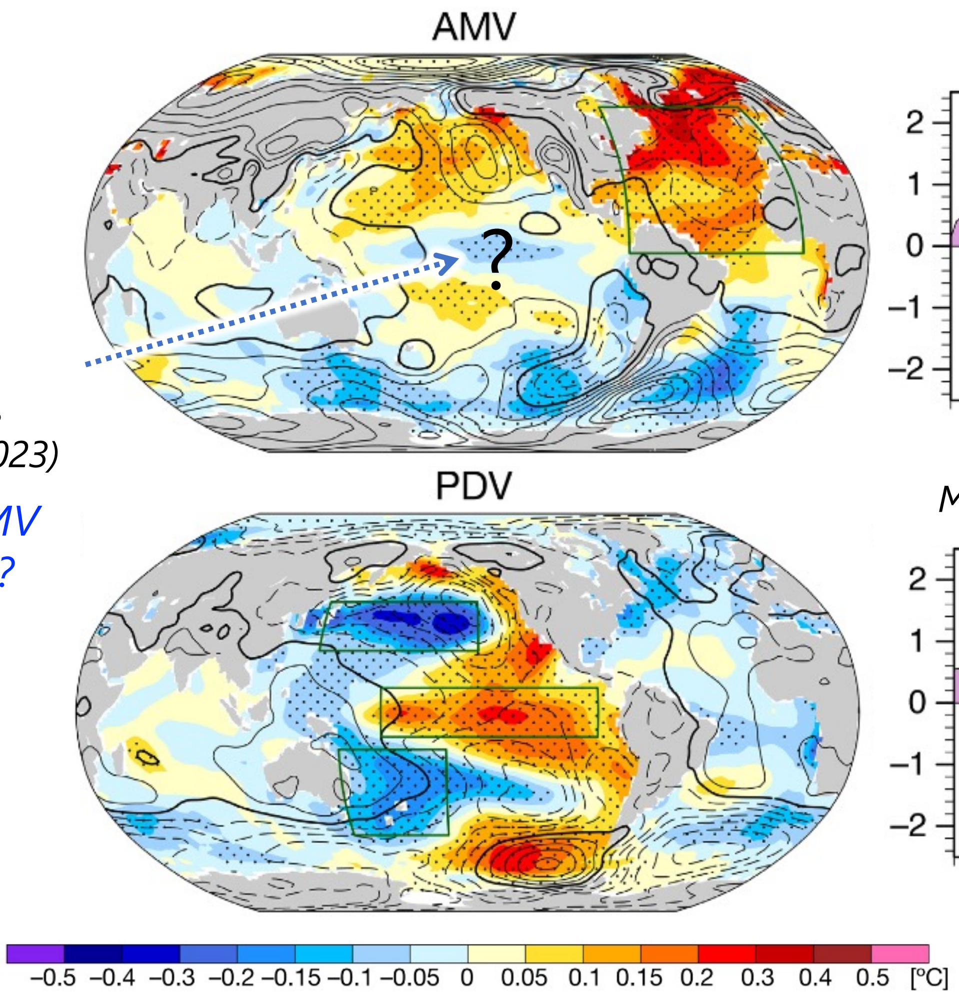


Hounsou-Gbo et al. (2020)
Also see *Rodríguez-Fonseca et al. (2009)*

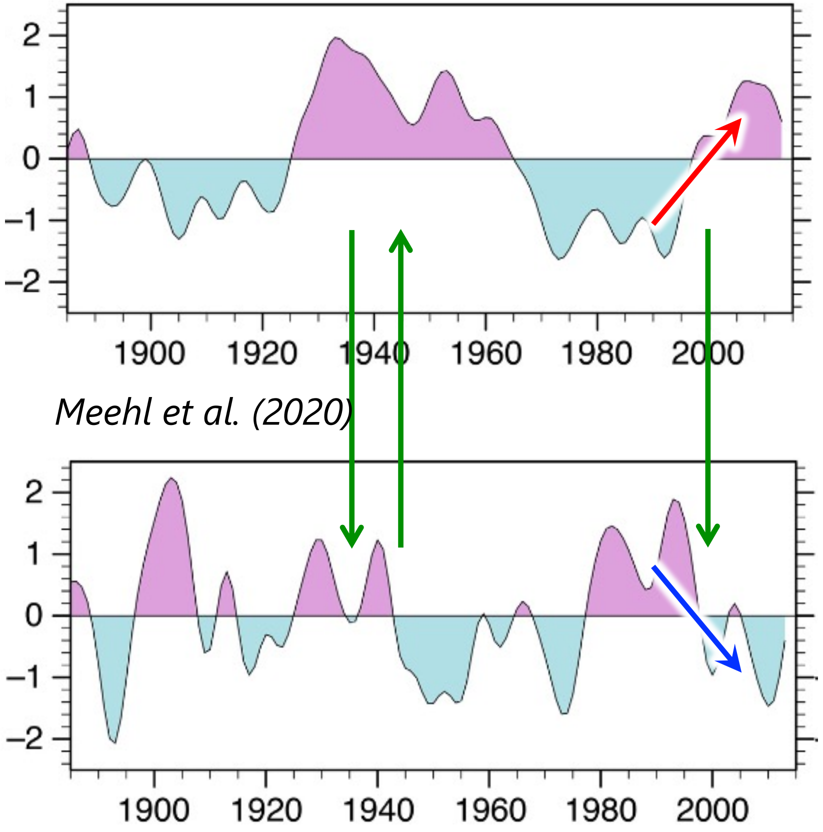
Atlantic-Pacific linkages in decadal variability

Pacific pattern is sensitive to trend removal methods
Deser and Phillips (2023)

How much are AMV and PDV related?



Johnson et al. (2020)

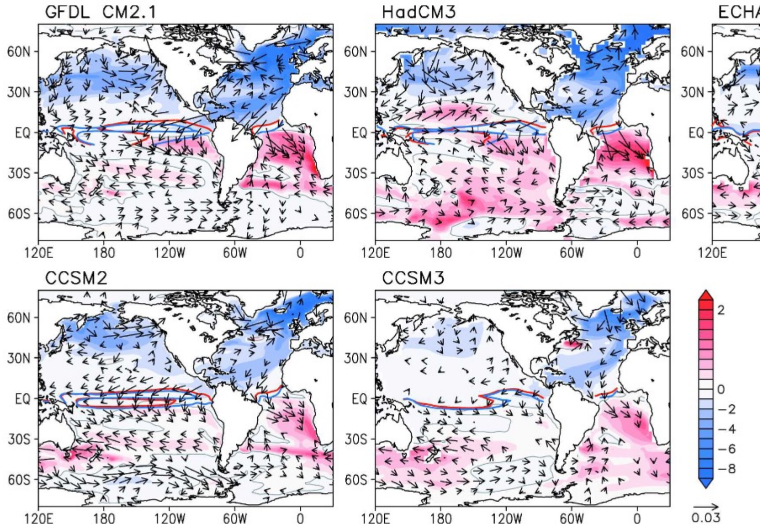


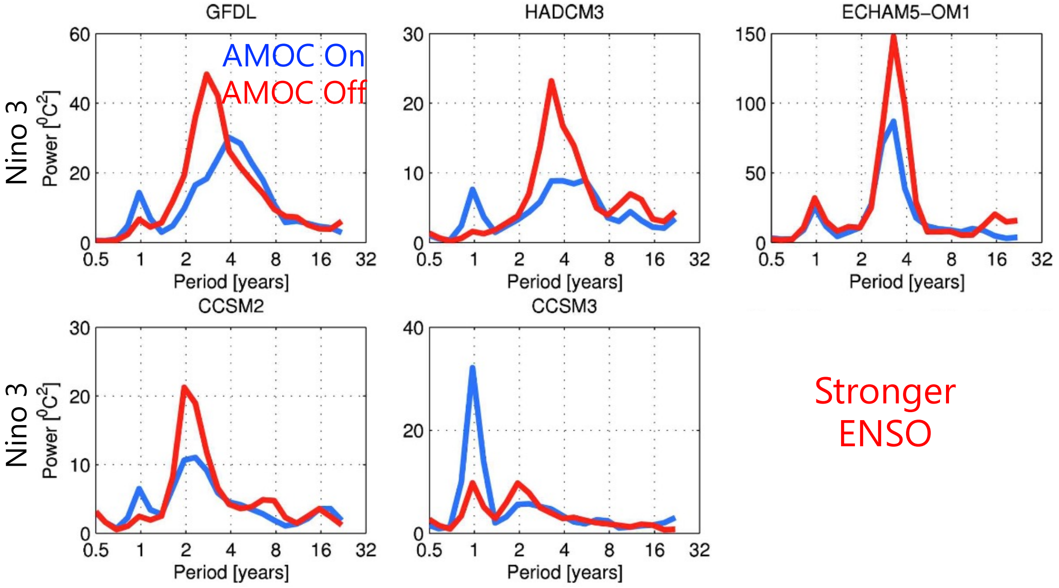
Meehl et al. (2020)

McGregor et al. (2014)
Li et al. (2016)
Chikamoto et al. (2016)
Kucharski et al. (2016)
Ruprich-Robert et al. (2017)

Impact of AMOC shutdown on Pacific mean climate and ENSO

GFDL CM2.1, HadCM3, ECHAM5-OM1, CCSM2 & 3
Timmerman, Okumura et al. (2007)

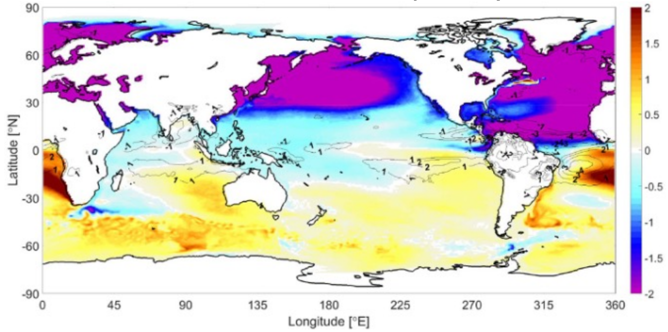


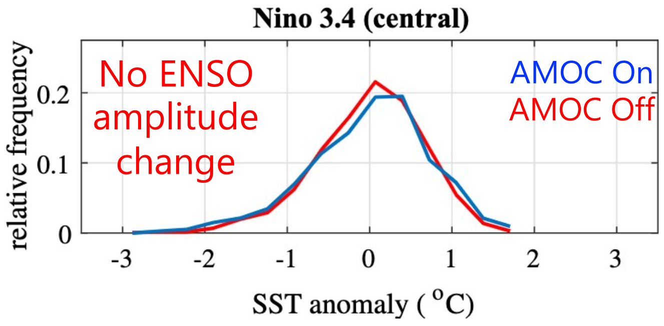


Stronger ENSO

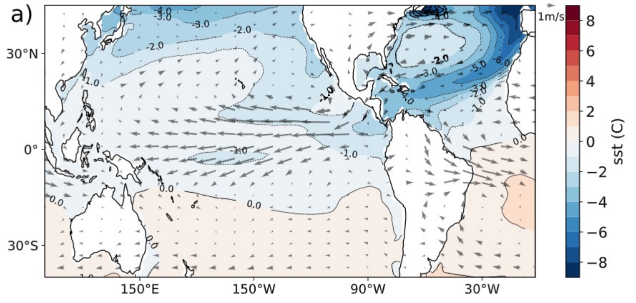
Various models' response to 1Sv freshwater forcing over the North Atlantic

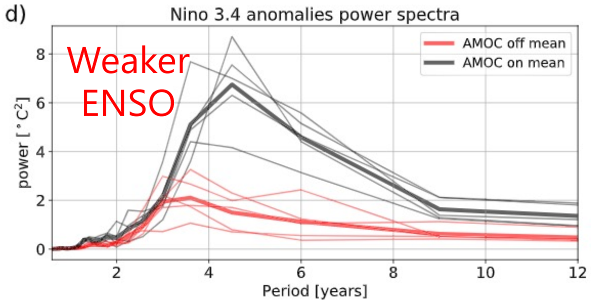
HadGM3
Williamson et al. (2018)





CESM1.2
Orihuela-Pinto et al. (2022)





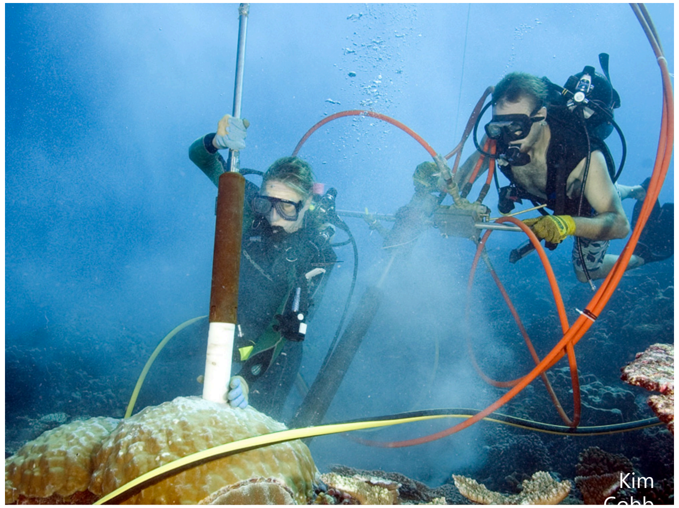
How does ENSO respond to AMOC shutdown?

