Assimilating the Southern Annular Mode over the Common Era using Drought Atlases and a Global Proxy Network

Jonathan King[1], Kevin Anchukaitis[1], Kathryn Allen[2], Tessa Vance[3], and Amy Hessl[4]

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November 24, 2022

Abstract

The Southern Annular Mode (SAM) is the leading mode of atmospheric variability in the extratropical Southern Hemisphere, and its variations affect westerly winds, regional storm tracks, midlatitude wildfire activity, Antarctic and Southern Ocean dynamics, and surface mass balance. The SAM is therefore of high importance to both ecosystems and societies across the Southern Hemisphere. The behavior of the SAM has been extensively studied during the instrumental era, but there is substantially less confidence and considerable disagreement in its decadal to centennial-scale variability over the Common Era. Studying these longer time scales requires millennial-length reconstructions, but the sparsity of multi-century proxy records in the Southern Hemisphere has hindered the production of such reconstructions. Consequently, variability and trends in the SAM remain uncertain through most of the Common Era. Here, we use paleoclimate data assimilation to reconstruct the austral summer (DJF) SAM index (SAMI) over the entire Common Era. Our method integrates the South American Drought Atlas, Australia-New Zealand Drought Atlas, and the PAGES2k temperature-sensitive proxy network with a multi-model ensemble of last millennium GCM simulations using an offline ensemble Kalman Filter with a stationary prior. We use a novel nested variance adjustment to correct for the effect of changing proxy availability through time. Our reconstruction is not calibrated to the observed SAMI, yet exhibits a correlation coefficient greater than 0.6 over the instrumental era. Using superposed-epoch and wavelet analyses, we find the reconstruction exhibits minimal response to volcanic and solar forcings and is instead dominated by internal climate variability until the late 20th century. Our data assimilation framework also facilitates the use of optimal-sensor analysis, which we use to identify key proxy sites at different time periods in the reconstruction. Prior to 1400 CE, the reconstruction is strongly influenced by two tree-ring records (Mt. Read, Tasmania and Oroko, New Zealand) and two ice-cores (WDC05A and Plateau Remote). Finally, we examine the coherence of our results against existing reconstructions and compare reconstructed 20th century trends with the instrumental record.

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[1] Department of Geosciences, University of Arizona, Tucson AZ USA
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[6] Centre of Excellence for Australian Biodiversity and Heritage, University of NSW, Australia
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The Southern Annular Mode (SAM) is the leading mode of atmospheric variability in the extratropical Southern Hemisphere, and its variations affect westerly winds, regional storm tracks, midlatitude wildfire activity, Antarctic and Southern Ocean dynamics, and surface mass balance. The SAM is therefore of high importance to both ecosystems and societies across the Southern Hemisphere. The behavior of the SAM has been extensively studied during the instrumental era, but there is substantially less confidence and considerable disagreement in its decadal to centennial-scale variability over the Common Era. Studying these longer time scales requires millennial-length reconstructions, but the sparsity of multi-century proxy records in the Southern Hemisphere has hindered the production of such reconstructions. Consequently, variability and trends in the SAM remain uncertain through most of the Common Era.

Here, we use paleoclimate data assimilation to reconstruct the austral summer (DJF) SAM index (SAMI) over the entire Common Era. Our method integrates the South American Drought Atlas, Australia-New Zealand Drought Atlas, and the PAGES2k temperature-sensitive proxy network with a multi-model ensemble of last millennium GCM simulations using an offline ensemble Kalman Filter with a stationary prior. We use a novel nested variance adjustment to correct for the effect of changing proxy availability through time. Our reconstruction is not calibrated to the observed SAMI, yet exhibits a correlation coefficient greater than 0.6 over the instrumental era. Using superposed-epoch and wavelet analyses, we find the reconstruction exhibits minimal response to volcanic and solar forcings and is instead dominated by internal climate variability until the late 20th century. Our data assimilation framework also facilitates the use of optimal-sensor analysis, which we use to identify key proxy sites at different time periods in the reconstruction. Prior to 1400 CE, the reconstruction is strongly influenced by two tree-ring records (Mt. Read, Tasmania and Oroko, New Zealand) and two ice-cores (WDC05A and Plateau Remote). Finally, we examine the coherence of our results against existing reconstructions and compare reconstructed 20th century trends with the instrumental record.

Reconstructing the Southern Annular Mode over the Common Era

by assimilating drought atlases and a global proxy network.

Jonathan King, Kevin Anchukaitis, Kathy Allen, Tessa Vance, Amy Hessl

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Context

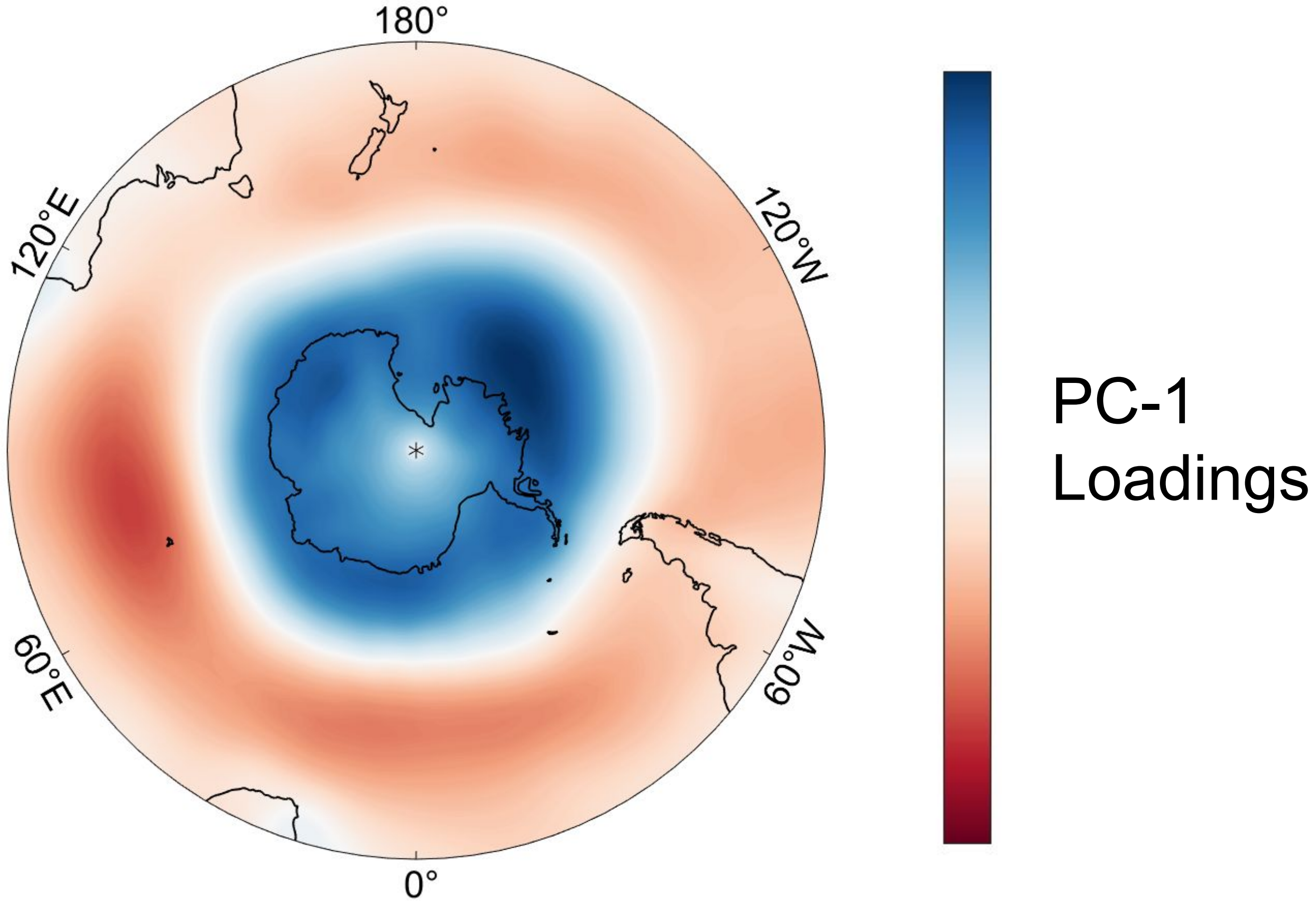
Data Assimilation Method

Results

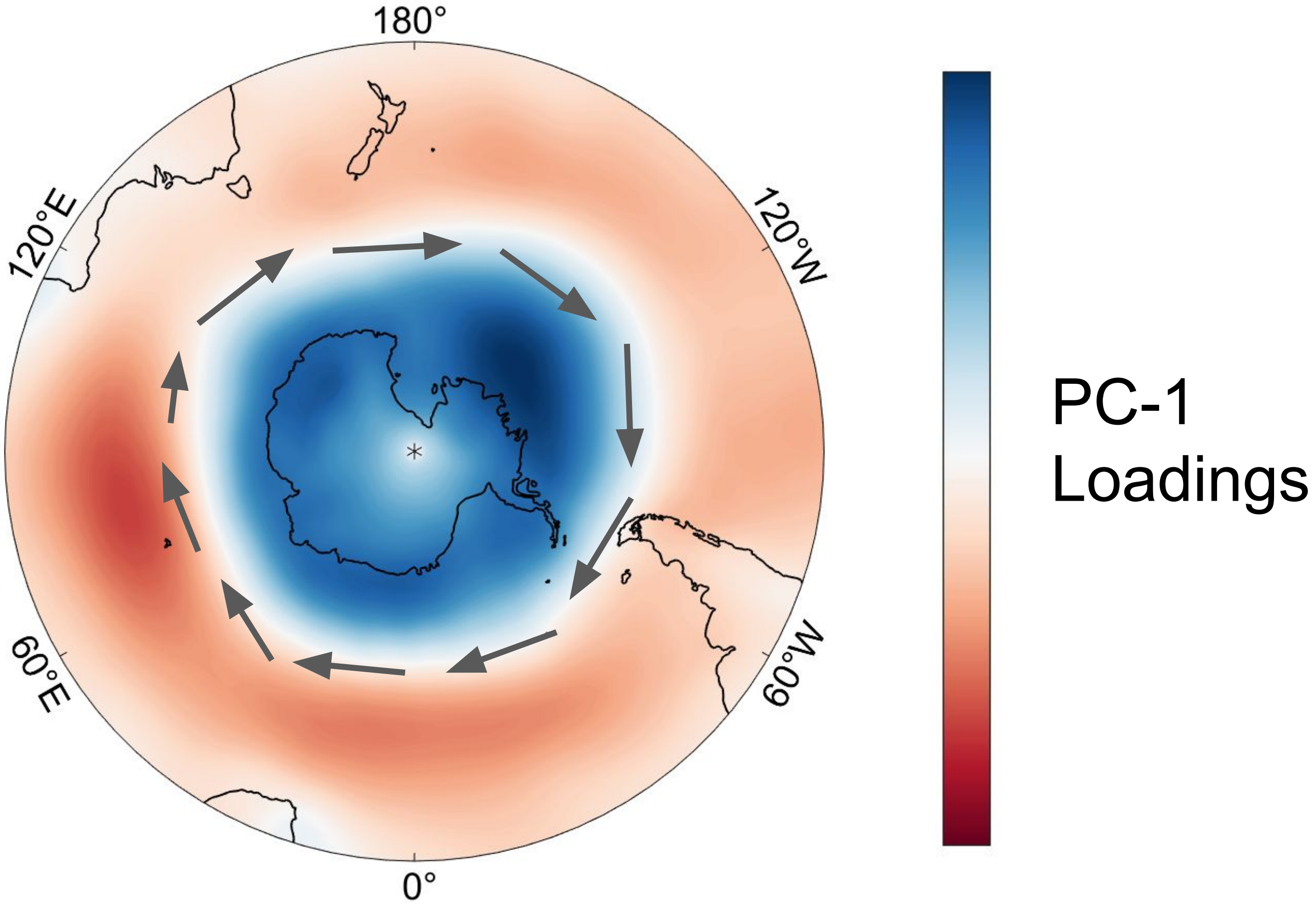
Southern Annular Mode (SAM)