What kinds of paleoclimate proxy records are available?
(seasonal-decadal temporal resolutions)

Main types of paleoclimate proxy records (tropics-mid-latitudes)

Corals

- $\delta^{18}O$ (temperature/salinity), Sr/Ca, Mg/Ca (temperature)
- High resolution (monthly-annual)
- Low age uncertainty (< 1 yr)
- Relatively short (< 100 yrs)
- Limited availability in cool tropical oceans and before 1800



Speleothems

- $\delta^{18}O$ (precipitation/temperature), Sr/Ca, growth rate
- High resolution (sub annual)
- Age uncertainty (< ±50 yrs)
- Continuous records (can be > 1000 yrs)
- Seasonality in climate sensitivity
- Variable water transit time, growth hiatuses

Main types of paleoclimate proxy records (mid-latitudes-polar)

Tree rings

- Ring width, $\delta^{18}O$ (temperature/precipitation)
- High resolution (sub annual-annual)
- Precise dates
- Continuous records (can be > 1000 yrs)
- Widespread distribution in mid-latitudes
- Inexpensive to produce records
- Seasonality in climate sensitivity
- Muted low-frequency variability due to detrending

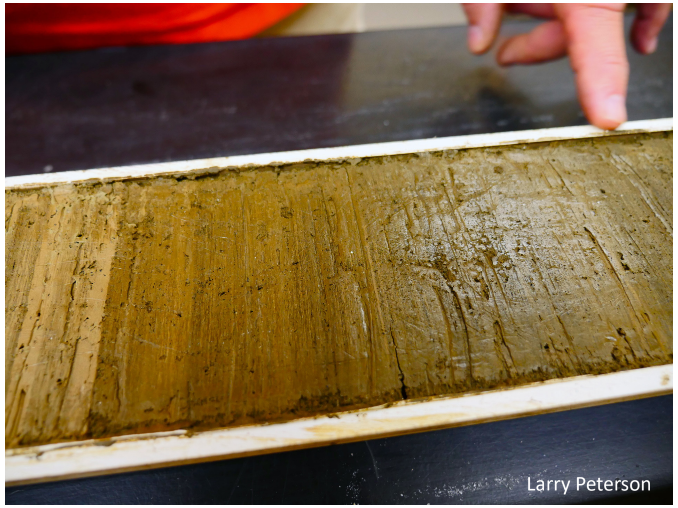
Ice cores

- $\delta^{18}O$, δD (temperature)
- High resolution (annual)
- Age uncertainty (< ±50 yrs)
- Continuous records (> 1000 yrs)
- Limited to polar and high-elevation regions

Main types of paleoclimate proxy records

Ocean/lake sediment cores

- Various quantities & climate interpretations
  For example,
  - Chemical composition or abundance of planktonic organisms (temperature, salinity)
  - Silt grain size (ocean bottom current)
  - Titanium content (river discharge)
- Resolution depends on the sedimentation rates (annual-decadal sampling is possible)
- Fieldwork can be very expensive



Other potential high-resolution proxies

- Bivalves, coralline algae, and other biological proxies
- Borehole temperatures

Climate Data Guide (new paleoclimate section)

NCAR | CLIMATE DATA GUIDE

HOME ABOUT CLIMATE DATA TOOLS & METHODS NETWORK OF EXPERTS UPDATES

Home / Climate Data / Paleoclimate

Paleoclimate

Paleoclimate data are derived from Earth's natural climate archives, including tree rings, ice cores, corals, speleothems, and ocean sediments. Such records are used to broaden the sampling of climate variability beyond what is possible from the instrumental record. Paleoclimate data are used to place recent changes into a long-term context, to understand the causes and impacts of climate change, and to explore the behavior of the climate system under vastly different boundary conditions than the present day.

To find only the datasets with expert-written commentaries, select the "Datasets with guidance" button when using the search box.

https://climatedataguide.ucar.edu/

Sub-categories

coral | ice core | lake sediments (paleolimnology) | Paleoclimate | pollen | tree ring (dendroclimatology)

- Developed in collaboration with the CLIVAR TBI RF Paleoclimate Working Group
- Expert guidance to various topics and datasets
- More new contents are under construction

Also, see a comprehensive review paper by *Jones et al. (2009)*

Tree-ring width chronologies: An overview of their use as climate proxies and of available databases

Years of record N/A

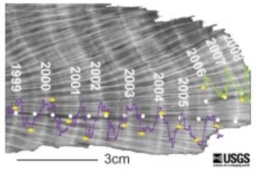
The width of an annual tree ring is a very simple indicator of the character of that year's weather, but collectively the global network of tree-ring width...

Main variables and Earth System components

N/A

Formats N/A **Timestep** Annual **Domain** Global **Collections** N/A

Experts contributing reviews St. George, Scott



Coral geochemical records: An overview of their use as climate proxies and of available databases

Years of record N/A

Coral records are one of the main types of high-resolution (annual to sub-annual) paleoclimate proxies, providing timeseries of environmental conditions reaching...

Main variables and Earth System components

Atmosphere | Evaporation | Evaporation-Precipitation | Precipitation | Ocean | Salinity | SST - sea surface temperature

Formats ascii | HTML Table | Linked Paleo Data (LiPD) | Matlab **Timestep** N/A

Domain Atlantic Ocean, Indian Ocean, Pacific Ocean, Tropics **Collections** N/A

Experts contributing reviews Lawman, Allison

An overview of paleoclimate information from high-resolution lake sediment records: Strengths, limitations and key databases

Years of record N/A

Accumulated sediments at the bottom of lakes are invaluable archives of past climate and environmental change. These sediments contain a variety of physical,...

Main variables and Earth System components

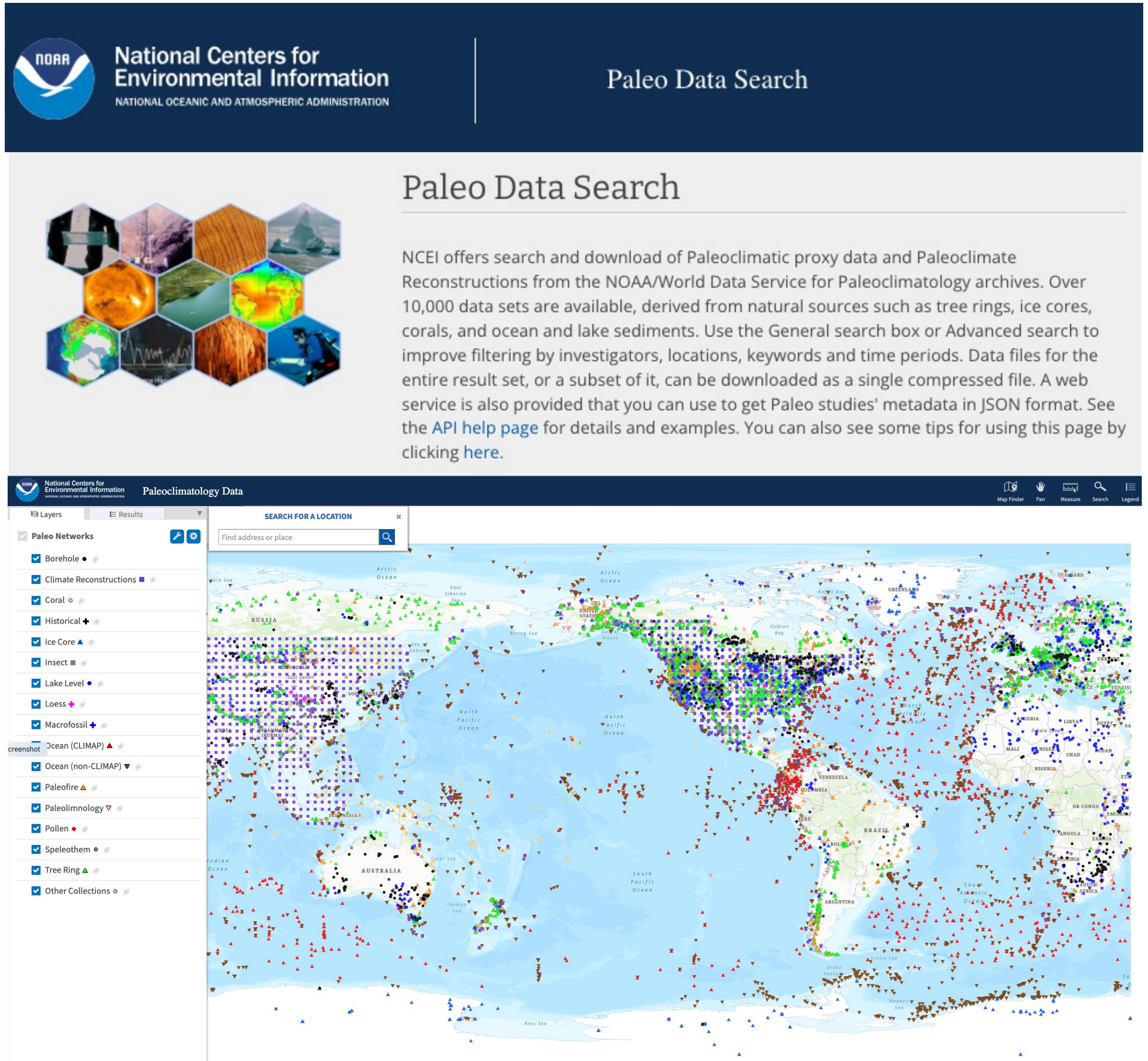
Atmosphere | Air Temperature | Precipitation | Biosphere | Pollen | Land

Formats ascii | csv | Linked Paleo Data (LiPD) **Timestep** Annual, Decadal, Irregular **Domain** Global **Collections** N/A

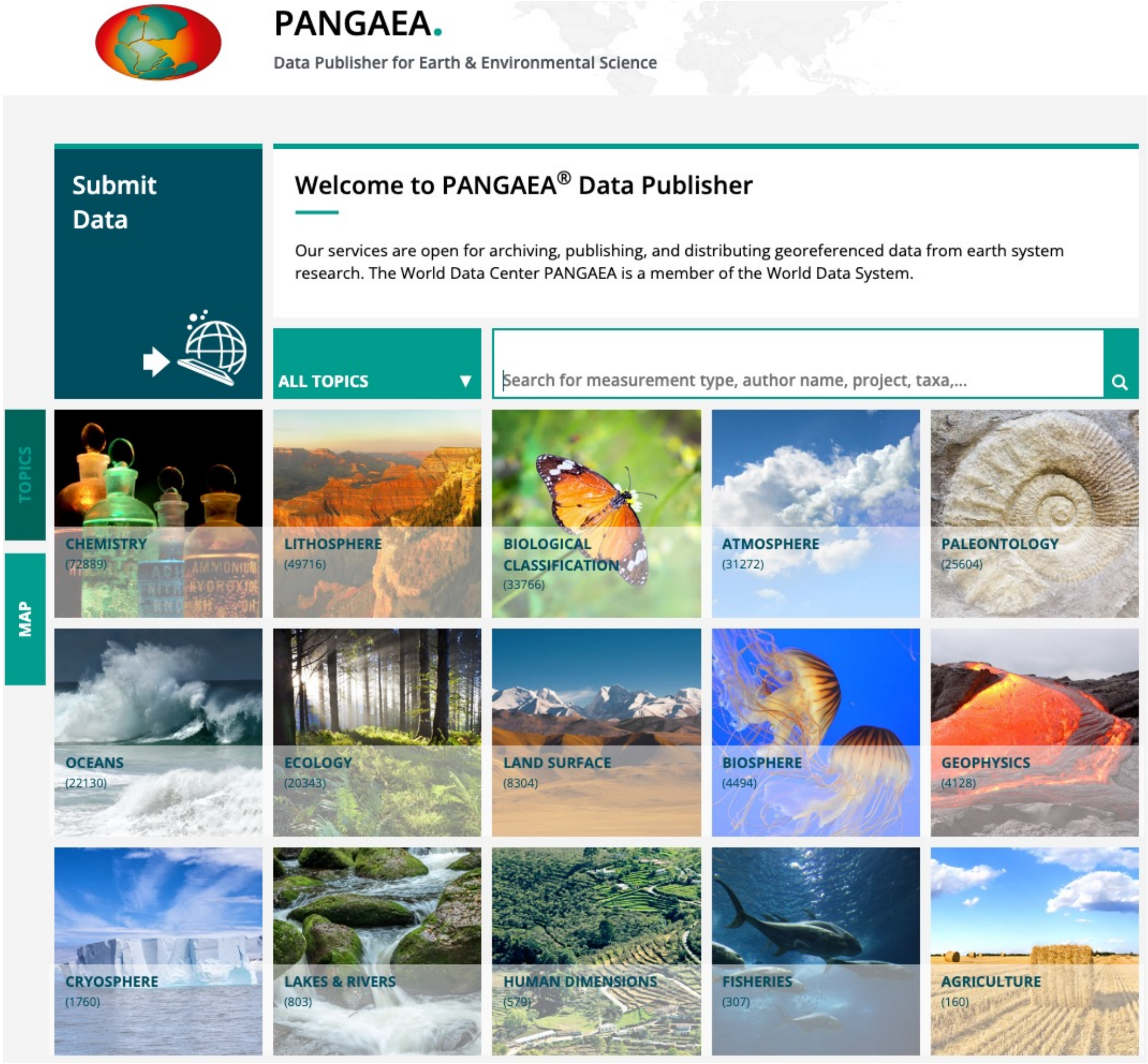
Experts contributing reviews Larocca, Laura | Broadman, Ellie

How many paleoclimate proxy records do we have? (0-2000CE)

Paleoclimate data archives at NOAA NCEI and PANGAEA



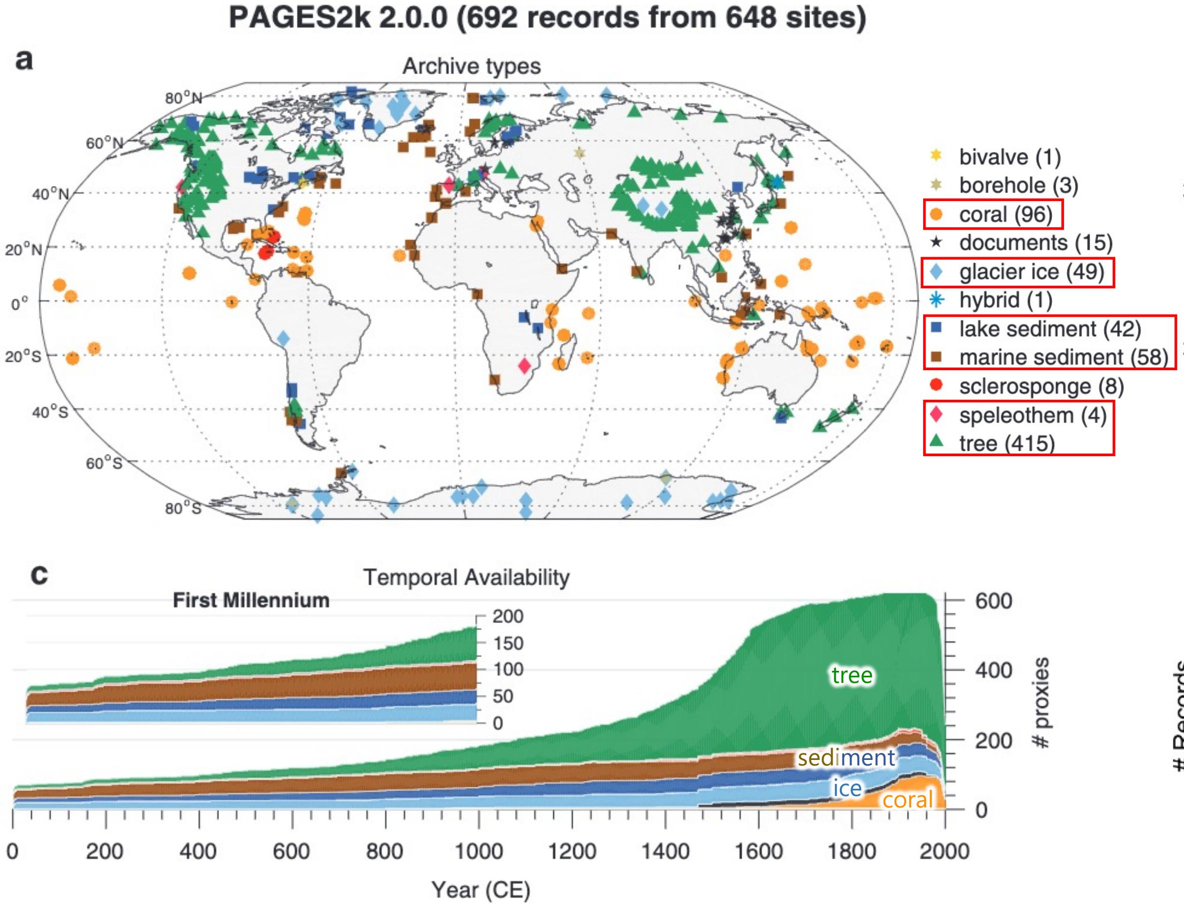
https://www.ncei.noaa.gov/products/paleoclimatology