Leading mode of atmospheric variability in the Southern Hemisphere

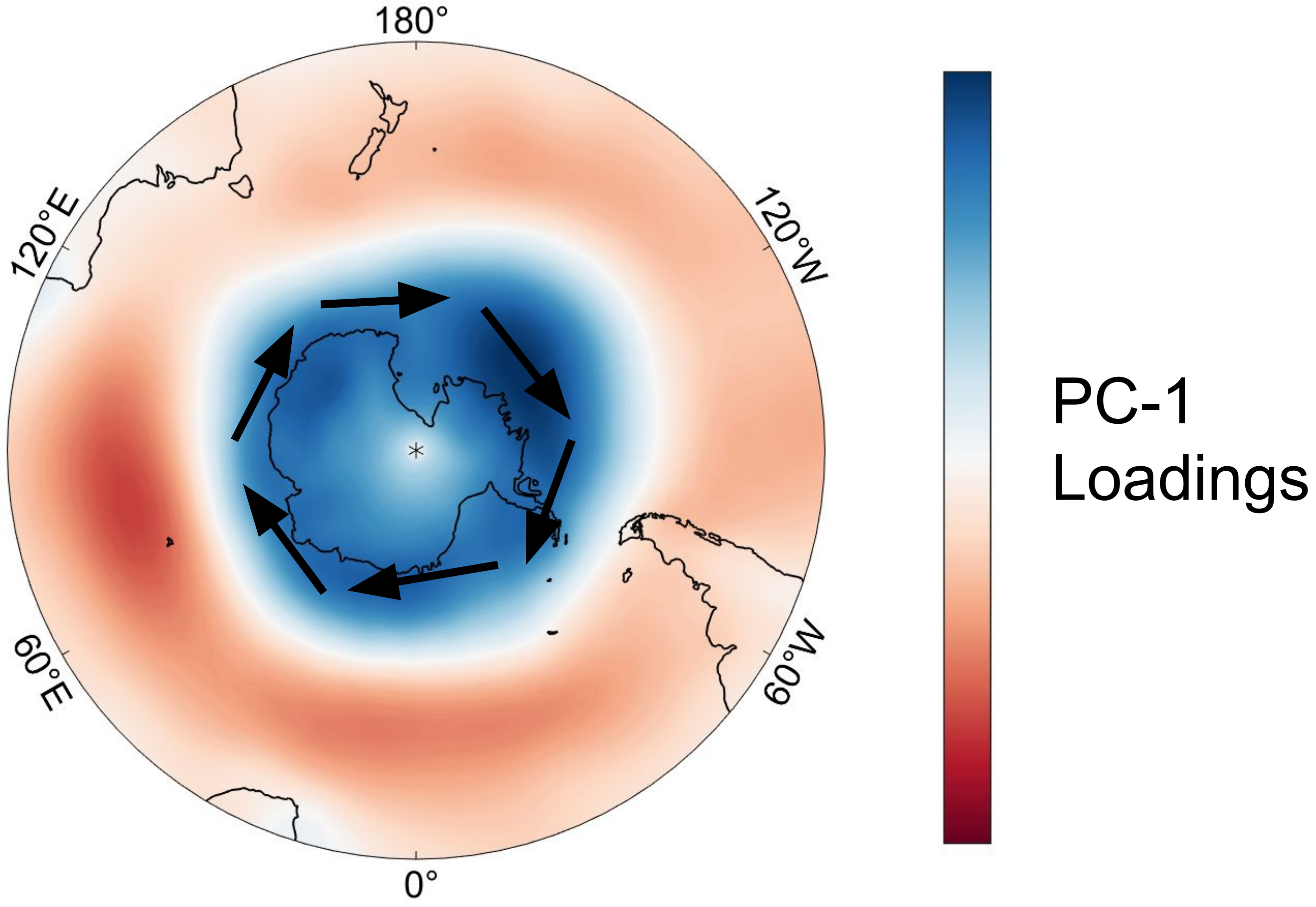
Southern Annular Mode (SAM)



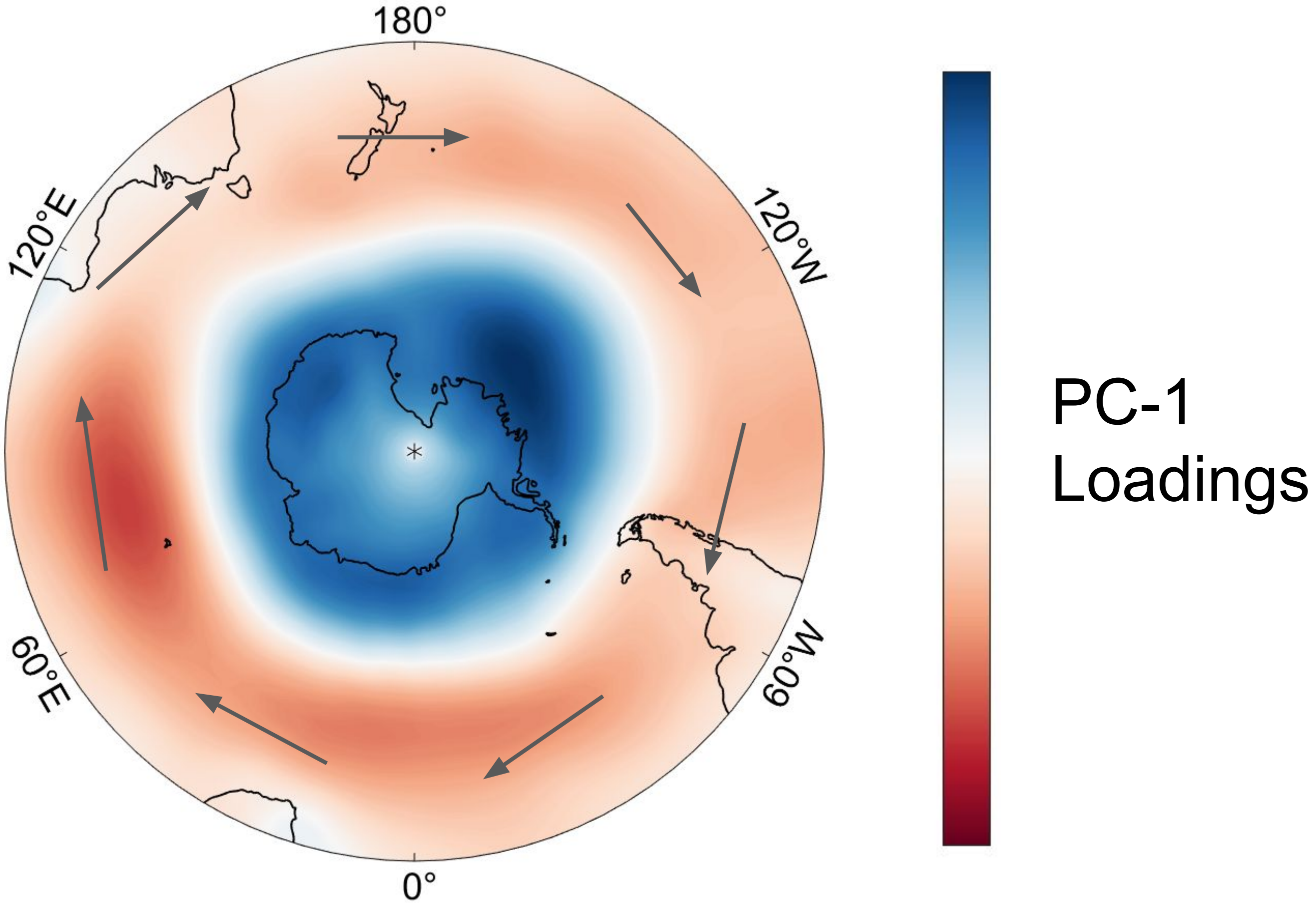
Westerly Winds



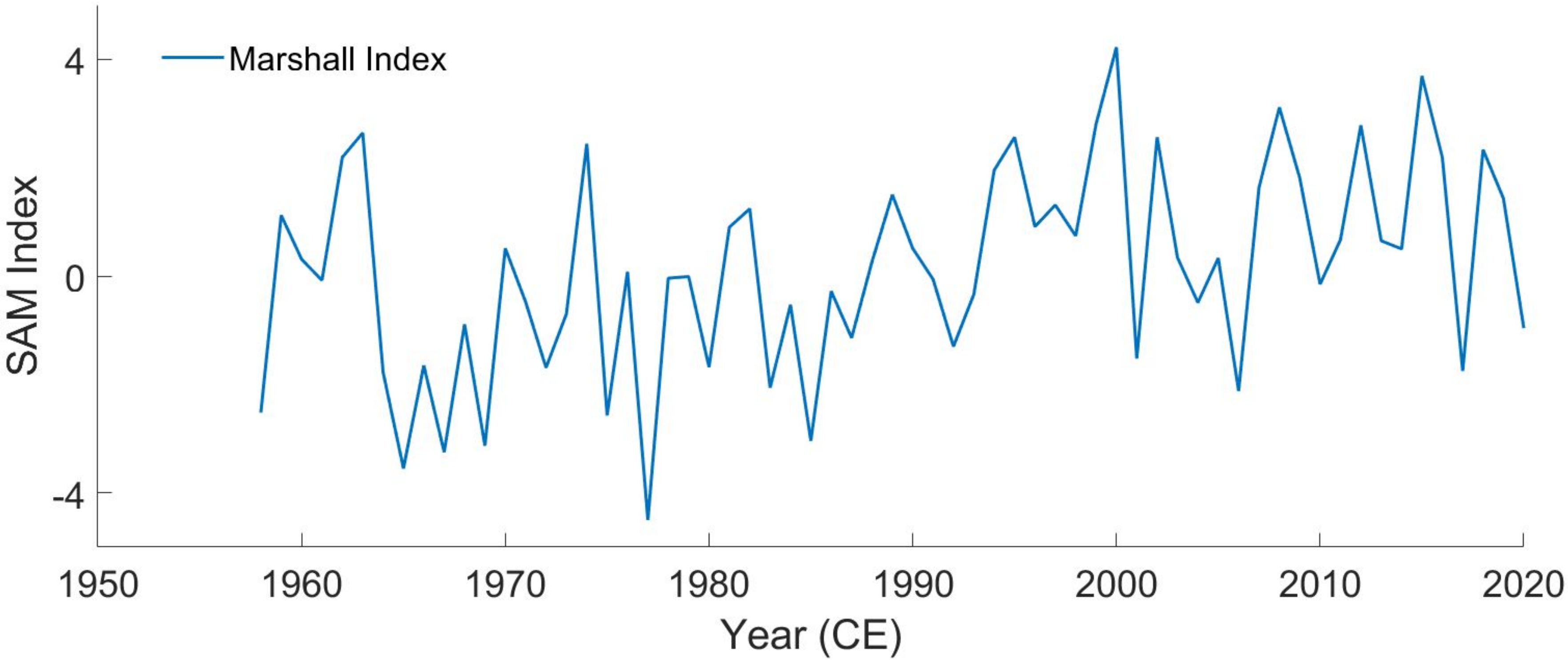
Positive Phase



Negative Phase

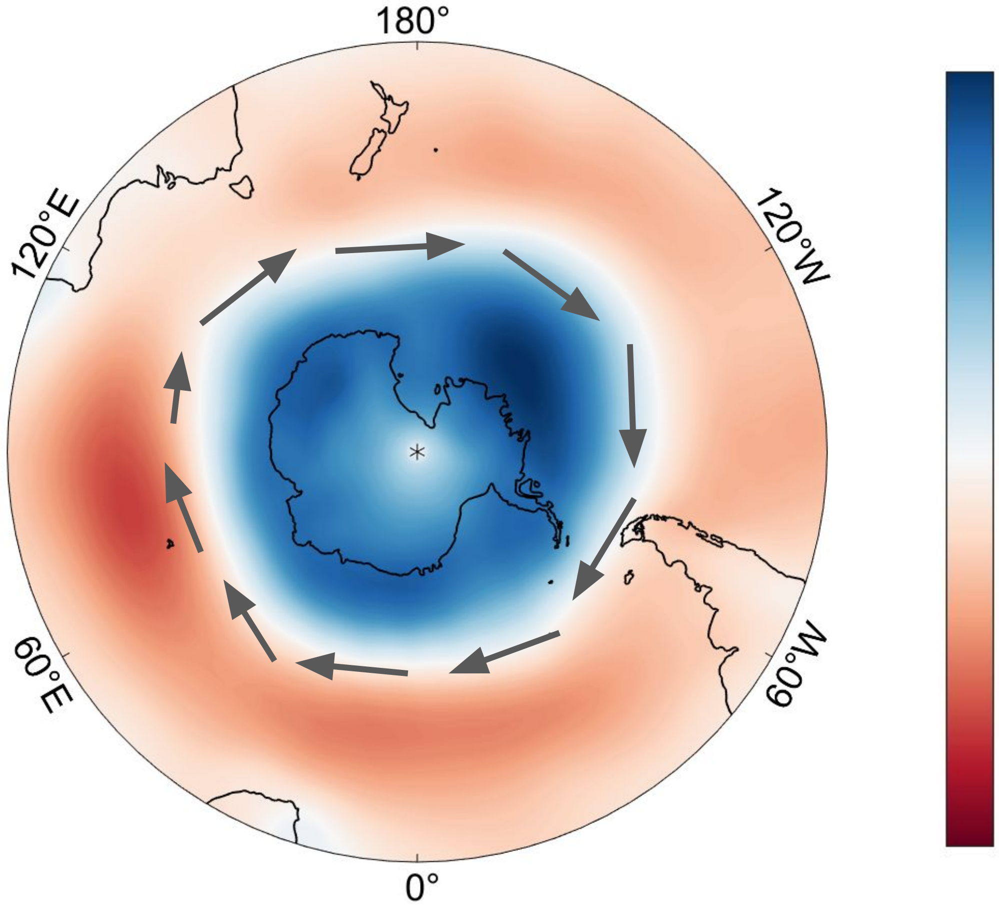


SAM Index



Marshall Index
4
0
-4
SAM Index
1950
1960
1970
1980
1990
2000
2010
2020
Year (CE)

Climate Impacts



PC-1
Loadings

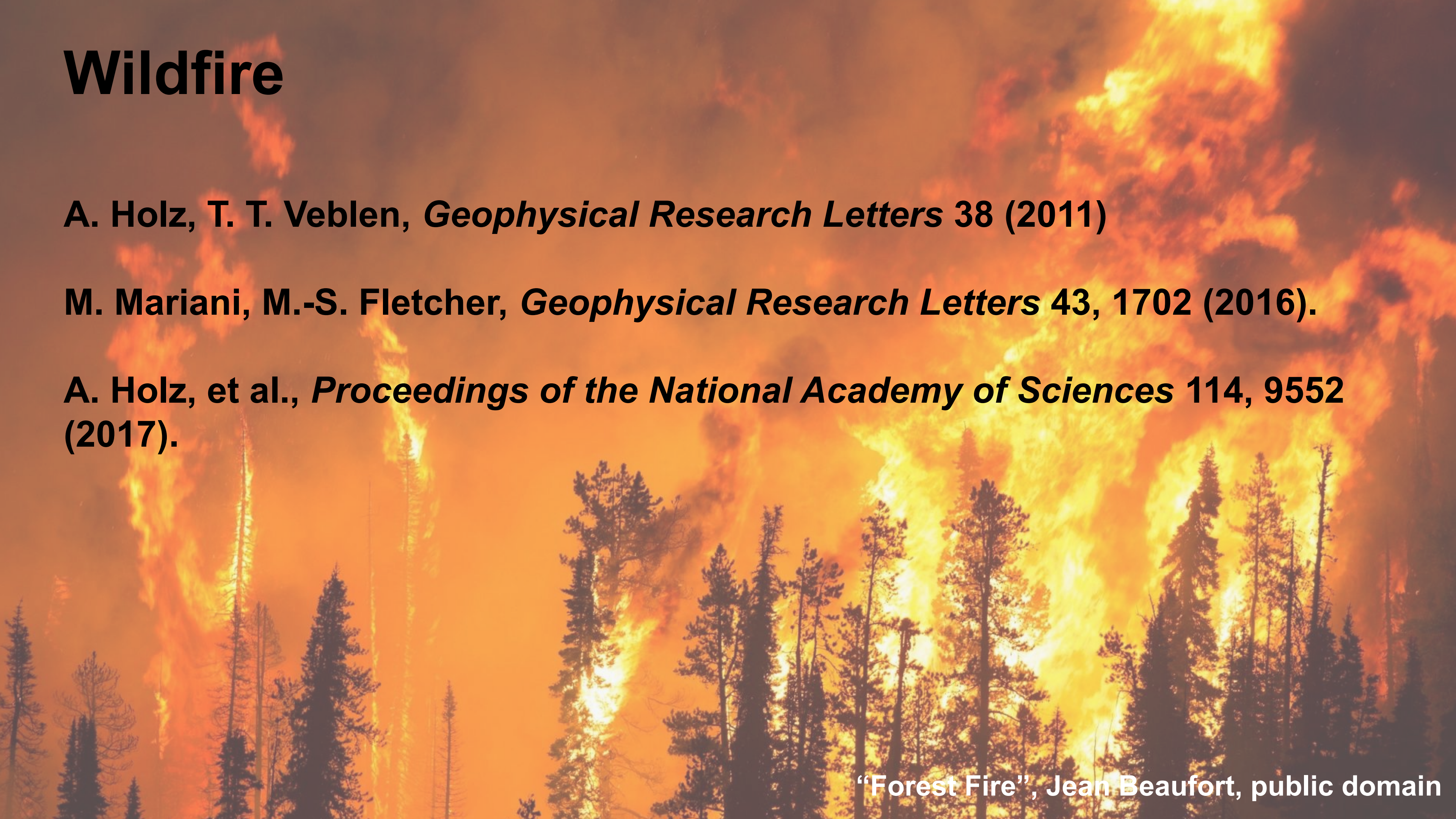
“Forest Fire”, Jean Beaufort, public domain