https://www.pangaea.de/

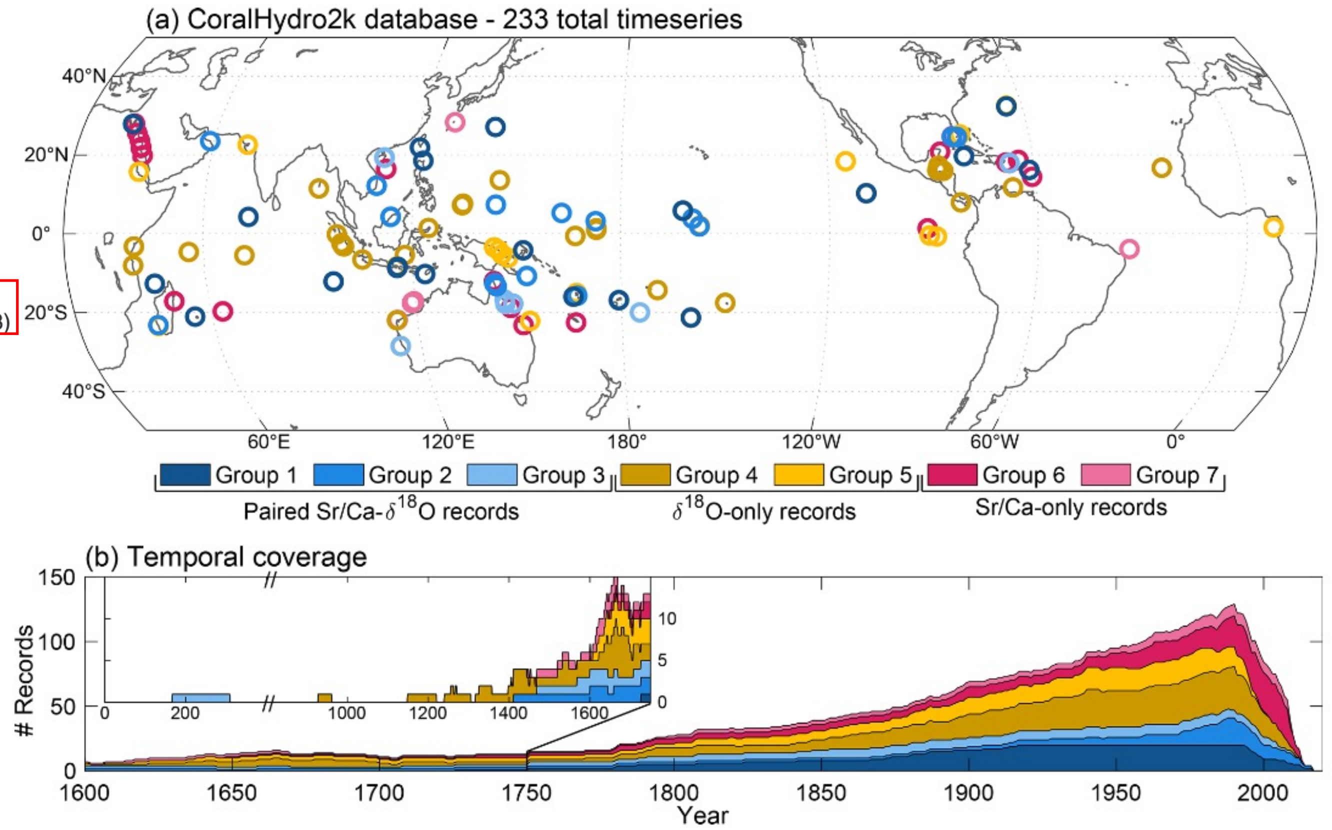
PAGES2k databases

PAGES2k—Temperature-sensitive proxies



Emile-Geay et al. (2017)

CoralHydro2k—Coral Sr/Ca & $\delta^{18}O$ (SST & SSS)



Walter et al. (2023)

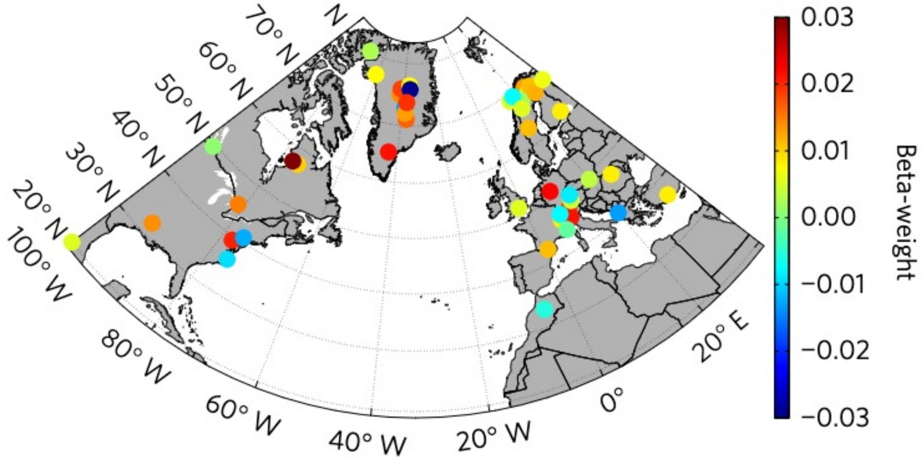
Available in the Linked Paleo Data format (readable in Python, MATLAB, and R) from NOAA NCEI's paleoclimate data archive.

Other PAGES2k databases include SISAL (speleothem; *Comas-Bru 2020*) and Iso2k ($\delta^{18}O$ & δD; *Konecky et al. 2020*)

Examples of AMV/TBI research using paleoclimate proxy records

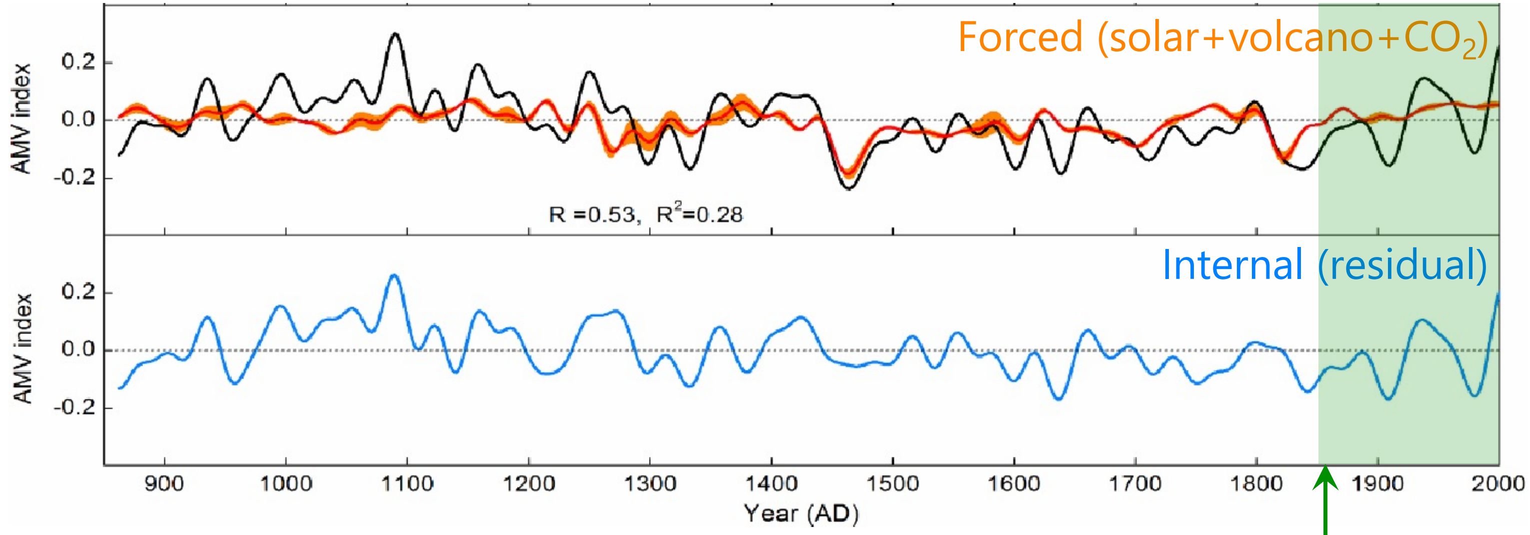
Role of external forcing in AMV

Locations and weights of annual tree ring and ice core data used for AMV reconstruction

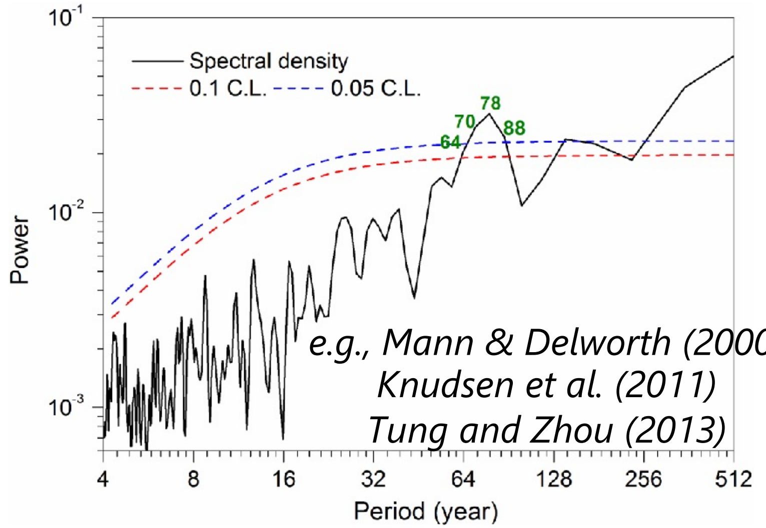


Wang et al. 2017

Reconstructed AMV index



Potential role of anthropogenic aerosols
e.g., *Booth et al. (2012), Si and Hu (2017), Bellomo et al. (2018)*



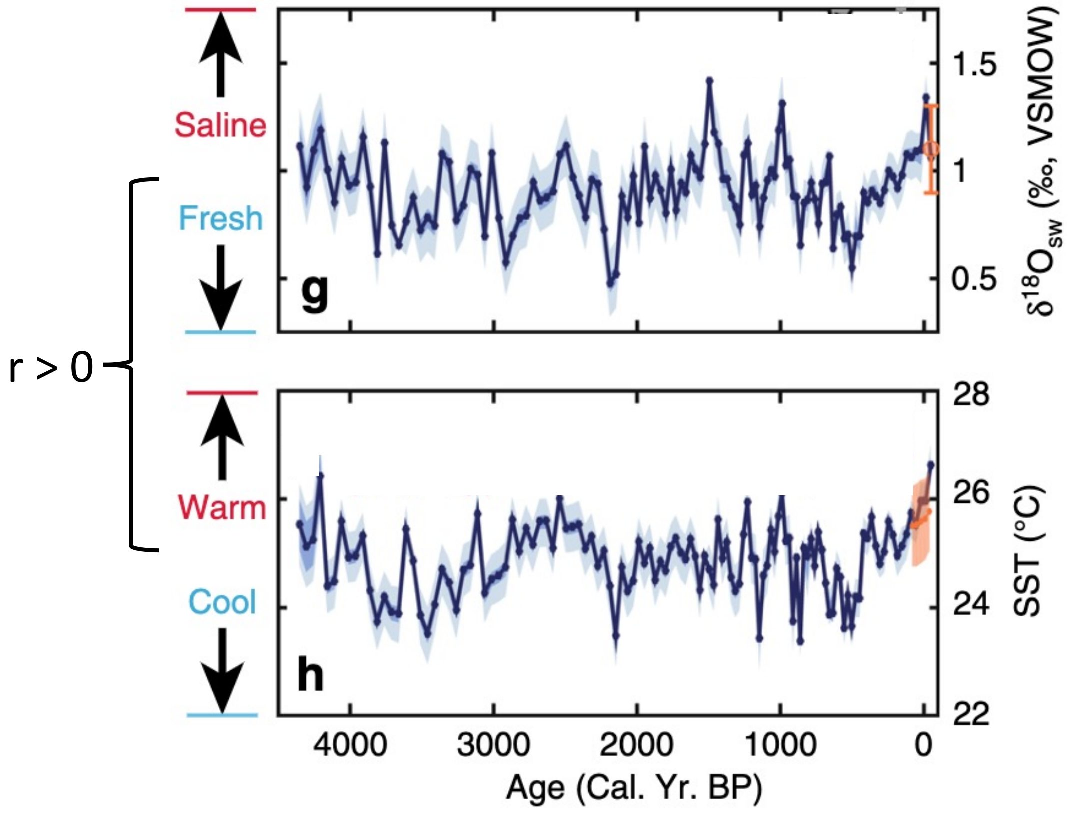
e.g., Mann & Delworth (2000)
Knudsen et al. (2011)
Tung and Zhou (2013)

↔

No significant multidecadal peaks
e.g., Rahmstorf et al. (2015)
Shigh et al. (2018)

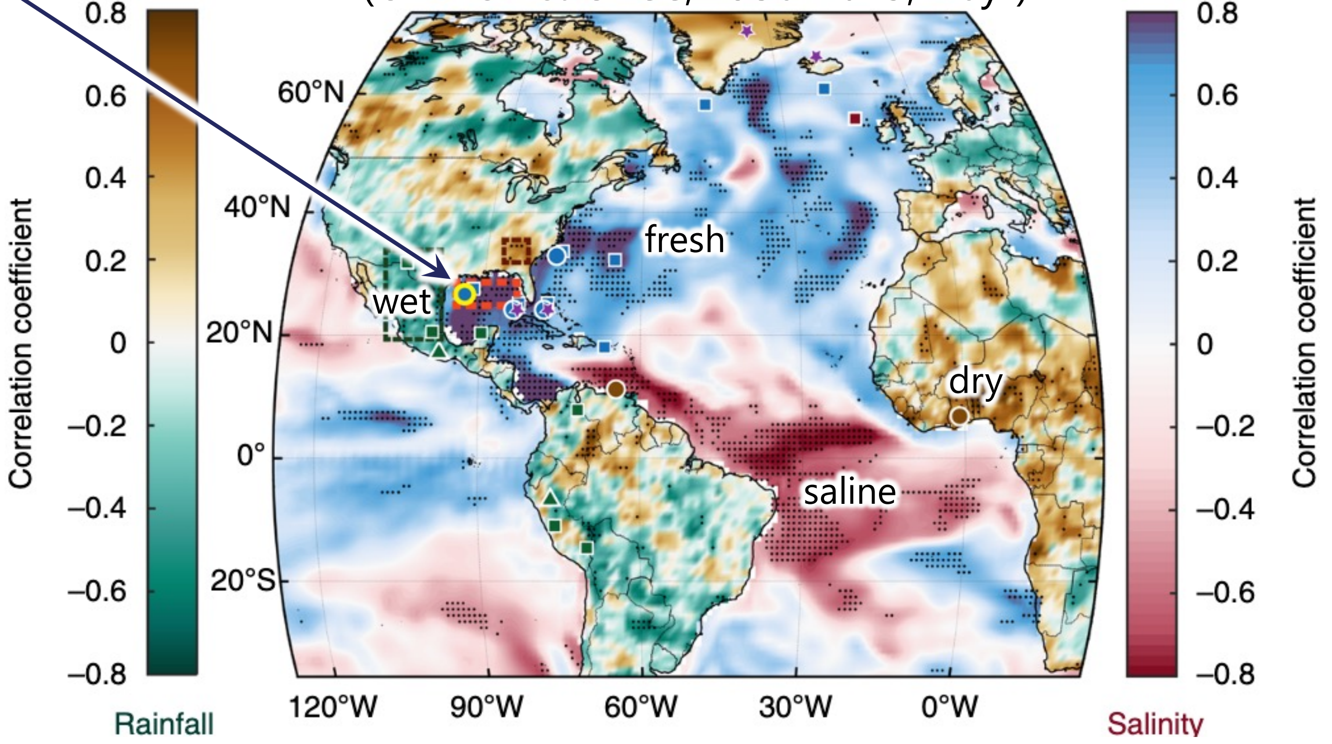
Role of salinity in centennial Atlantic variability

SST and sea surface salinity (SSS) reconstructions based on ocean sediment cores from the northern Gulf of Mexico (Mg/Ca and $\delta^{18}O$ of planktic foraminifer)



Thirumalai, Okumura et al. (2018)

SSS and land precipitation correlations with the northern Gulf of Mexico SSS index (ORA-S4 & GPCC, 1958-2013, >8yr)

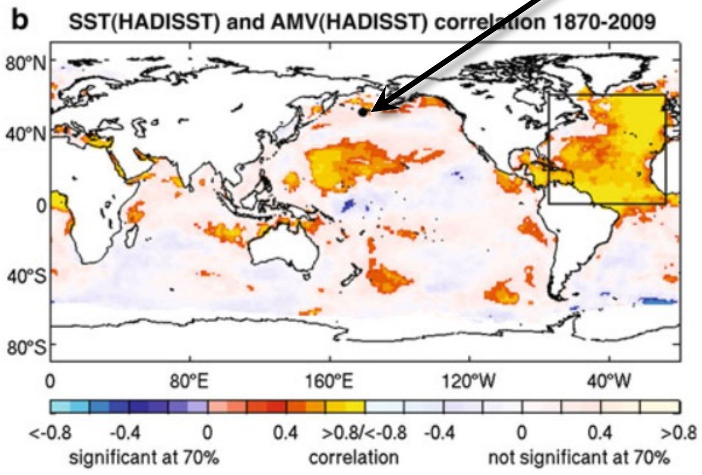


○-sediment, △-speleothem, dashed box-tree, □-others

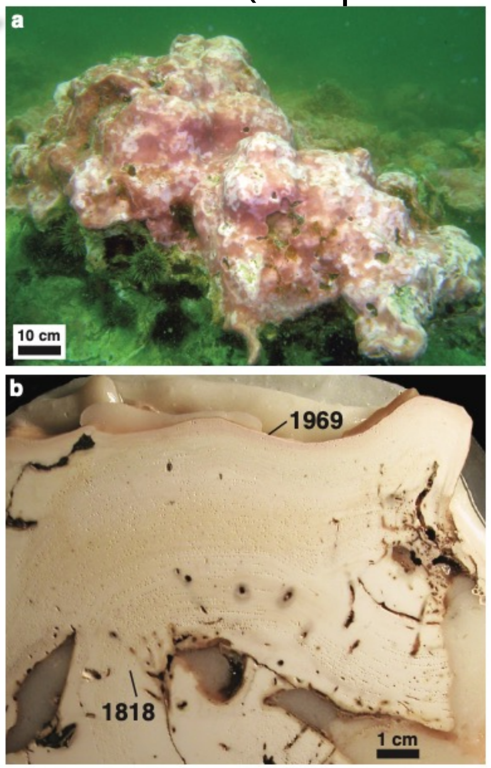
Colors indicate the sign of anomalies during the LIA

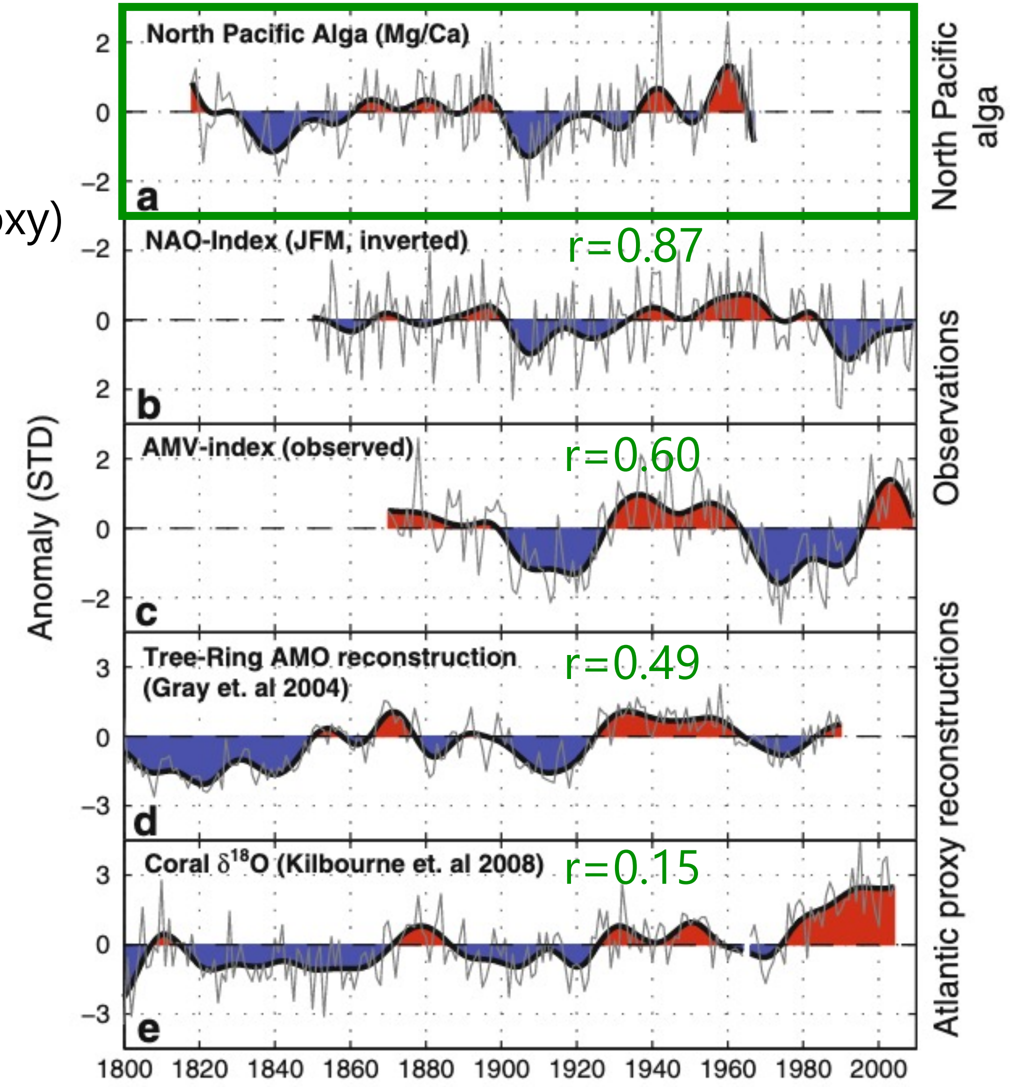
Atlantic-Pacific linkage in decadal climate variability

Coralline algae Mg/Ca record from
the Aleutian Islands (temperature proxy)



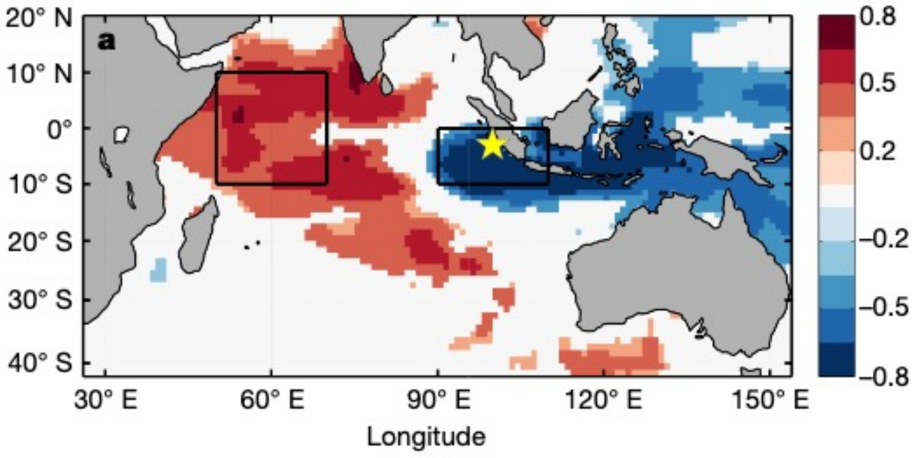
Hetzinger et al. (2012)



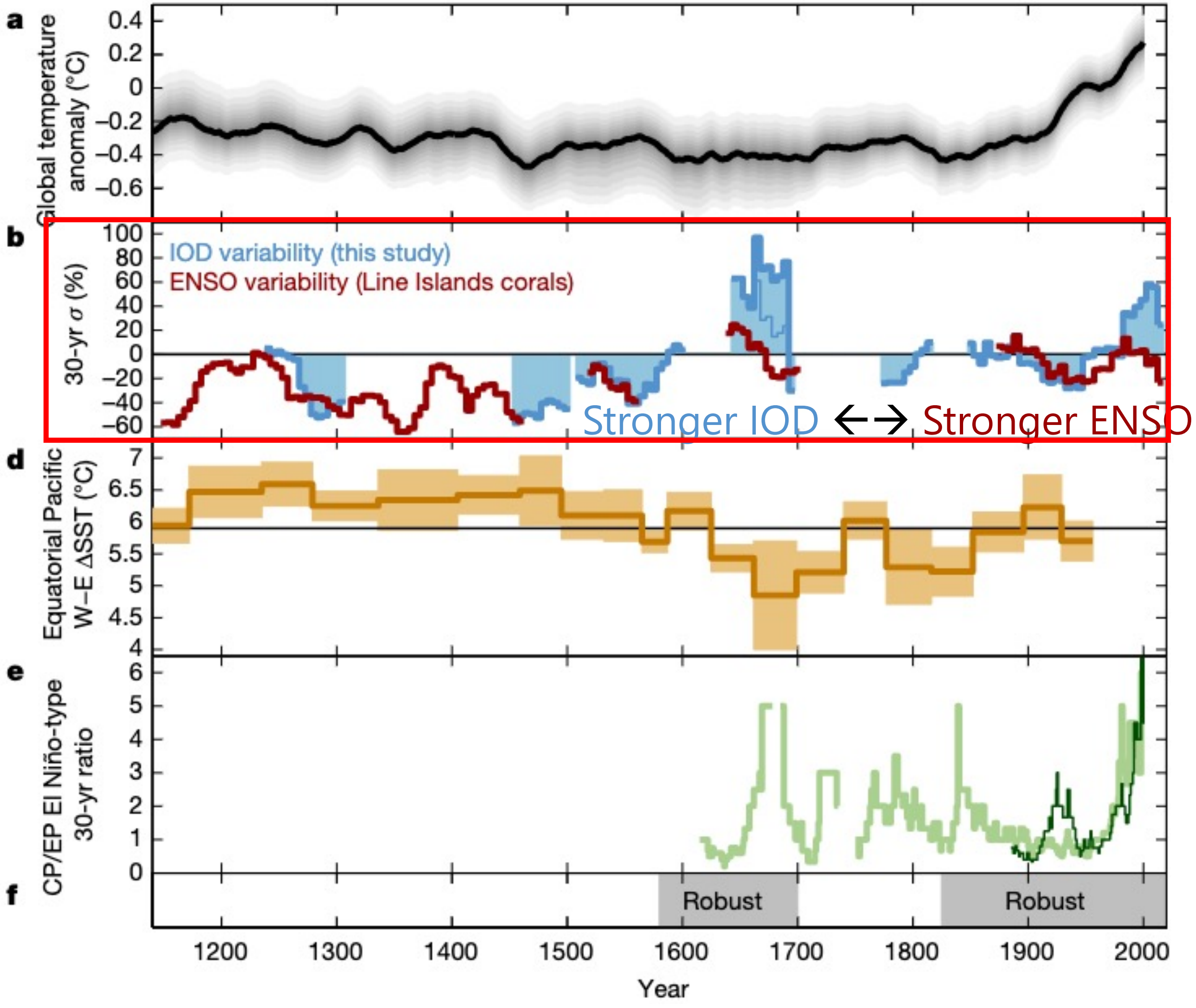


Linkage between decadal modulation of ENSO and IOD

Modern/fossil coral δ^{18}O from offshore of Sumatra
(r=0.79 with Jul-Dec IOD index, 1982-2000)