Wildfire

A. Holz, T. T. Veblen, *Geophysical Research Letters* 38 (2011)

M. Mariani, M.-S. Fletcher, *Geophysical Research Letters* 43, 1702 (2016).

A. Holz, et al., *Proceedings of the National Academy of Sciences* 114, 9552 (2017).



"Forest Fire", Jean Beaufort, public domain

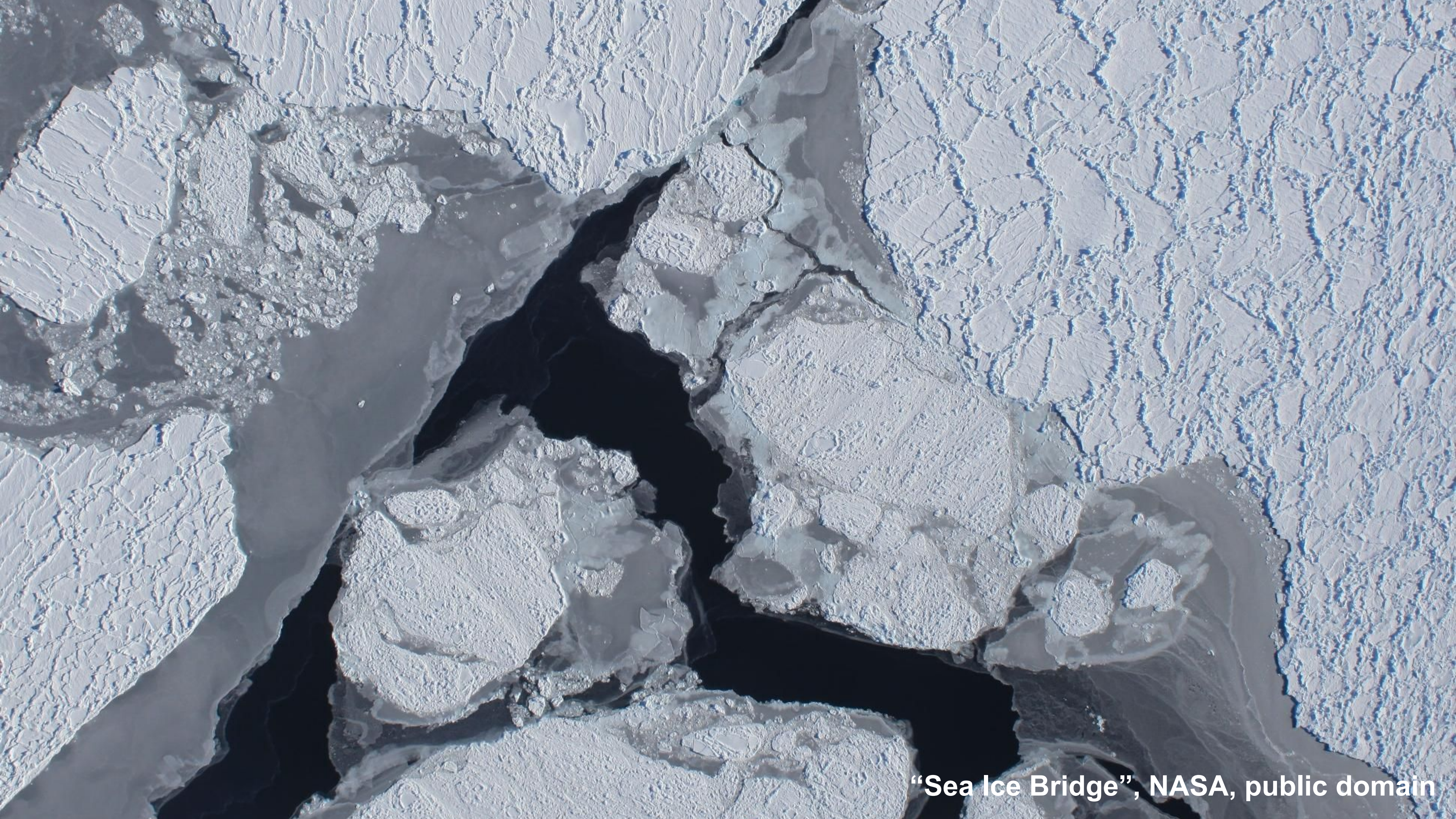

“Dry soil”, Francesco Ungaro, public domain

Drought

P. M. Sousa, R. C. Blamey, C. J. Reason, A. M. Ramos, R. M. Trigo, *Environmental Research Letters* 13, 124025 (2018).

D. C. Verdon-Kidd, A. S. Kiem, *Geophysical Research Letters* 36(2009).

W. Cai, P. Van Rensch, S. Borlace, T. Cowan, *Geophysical Research Letters* 38 (2011).



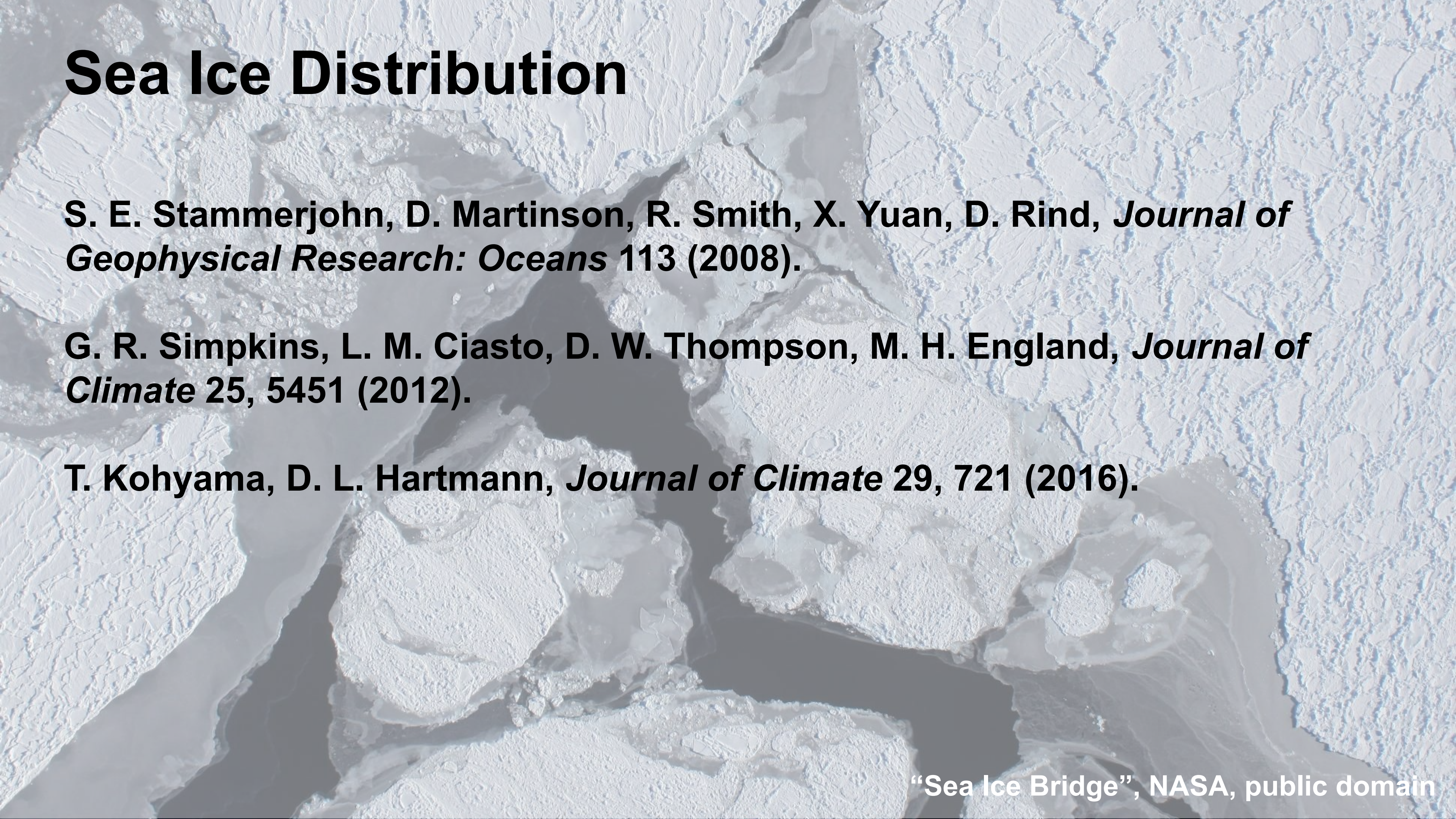
“Sea Ice Bridge”, NASA, public domain

Sea Ice Distribution

S. E. Stammerjohn, D. Martinson, R. Smith, X. Yuan, D. Rind, *Journal of Geophysical Research: Oceans* 113 (2008).

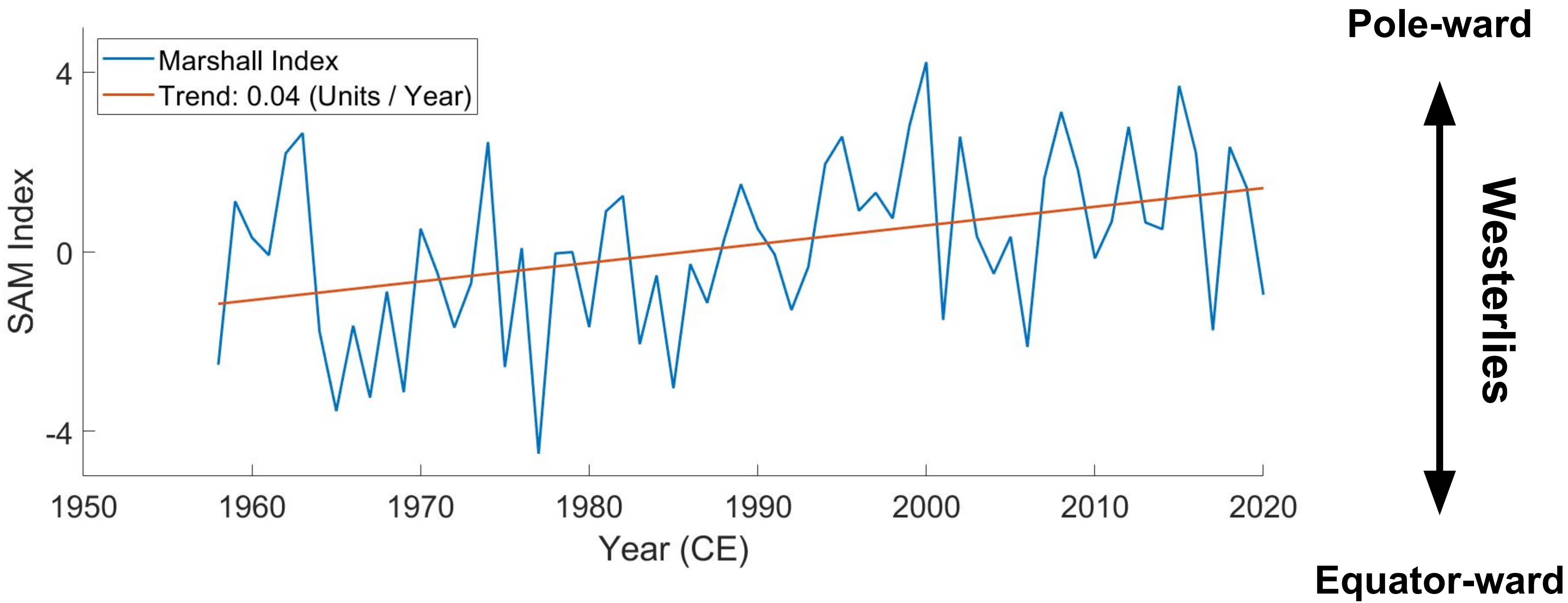
G. R. Simpkins, L. M. Ciasto, D. W. Thompson, M. H. England, *Journal of Climate* 25, 5451 (2012).