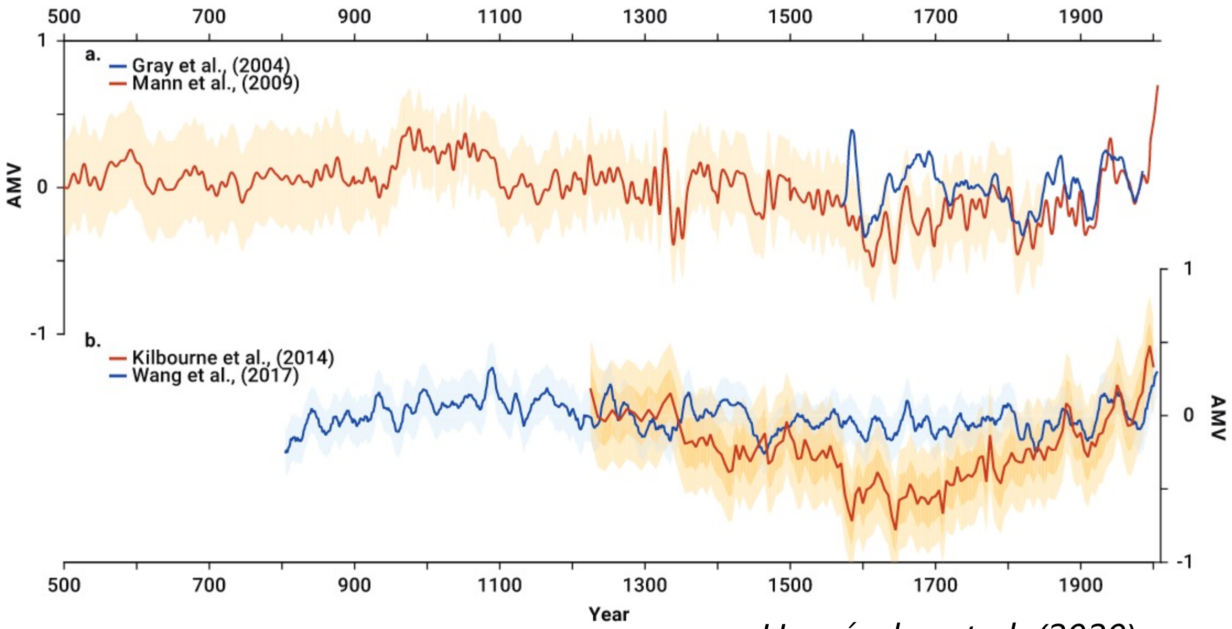
Abram et al. (2020)



How well can we reconstruct modes of climate variability?

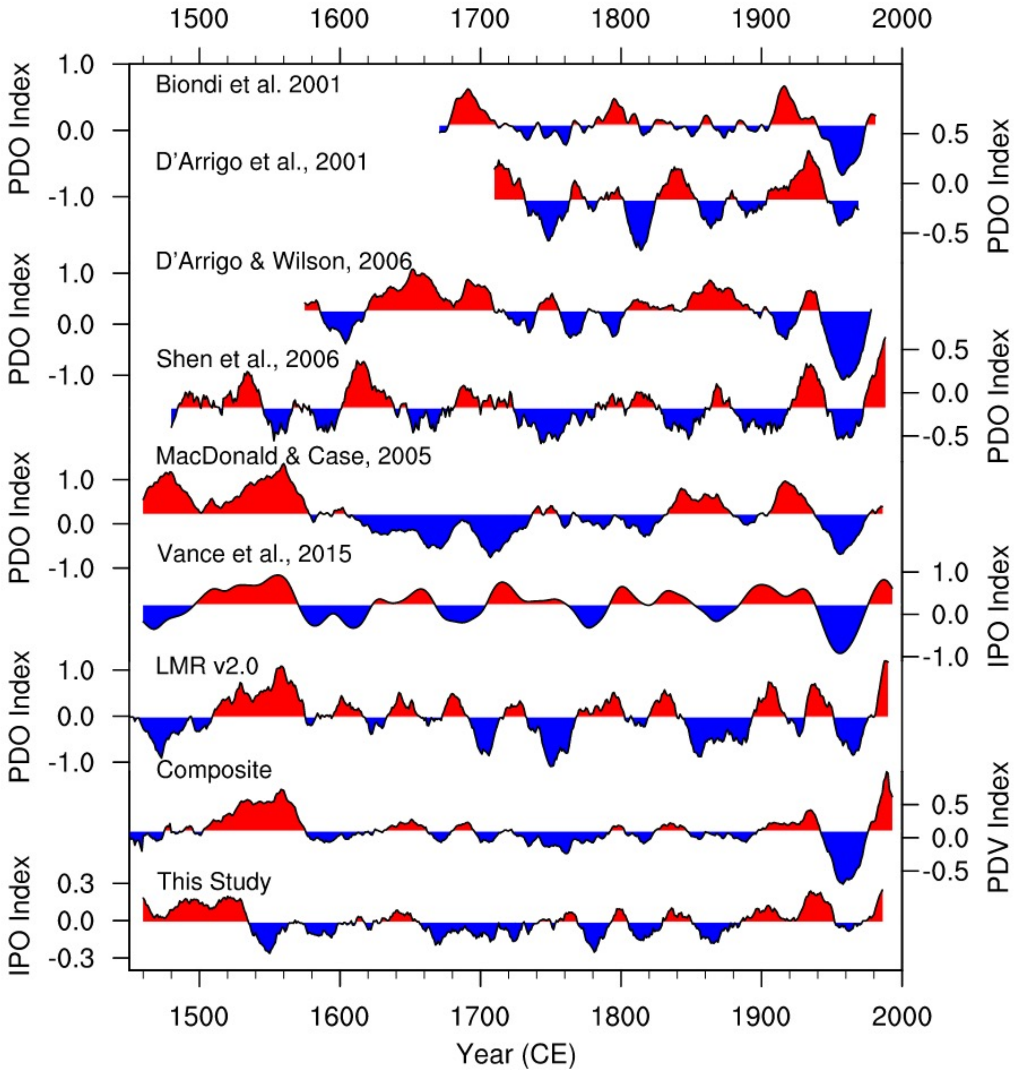
Inconsistencies among reconstructions of climate modes

Reconstructed AMV indices



Hernández et al. (2020)

Reconstructed PDV indices



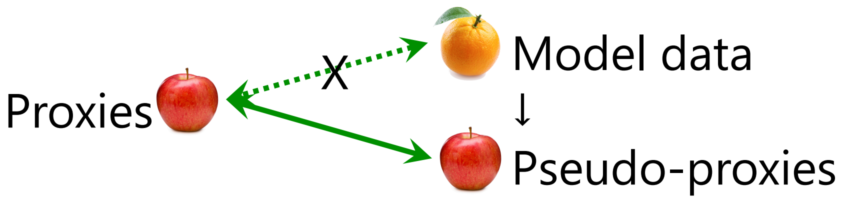
Porter et al. (2021)

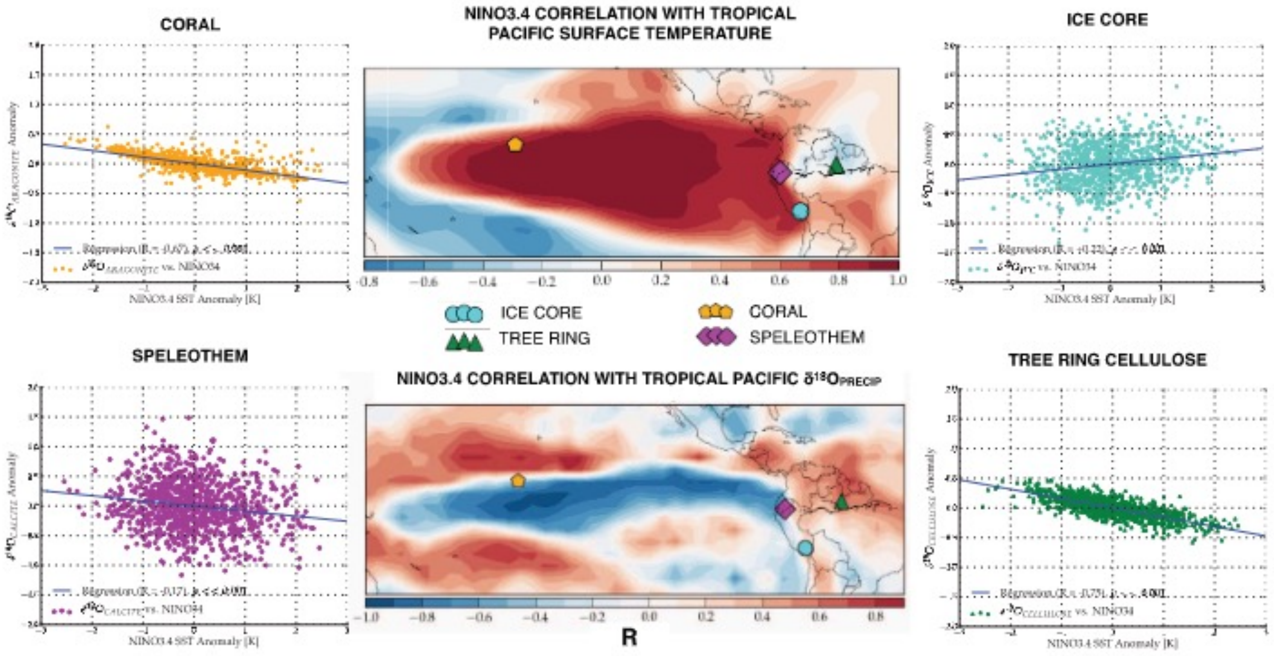
"Paleo-Spaghetti" (*Henley 2017*)

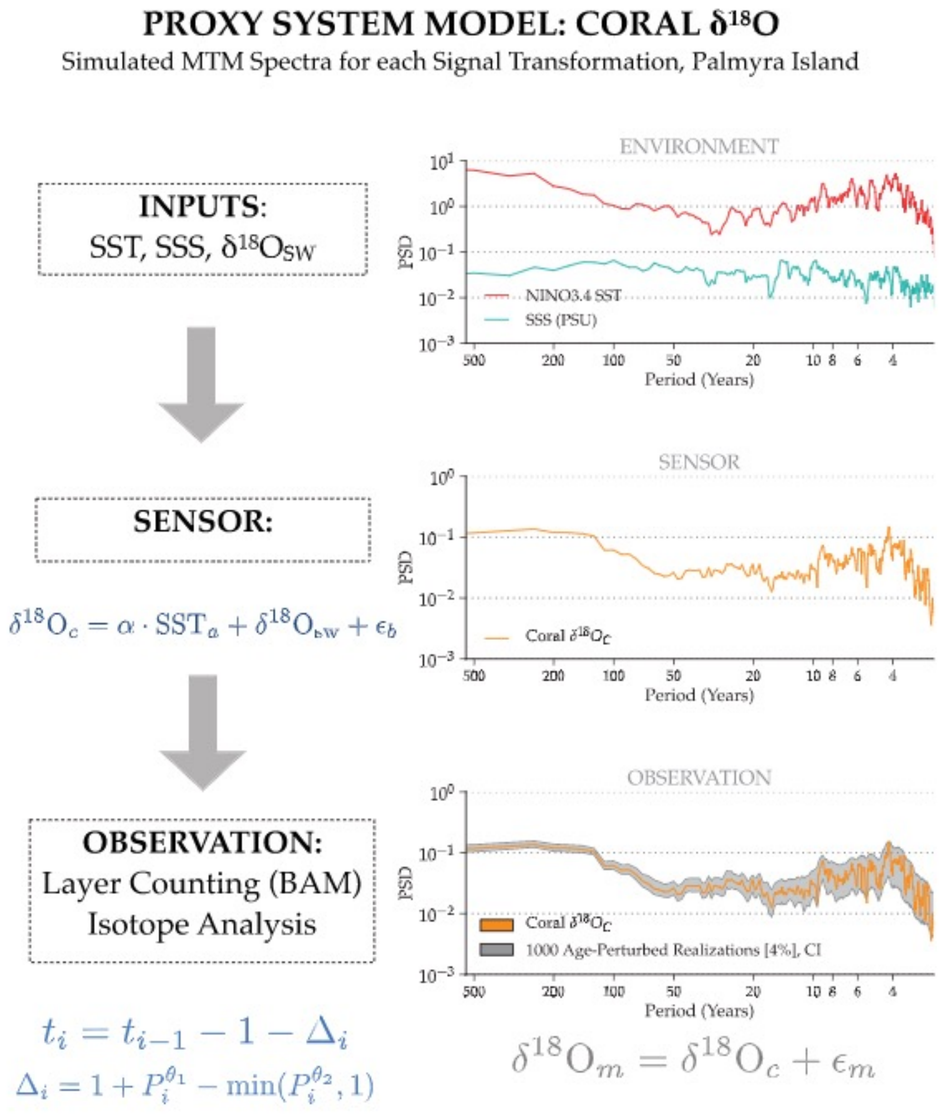
These inconsistencies are likely to arise from different proxies and methods used for reconstruction.

Is there a better method to reconstruct climate modes?
(paleoclimate reanalysis = proxy + model)

Proxy system models







Dee et al. (2015)

Paleoclimate data assimilation (offline)

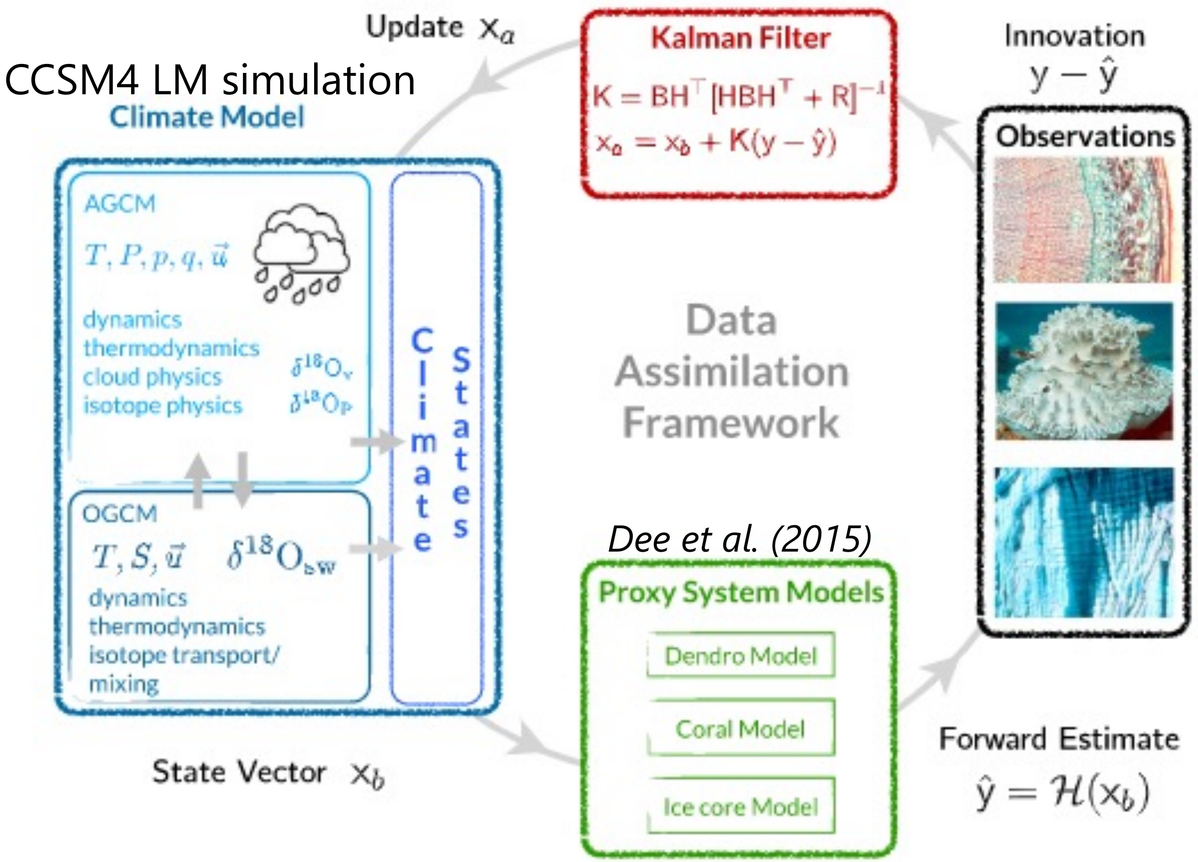


Figure 1. Conceptual framework for the Last Millennium Reanalysis, outlining our paleoassimilation approach. Starting from the prior (a collection of simulated climate states) from which random draws are pulled, the states are mapped to proxy space via a proxy system model (PSM). These predictions $\hat{y}$ are compared to the actual proxy measurements y to compute the innovation, $\hat{y} - y$. These innovations are then used to update the prior via the Kalman filter equations, which also update the error covariance. The cycle is repeated many (10^4) times to sample the distribution of the prior ensemble.

Hakim et al. (2016)

Last Millennium Reanalysis (LMR)

Hakim et al. (2016), Tardif et al. (2019)

544 proxies (temperature, seasonal-annual)
→ 2-deg annual dataset for 0-2000CE

Paleo Hydrodynamics Data Assimilation (PHYDA)

Steiger et al. (2018)

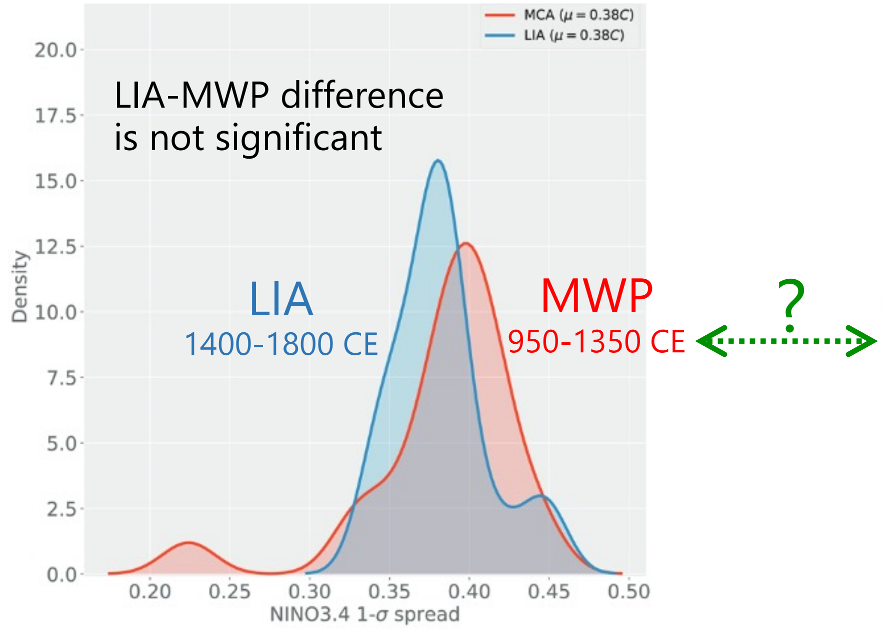
2978 proxies (hydroclimate, seasonal-annual)
→ 2-deg annual/seasonal dataset for 0-2000CE

Both datasets are available from the NOAA NCEI's paleoclimate data archive.

ENSO during the Little Ice Age and Medieval Warm Period in LMR

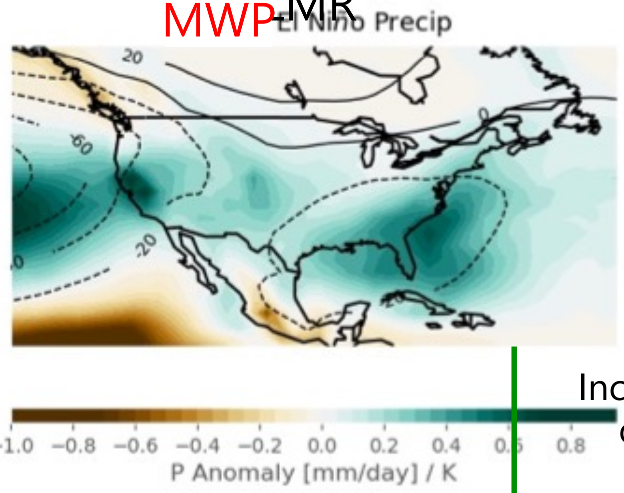
Li et al. (2011) suggest ENSO was stronger during LIA than MWP based on N American tree ring records

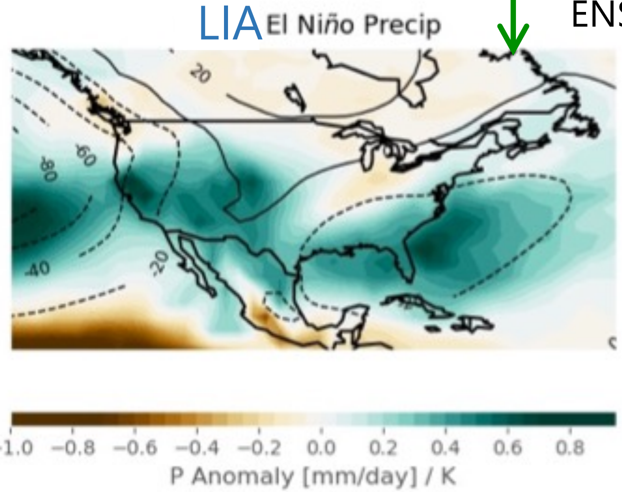
Distribution of Nino3.4 SD in the LMR ensemble



Dee, Okumura et al. (2020, GRL)

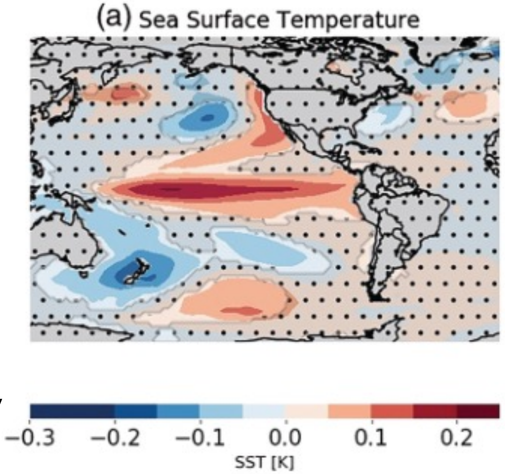
El Nino teleconnection in LMR

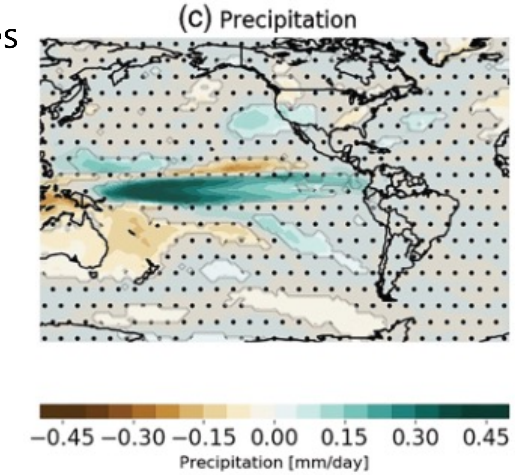




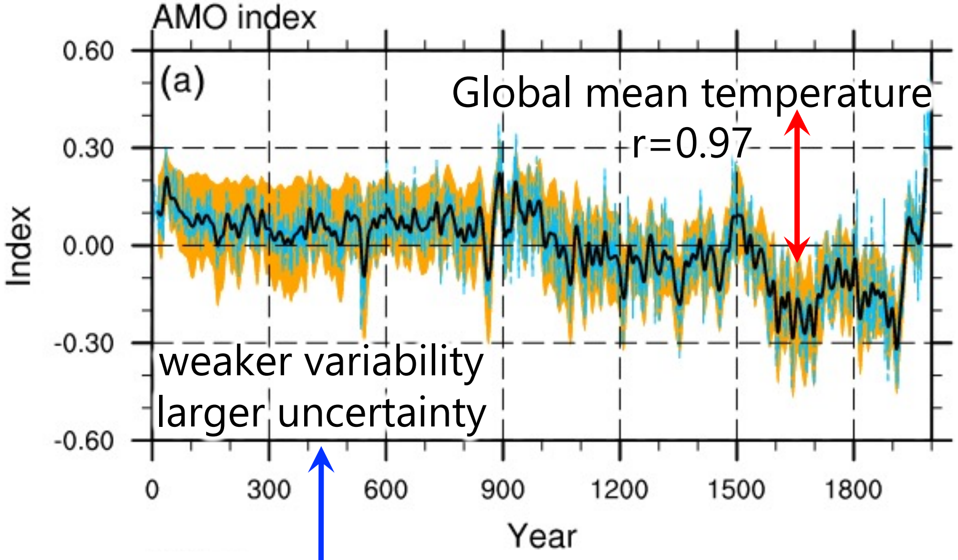
Increased sensitivity of atmospheric convection to ENSO SST anomalies

LIA-MWP mean state change in LMR



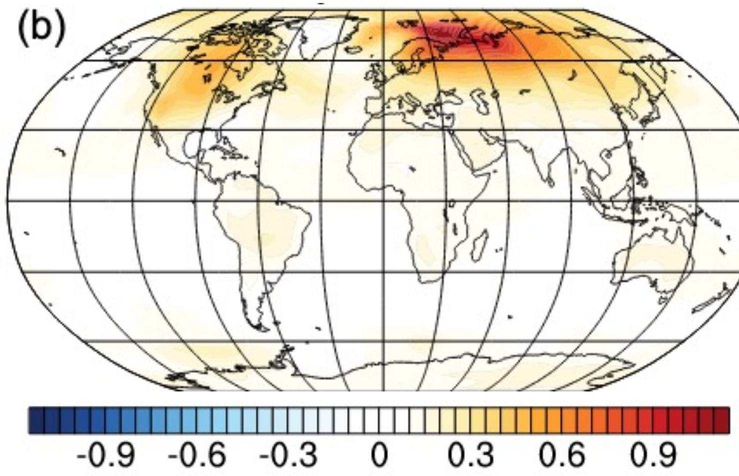


No Atlantic "multidecadal" variability in LMR

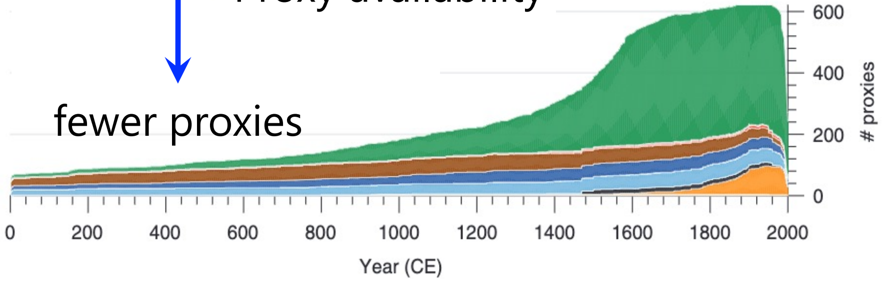


Singh et al. (2018)

Surface temperature regression

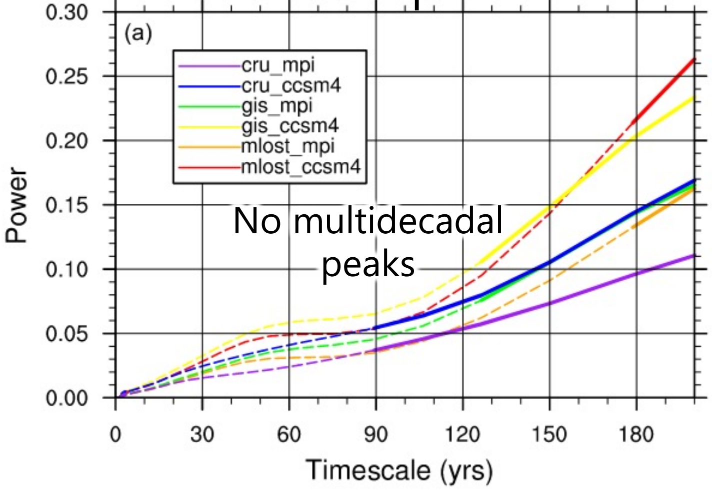


Proxy availability



Emile-Geay et al. (2017)