T. Kohyama, D. L. Hartmann, *Journal of Climate* 29, 721 (2016).

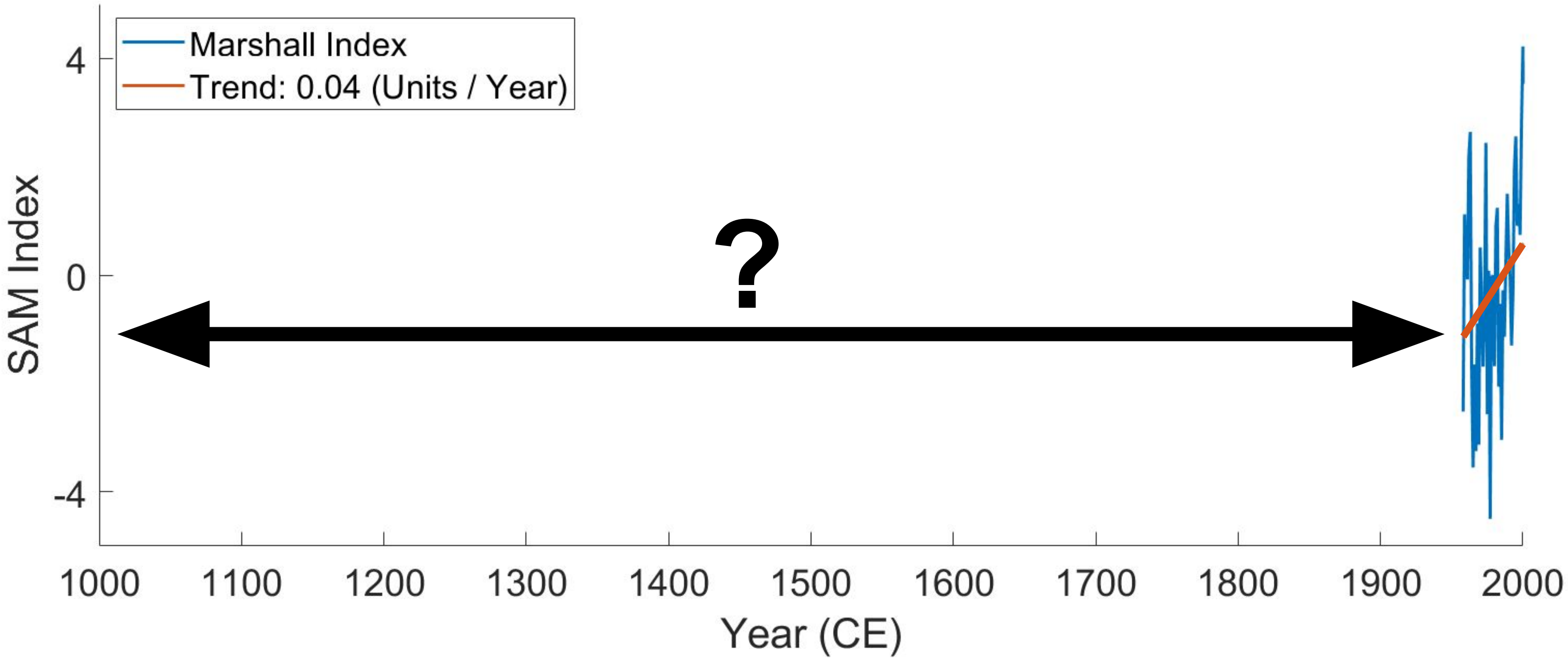


“Sea Ice Bridge”, NASA, public domain

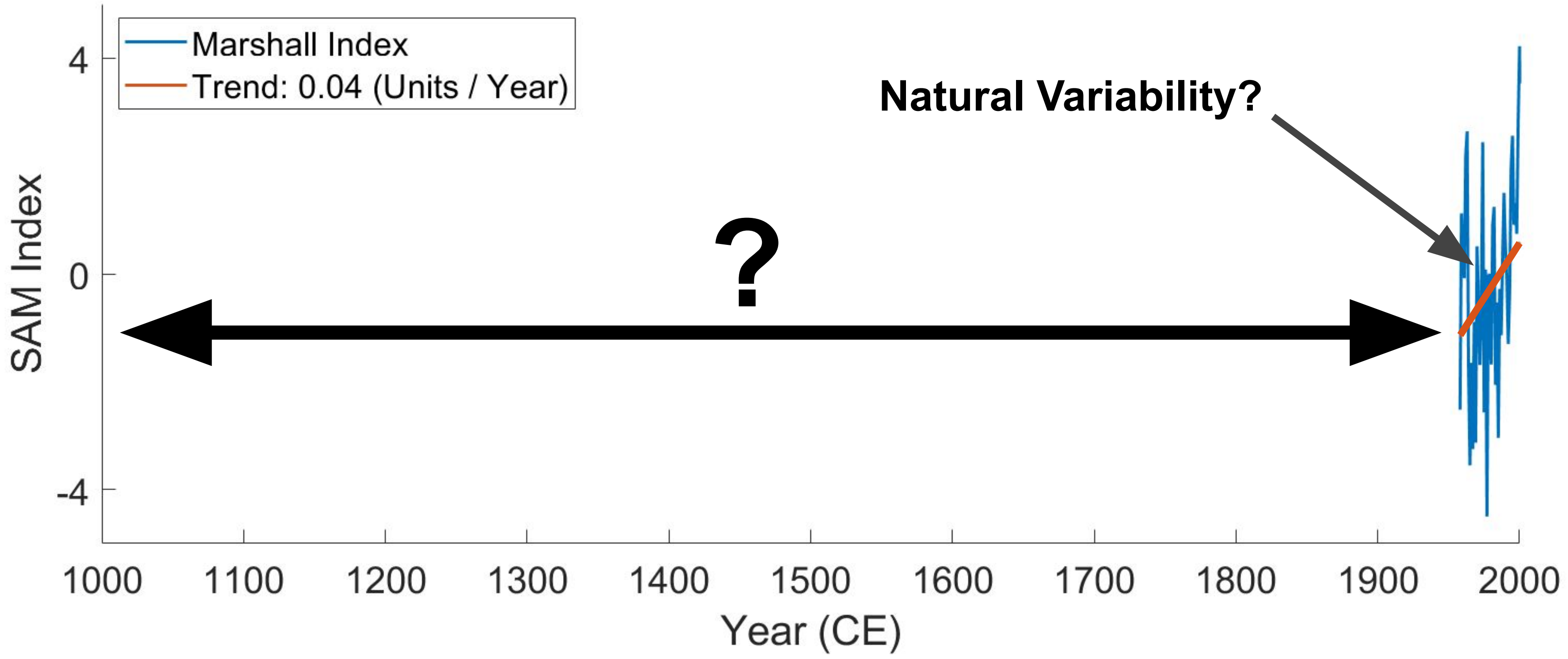
Modern Trend



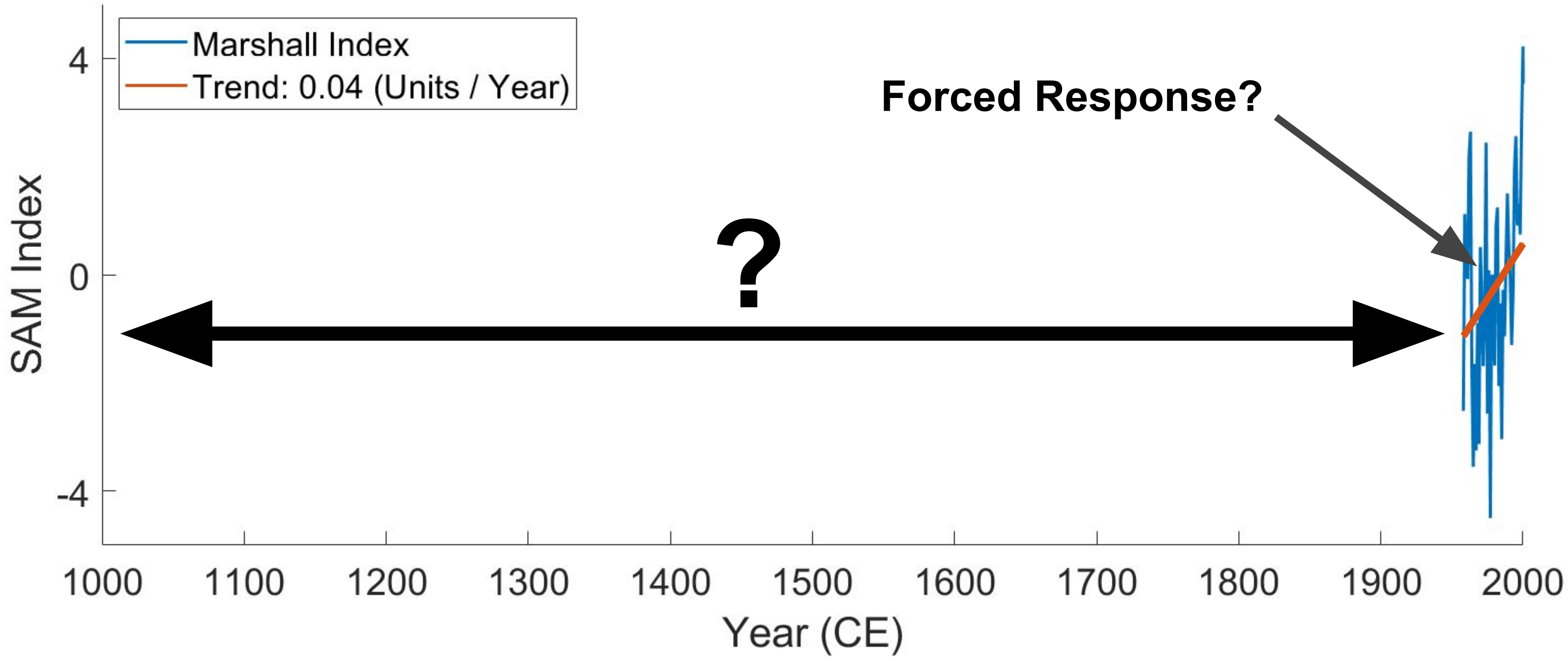
Long-term Context



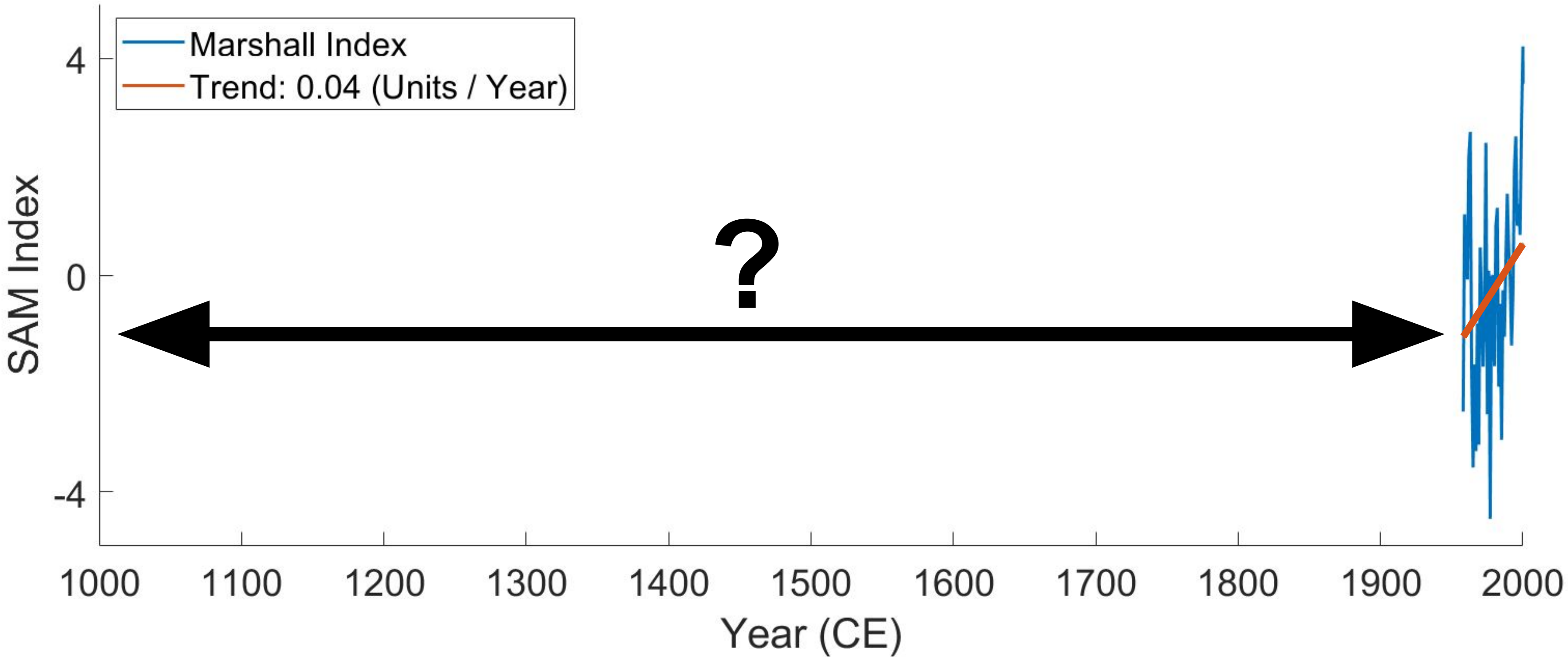
Long-term Context



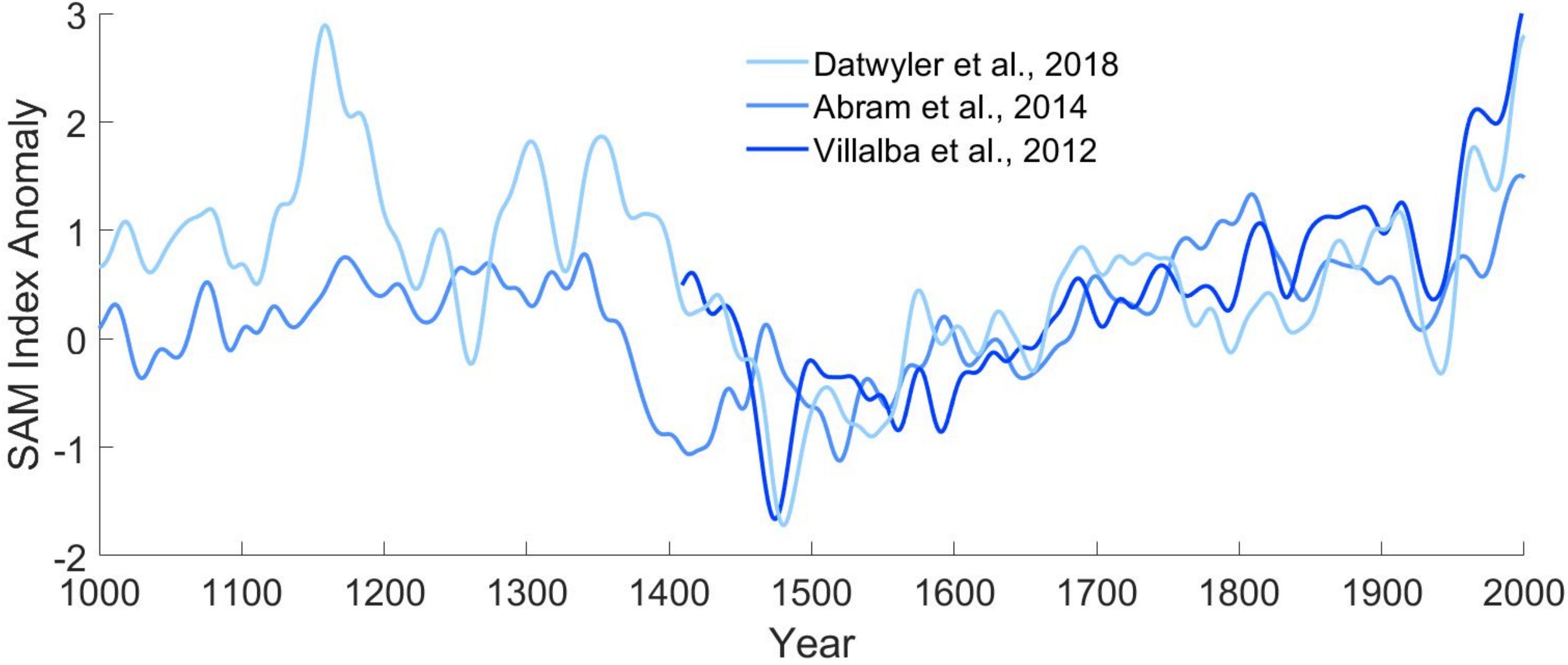
Long-term Context



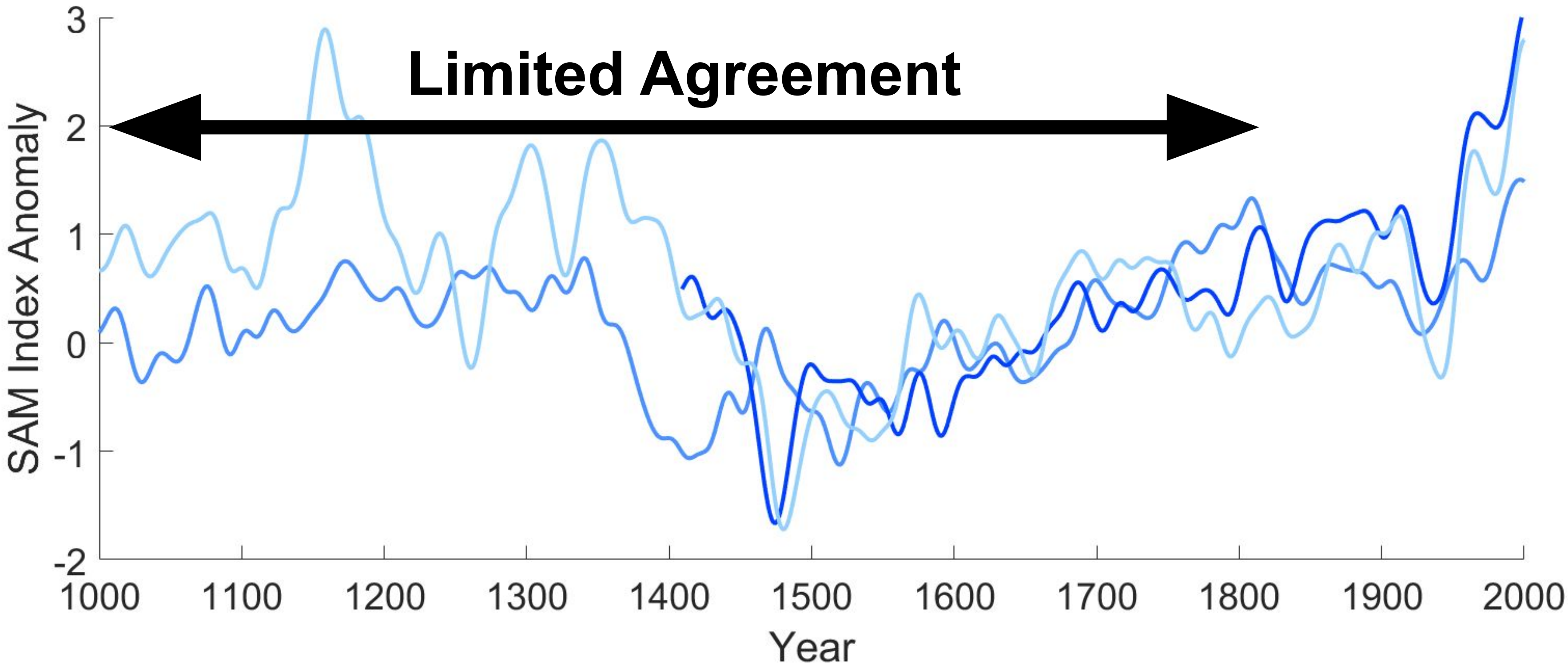
Long-term Context



SAM Reconstructions



SAM Reconstructions



IPCC AR6

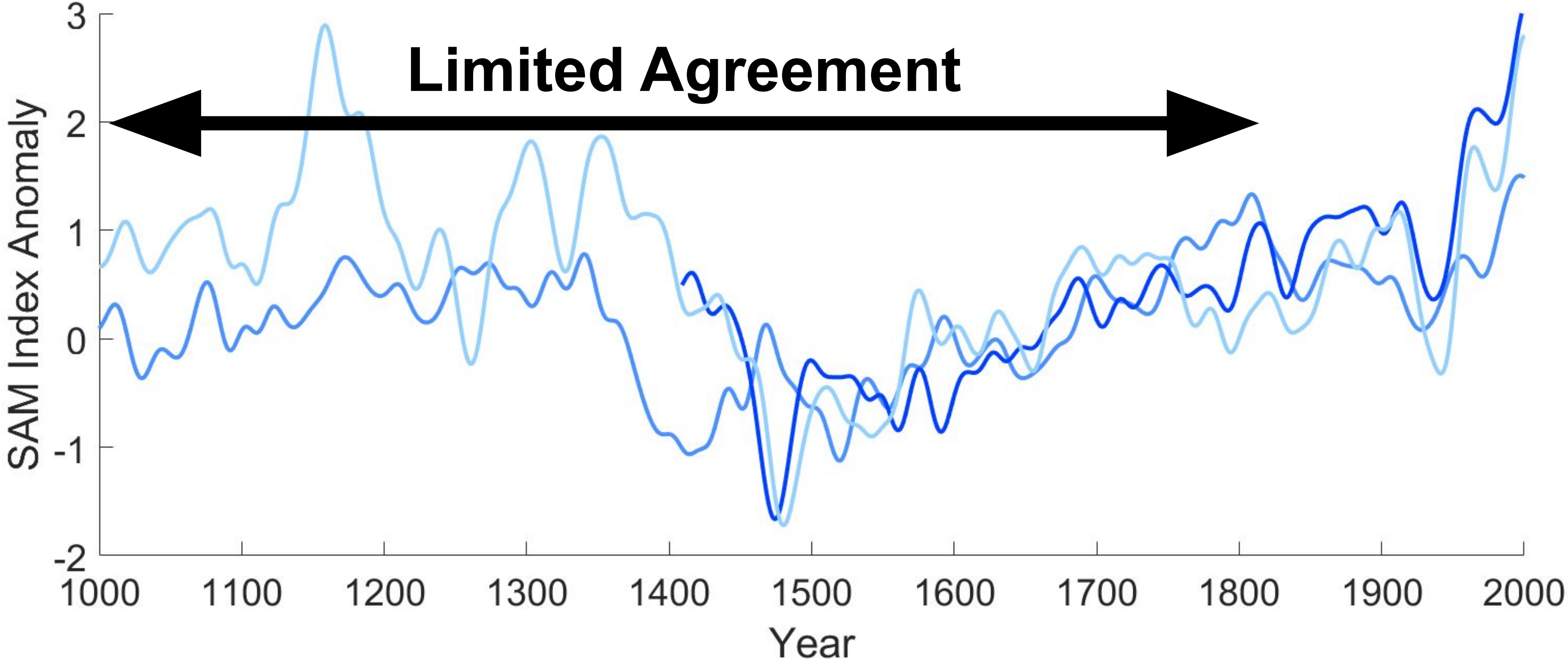
“The recent positive trend in the SAM is *likely* unprecedented in at least the past millennium,

although ***medium confidence*** **arises due to the differences between proxy records before 1800 CE.”**