Power spectra



A way forward:
1) Mechanistic understanding of reconstruction skills

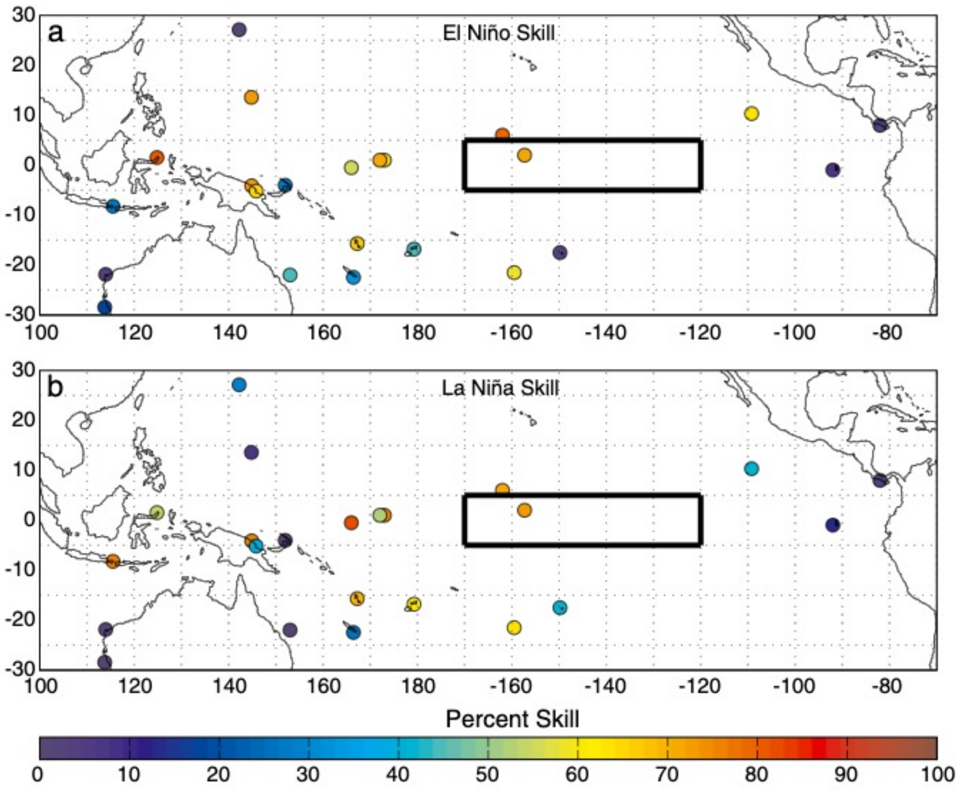
Asymmetric skills of corals in detecting El Niño and La Niña

ENSO event detection skills of pseudo coral $\delta^{18}O$ records derived from observed SST and SSS data

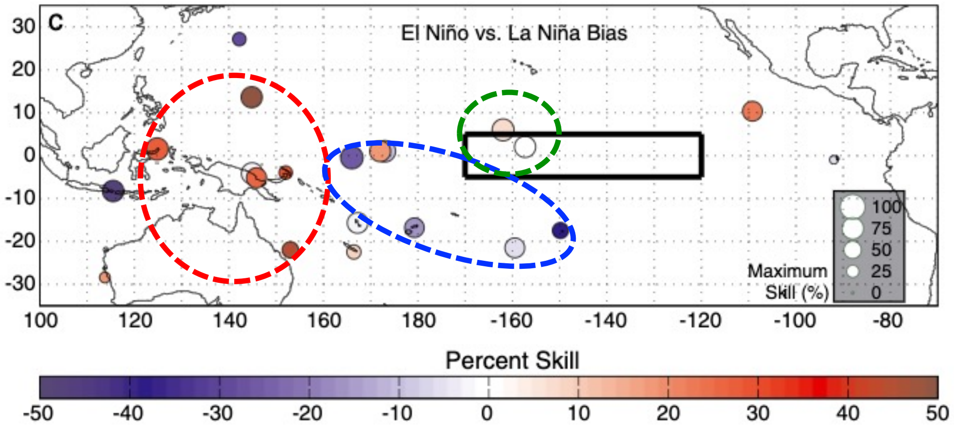
$$\delta^{18}O_{anom} = a_1 \mathrm{SST}_{anom} + a_2 \mathrm{SSS}_{anom}$$

El Niño skill

La Niña skill



El Niño skill – La Niña skill



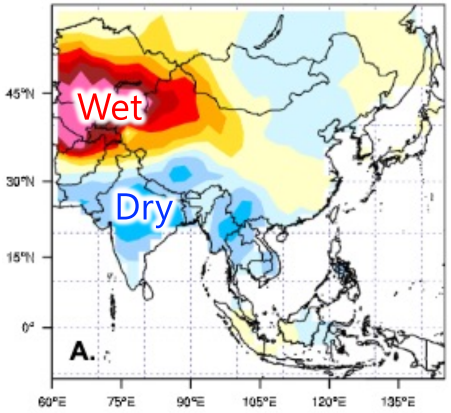
Hereid, Okumura et al. (2013)

ENSO phases embedded in tree ring data

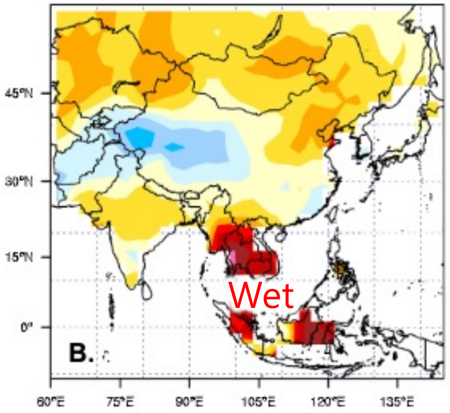
EOF analysis of Monsoon Asia Drought Atlas (MADA), 1300-1989

Summer PDSI reconstruction based on 327 tree rings (*Cook et al., 2010*)

MADA EOF1 (15%)

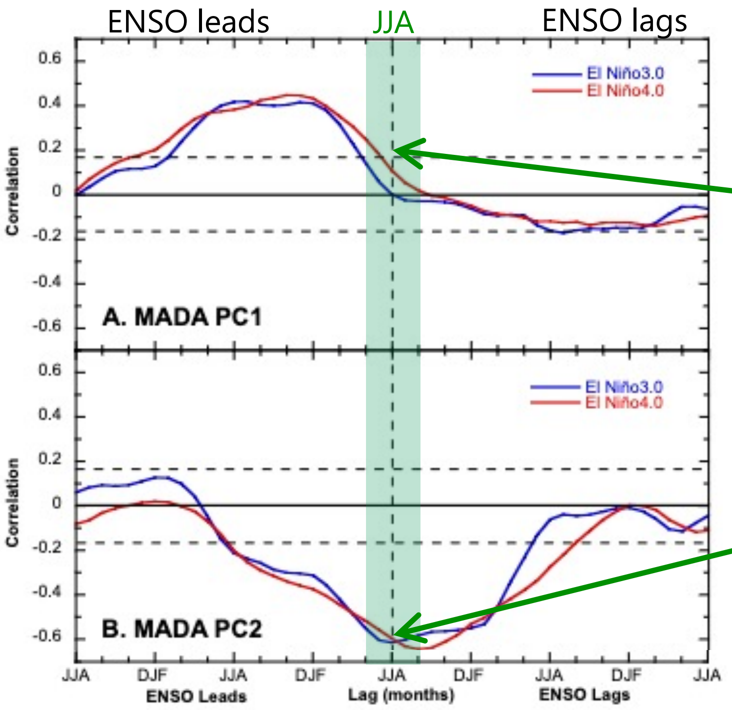


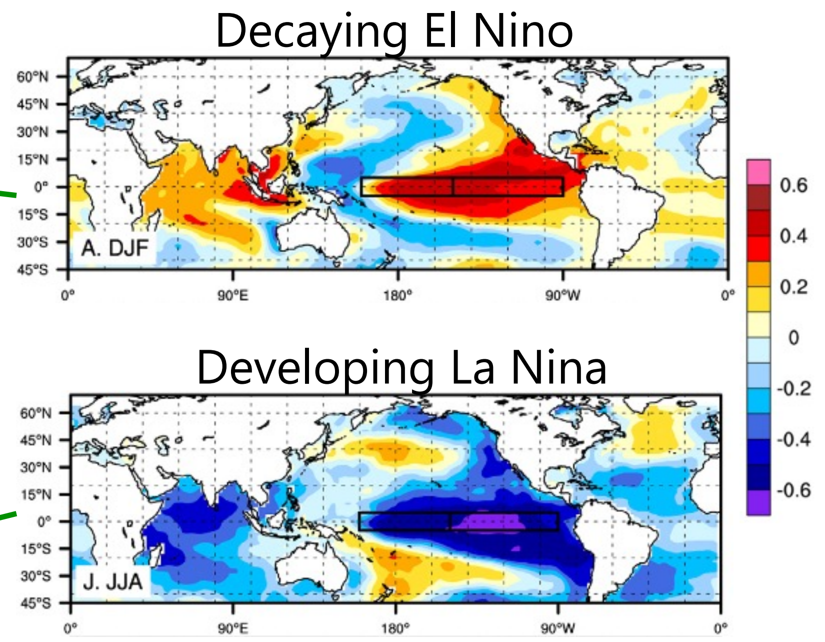
MADA EOF2 (10%)



Li et al. (2014)

Lead-lag correlation with Nino3 & Nino4



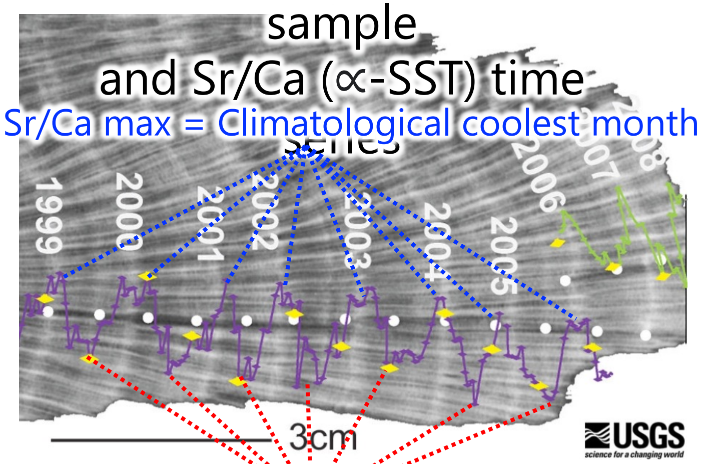


Impact of SST seasonal cycle on coral chronology

X-ray image of a coral sample
and Sr/Ca (∝-SST) time series

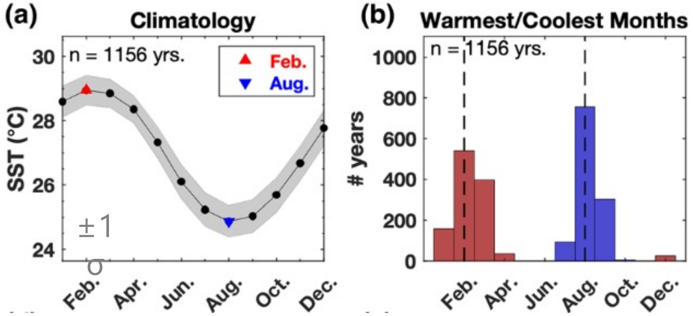
Sr/Ca max = Climatological coolest month

Interpolate to evenly-spaced monthly values

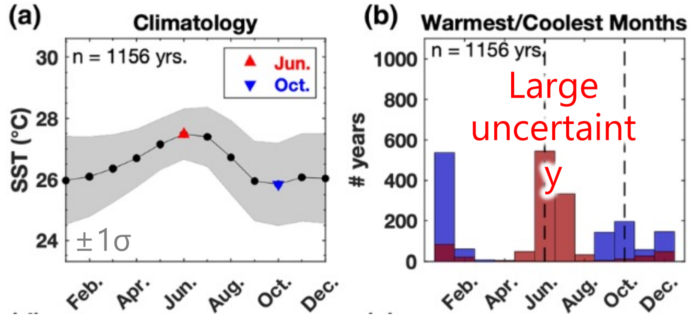


Sr/Ca min = Climatological warmest month

Vanuatu (SW Pacific)

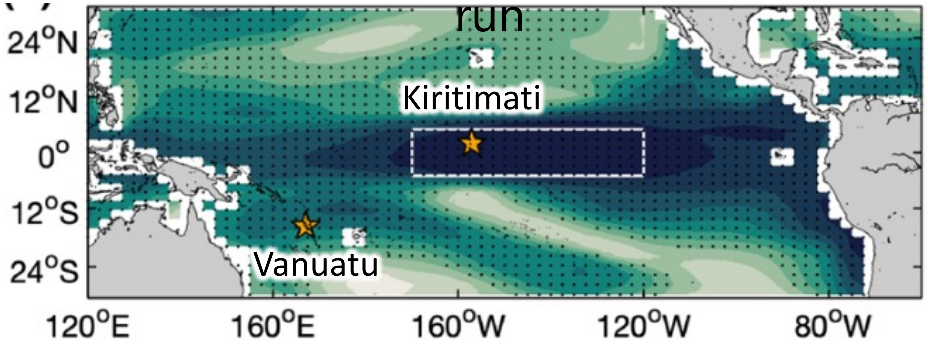


Kiritimati (C Eq Pacific)

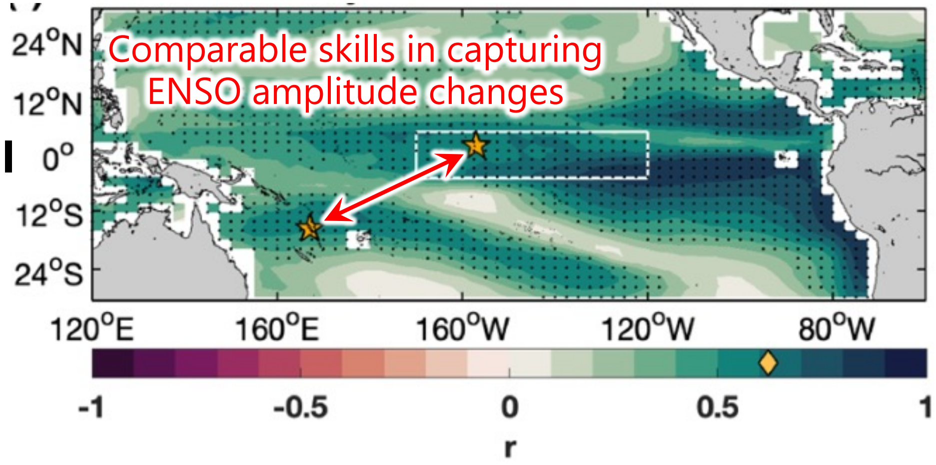


20-yr running σ correlation between Nino3.4 index and pseudo-coral $\delta^{18}O$ in CESM1 control run