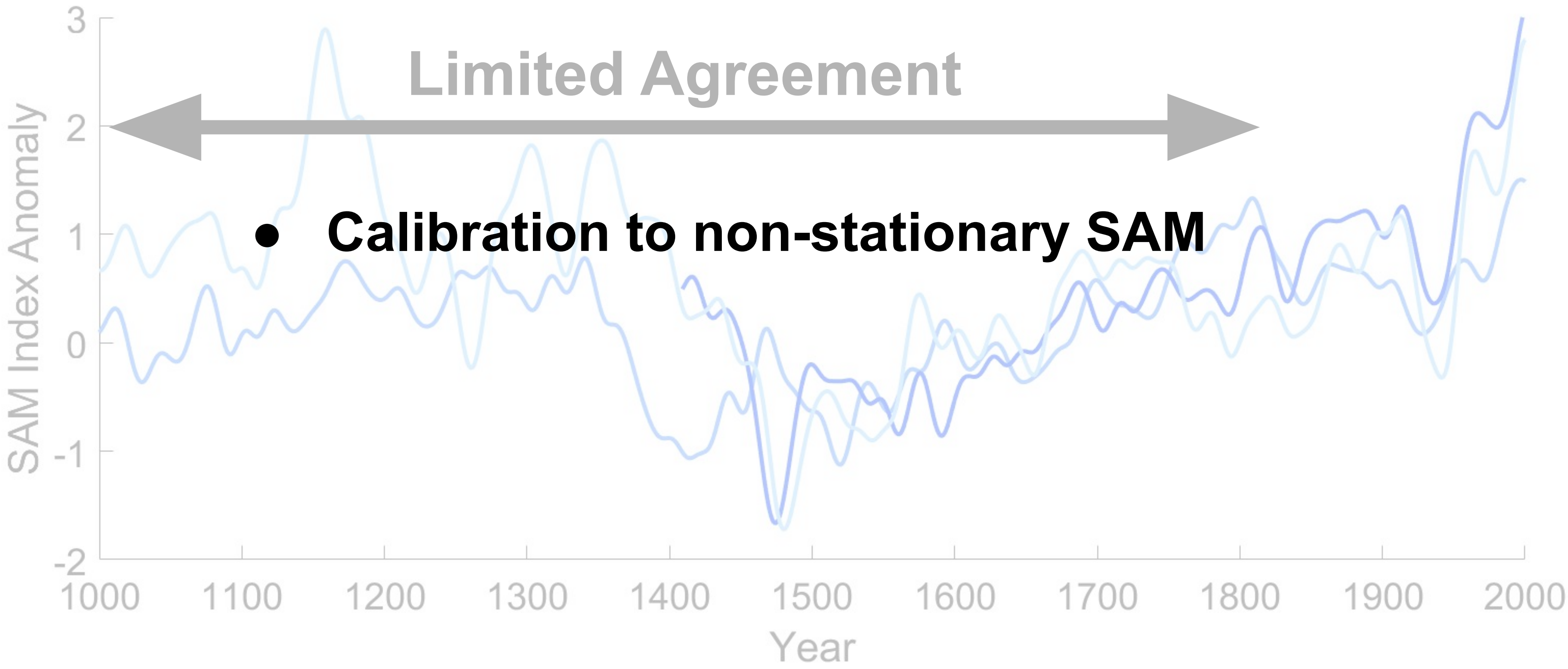
- IPCC AR6, 2021*

* The Physical Science Basis, Chapter 2

SAM Reconstructions

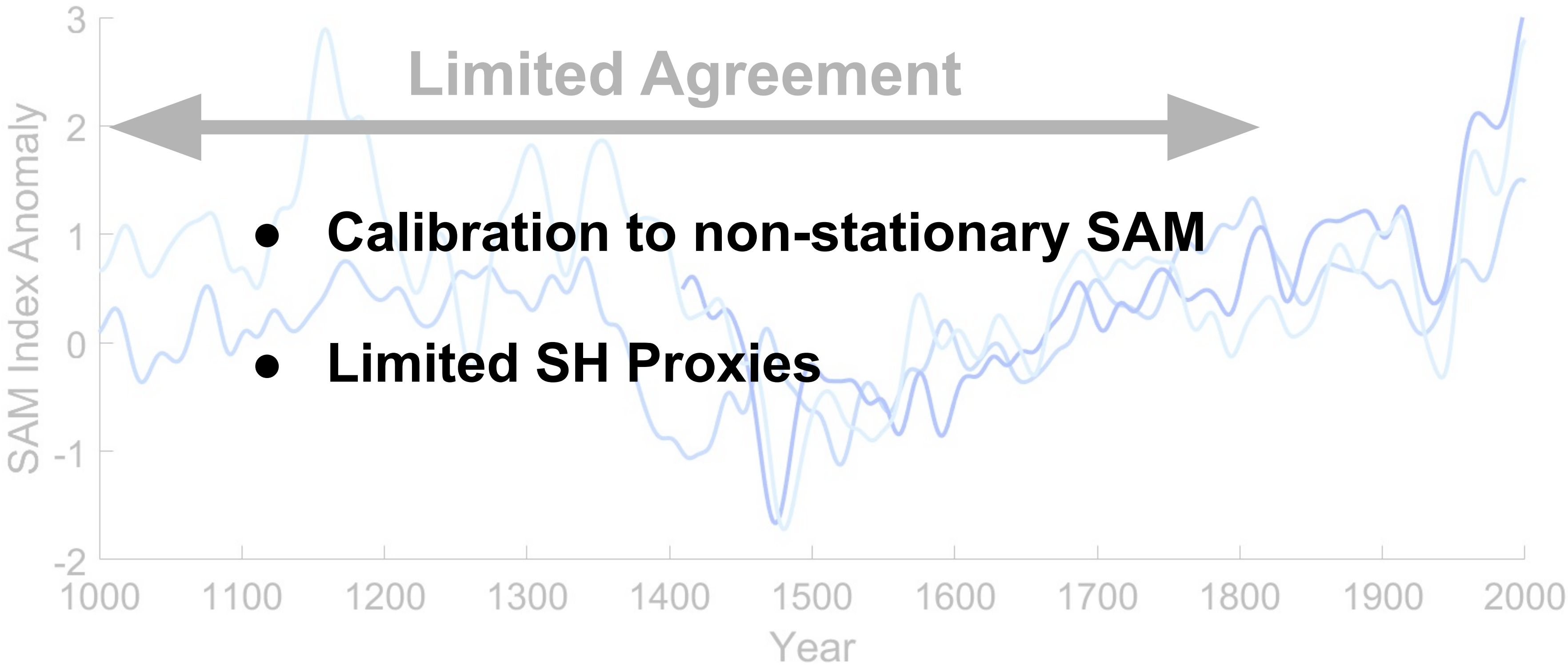


SAM Reconstructions



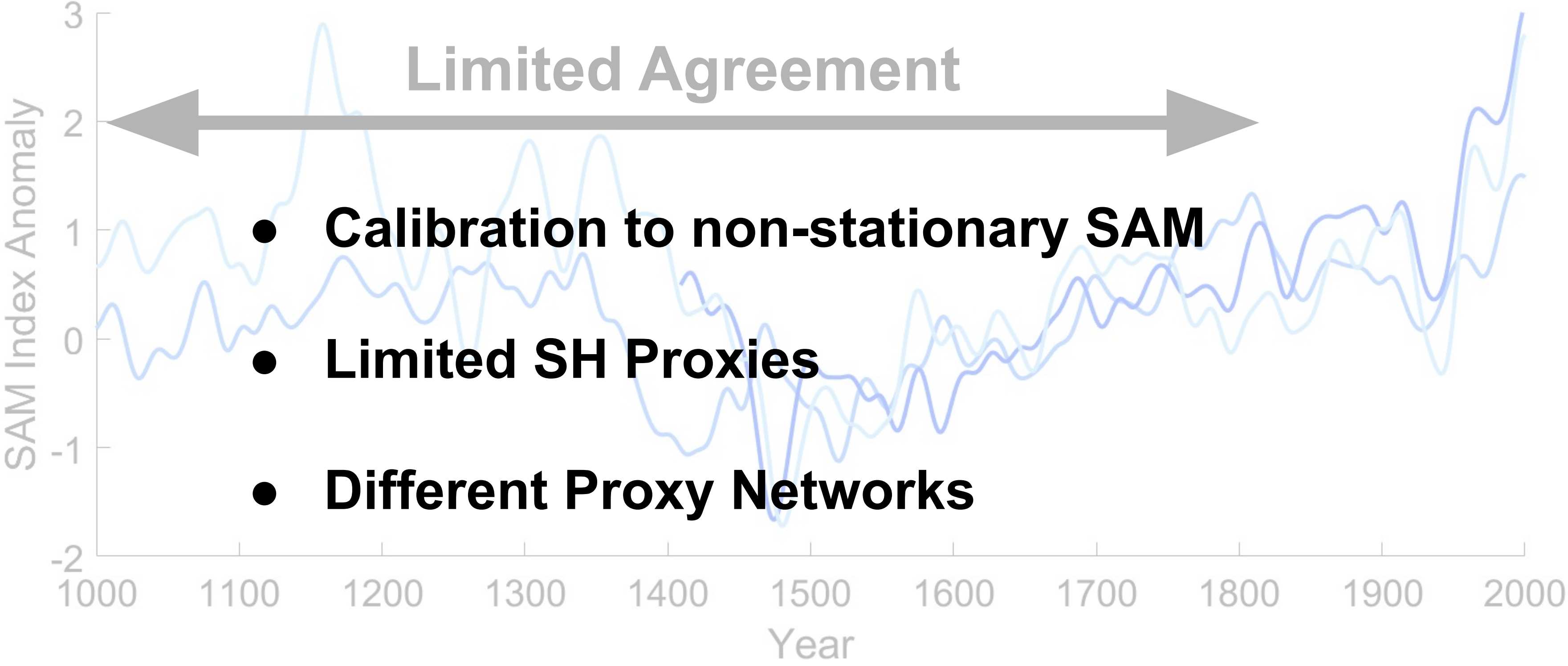
- **Calibration to non-stationary SAM**

SAM Reconstructions



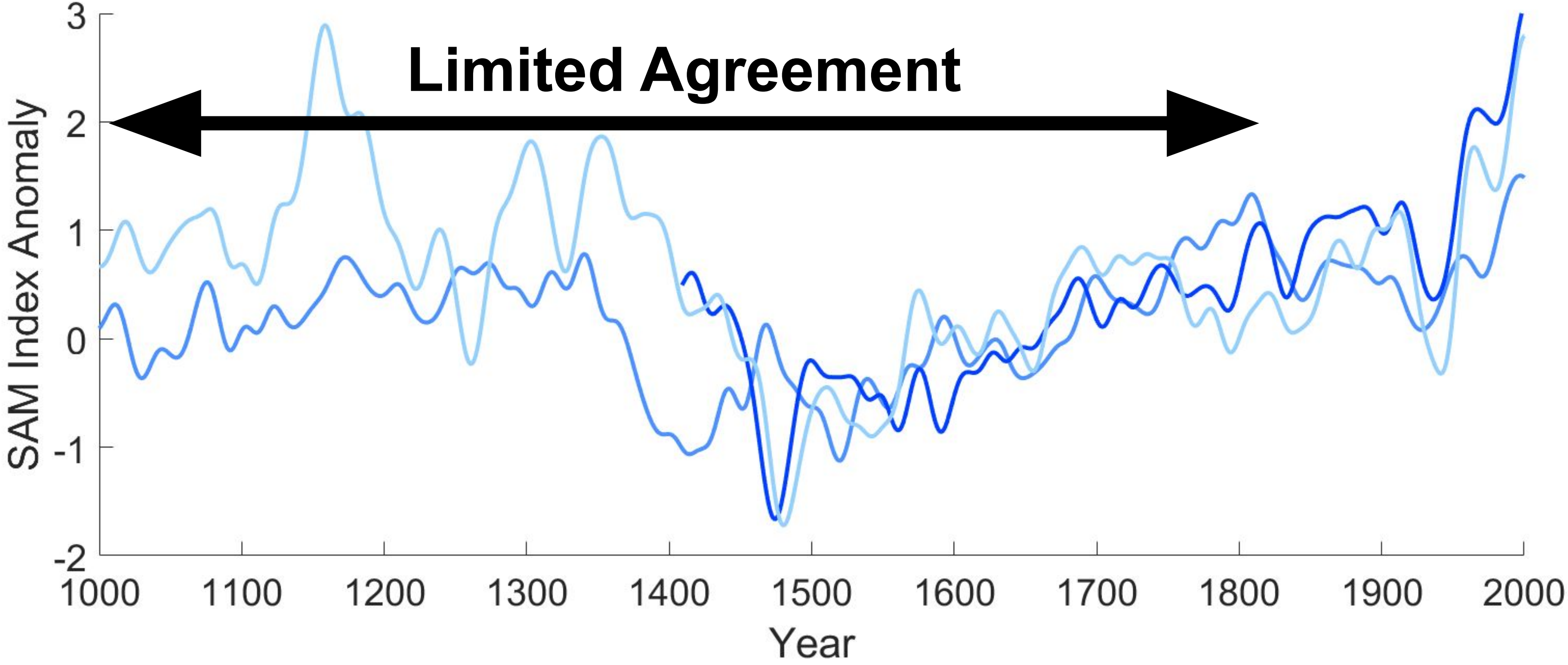
- **Calibration to non-stationary SAM**
- **Limited SH Proxies**

SAM Reconstructions

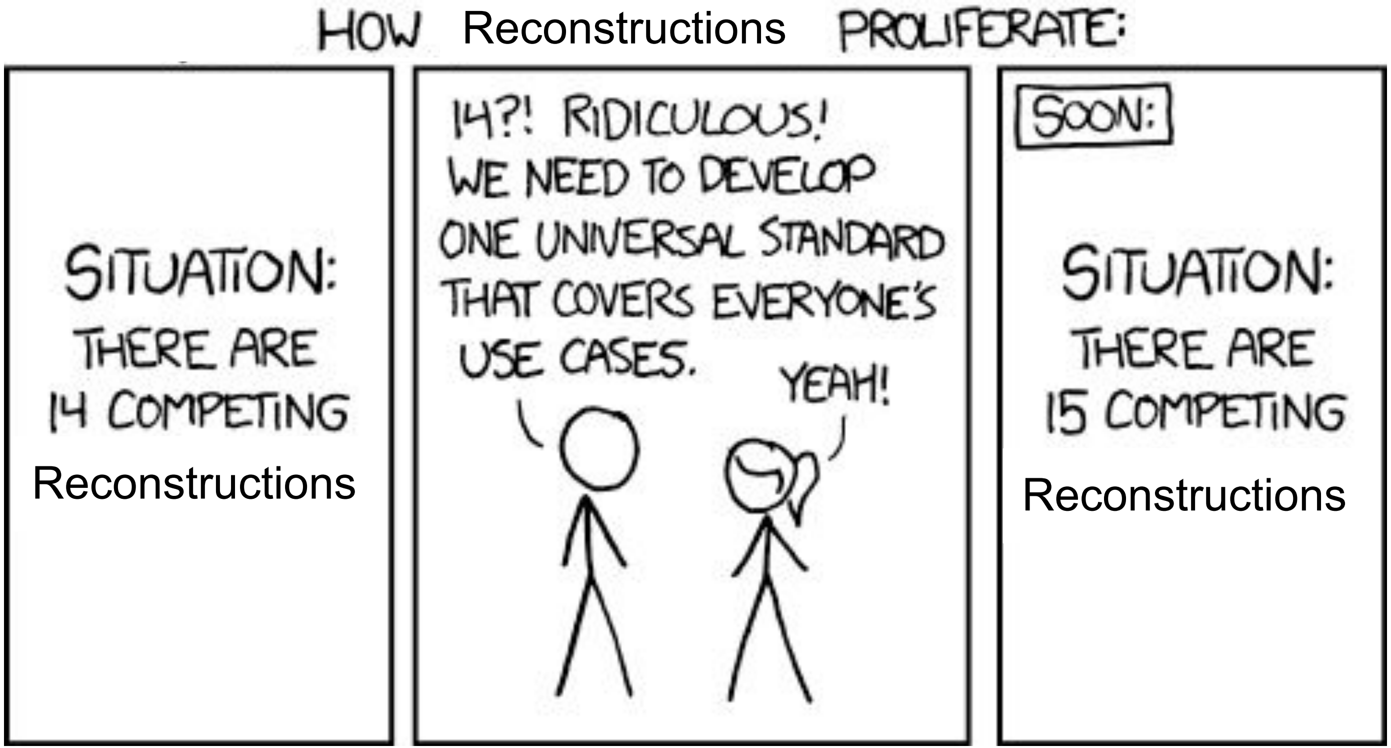


- **Calibration to non-stationary SAM**
- **Limited SH Proxies**
- **Different Proxy Networks**

SAM Reconstructions



A New Reconstruction



Adapted from "Standards" by Randall Munroe on xkcd.com, <u>CC-BY-NC 2.5</u>

Context

Data Assimilation Method

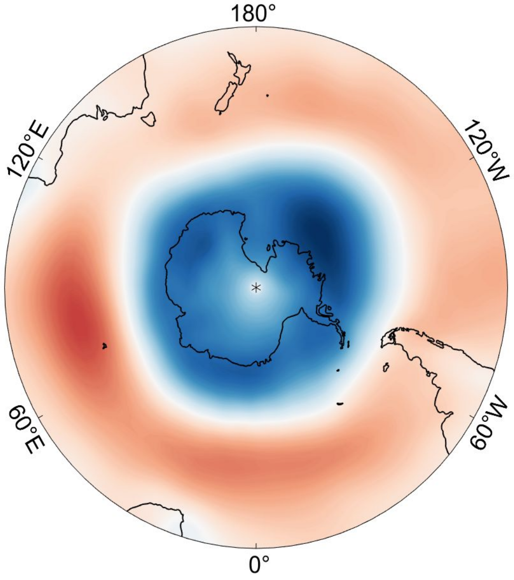
Results

Data Assimilation

Climate Models

Proxy Records

Data Assimilation!