Without chronological uncertainty



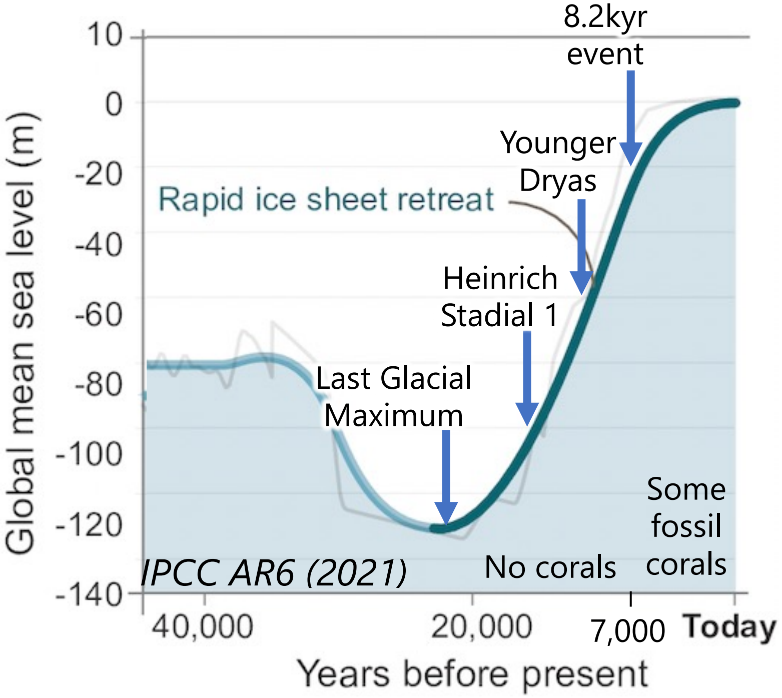
With chronological uncertainty

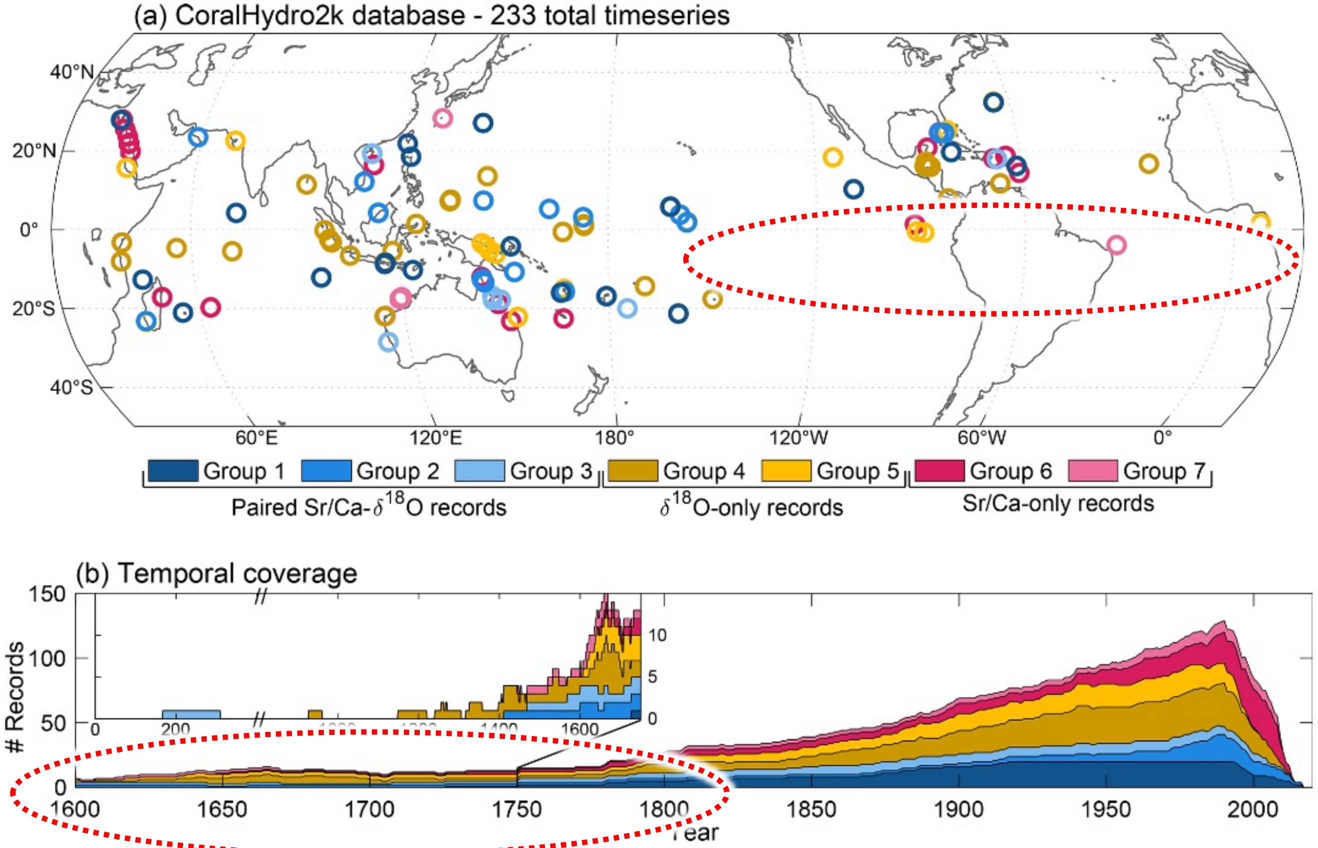


Lawman et al. (2020)

A way forward:
2) Obtain more proxies from key regions & periods

Lack of tropical proxy records in cool tropical oceans and before 1800



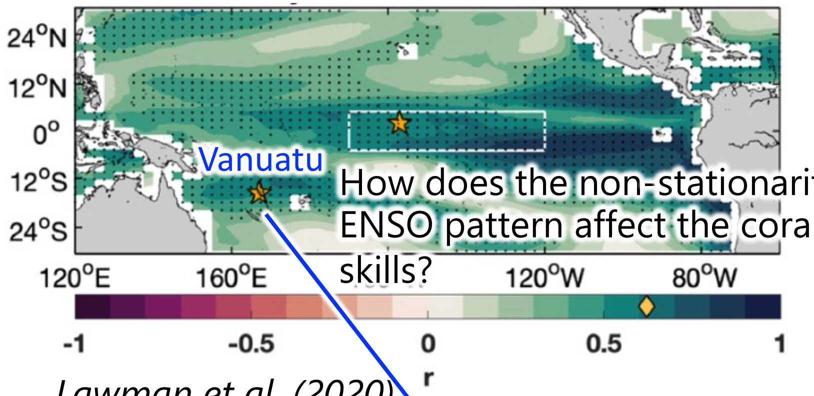


Walter et al. (2023)

Lack of direct evidence of forced ENSO changes
(See a review by *Lu et al. 2018*)

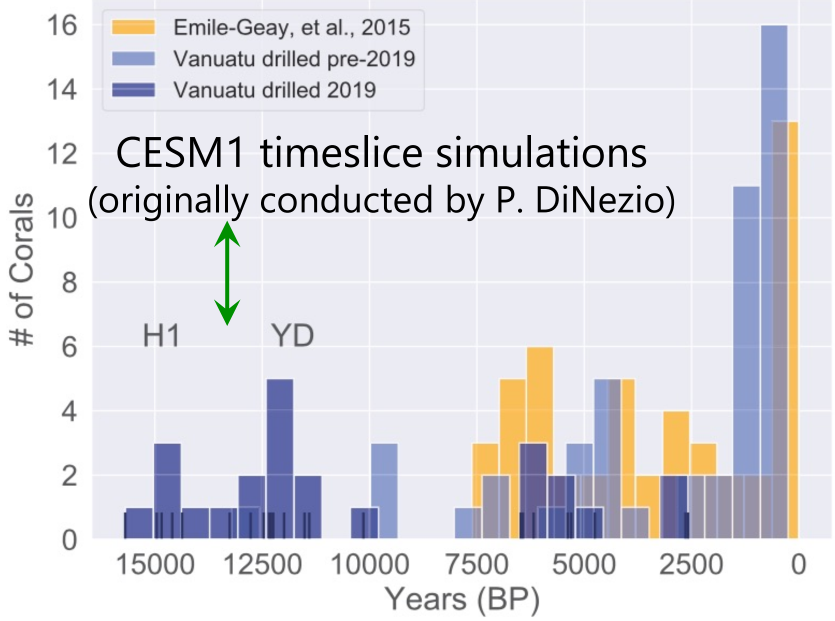
Fast-growing coral species (*Porites*) commonly used for paleoclimate reconstructions do not typically live more than a few hundred years.
Most fossil coral records are also short (~30 yrs on average).

Fossil corals from Vanuatu—Evidence for forced ENSO changes



How does the non-stationarity of ENSO pattern affect the coral skills?

Lawman et al. (2020)



CESM1 timeslice simulations (originally conducted by P. DiNezio)

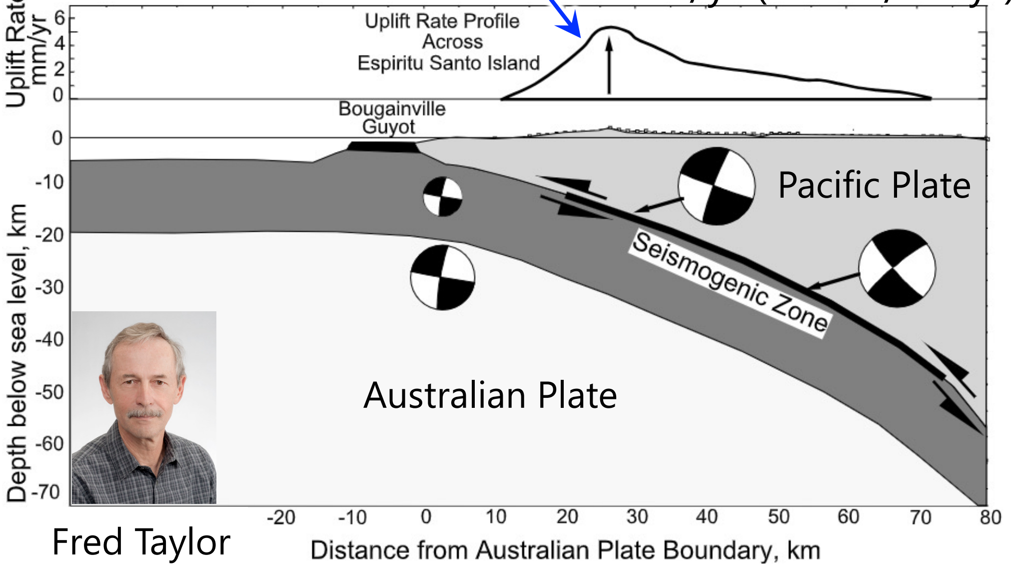
Jud Partin (lead PI)

AGS-2103078

Rob Domeyko (student)

Yuko Okumura

+6 mm/yr (120 m/20kyr)



Fred Taylor

Taylor et al. (2005)

Ultra-portable drill developed by Eddie Wheeler/Tech-2000

Summary

- Paleoclimate proxy data has the potential to address many important science questions related to AMV/AMOC and TBI
- Recent compilations of PAGES2k databases and reanalysis products make paleoclimate proxy data more accessible
- Available reconstructions of climate modes poorly agree with each other to derive robust conclusions about the nature of variability
- To move forward, we need to better understand climate processes affecting various proxy records and develop robust methods for reconstruction
- We also need to enhance both spatial and temporal coverage of high-resolution proxy records, particularly in the tropical Atlantic and eastern Pacific and before 1800

These efforts require close collaborations between climate dynamics/modeling and paleoclimate research communities

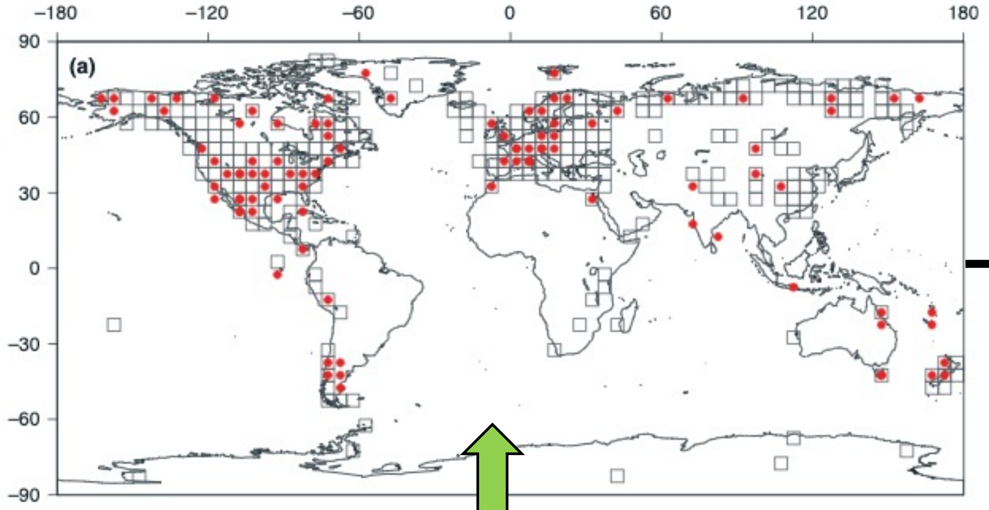
Focus Article WIREs Clim Change 2012, 3:63–77. doi: 10.1002/wcc.149

Climate models as a test bed for climate reconstruction methods: pseudoproxy experiments

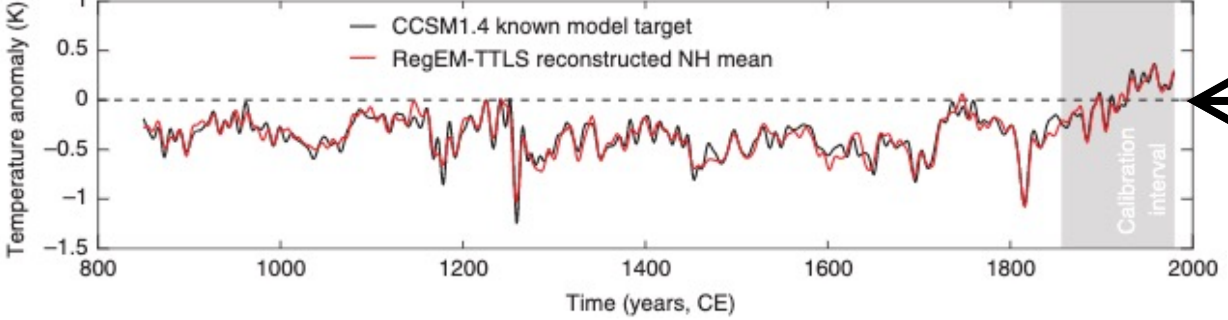
Jason E. Smerdon*

Application to climate mode reconstructions
NAO—*Ortega et al. (2015)*
ENSO—*Batehup et al. (2015)*
IPO—*Henke et al. (2017)*
ENSO, PDV, AMV—*Midhun et al. (2020)*

Climate Model Data



Calibration & Reconstruction



Pseudoproxies = Model output + Noise