Climate Reconstructions

New Reconstruction

1. **Data Assimilation**
    a. **Method: Offline ensemble Kalman filter**

- Evensen et al., (1994)
- Oke et al., (2002)
- Evensen et al., (2003)

New Reconstruction

1. **Data Assimilation**
   a. Method: Offline ensemble Kalman filter
   b. **Prior: Stationary multi-model**

- Parsons et al., (2021)
- King et al., (2021)

New Reconstruction

1. **Data Assimilation**
    a. Method: Offline ensemble Kalman filter
    b. Prior: Stationary multi-model
    c. **Proxy system models:**

- Evans et al., (2013)

New Reconstruction

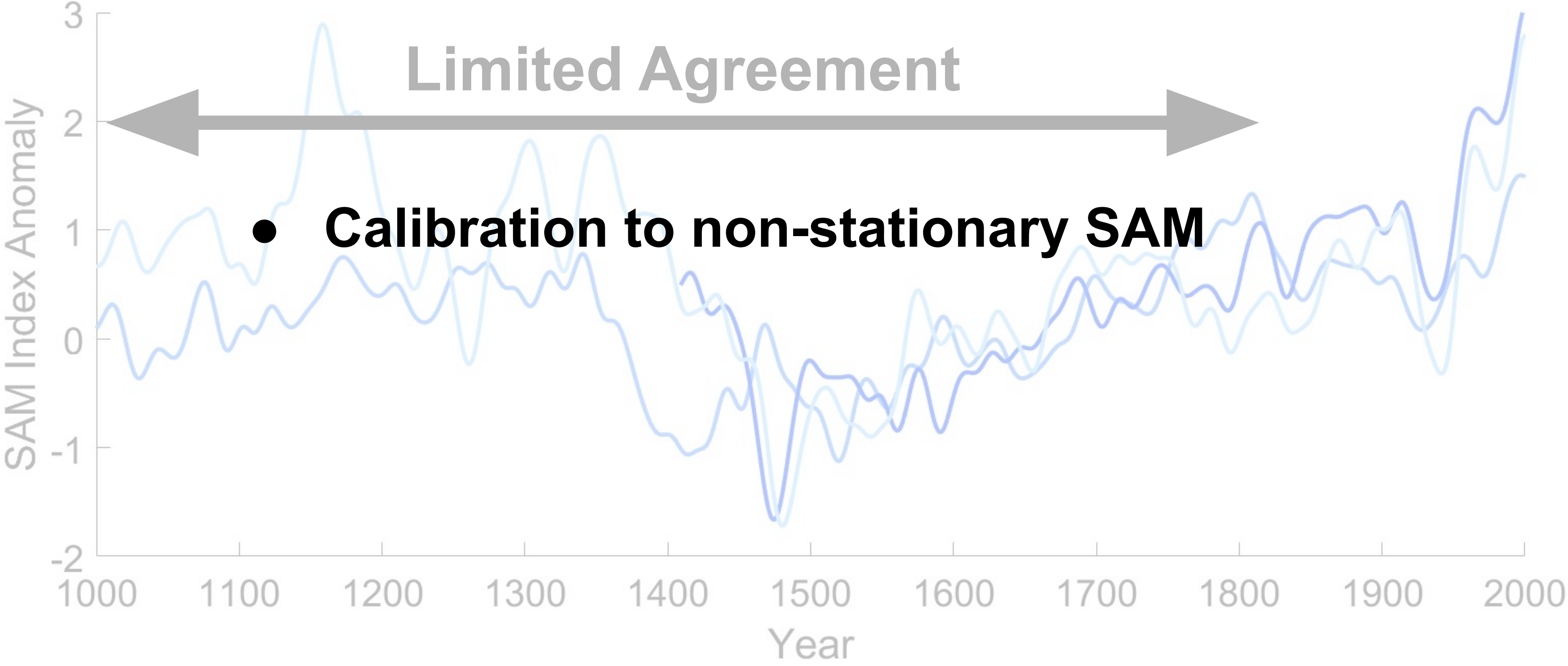
A. Data Assimilation

1. Method: Offline ensemble Kalman filter
2. Prior: Stationary multi-model
3. Proxy system models:

B. Advantages

1.
2.
3.

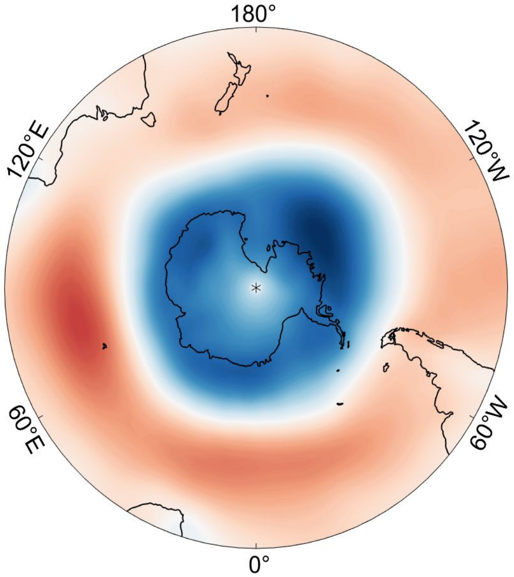
SAM Reconstructions



- **Calibration to non-stationary SAM**

Calibration: Existing Reconstructions

Climate Proxies



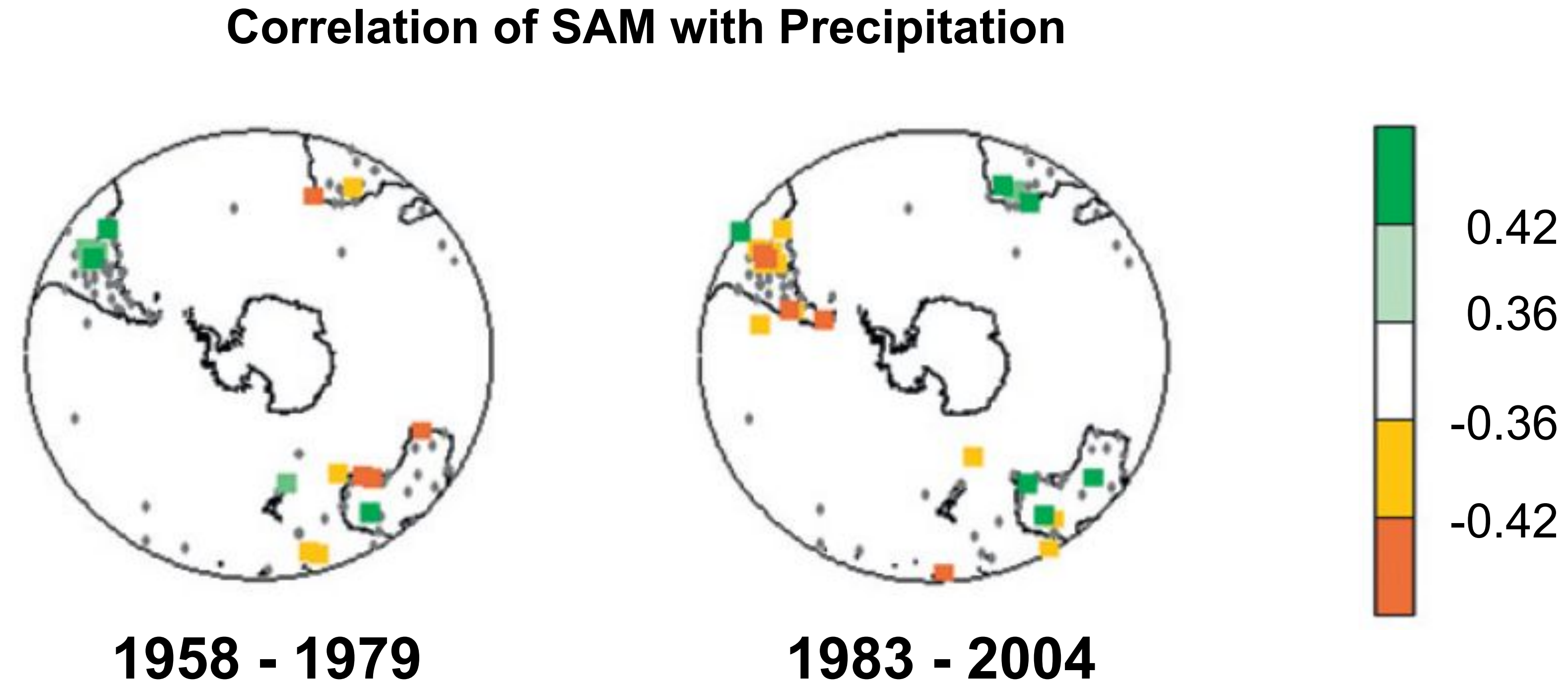
SAM

Calibration

Assumption:

Unchanging relationship between SAM and local climate variables.

Non-stationary SAM



Adapted from Silvestri and Vera, (2009). Figure 1ab

Calibration: Data Assimilation

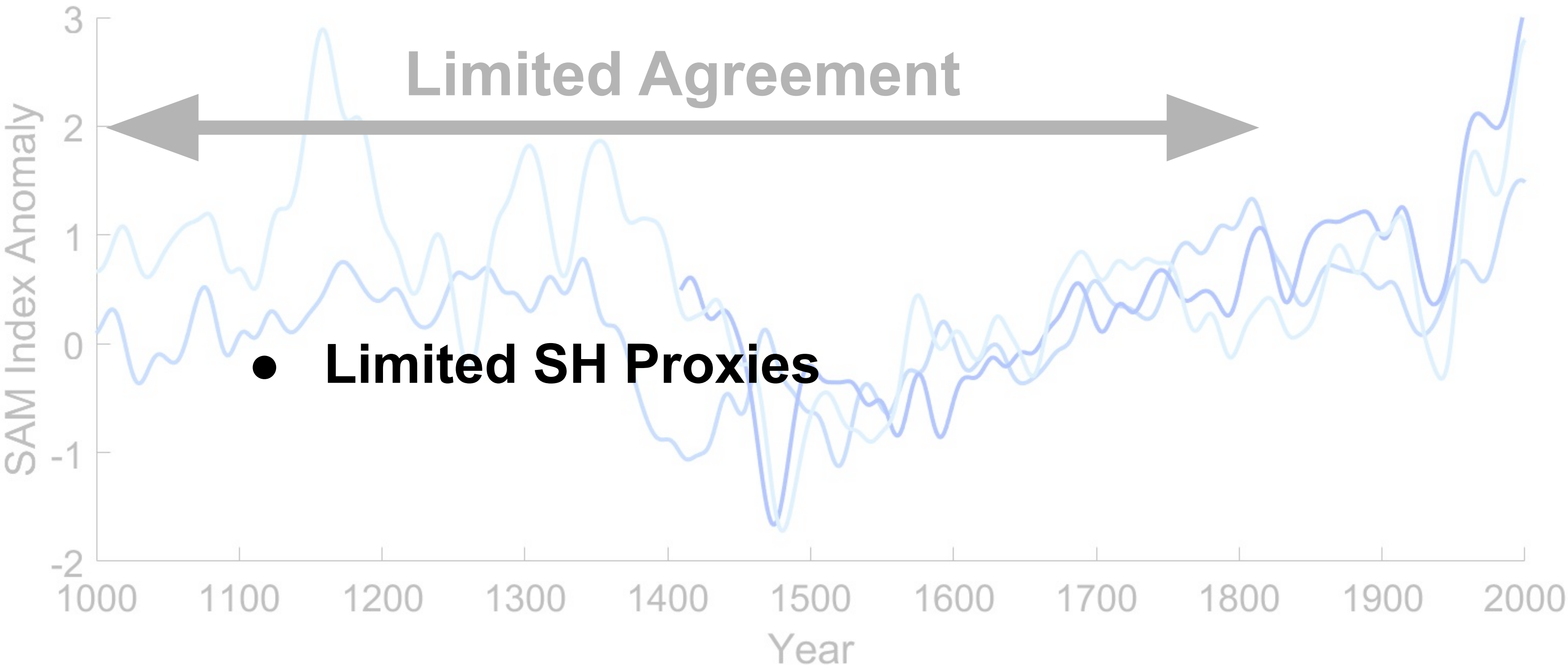
Climate Proxies **Local Climate Variables**

New Reconstruction

A. **Data Assimilation**
   1. Method: Offline ensemble Kalman filter
   2. Prior: Stationary multi-model
   3. Proxy system models:

B. **Advantages**
   1. Not calibrated to SAM index
   2.
   3.

SAM Reconstructions

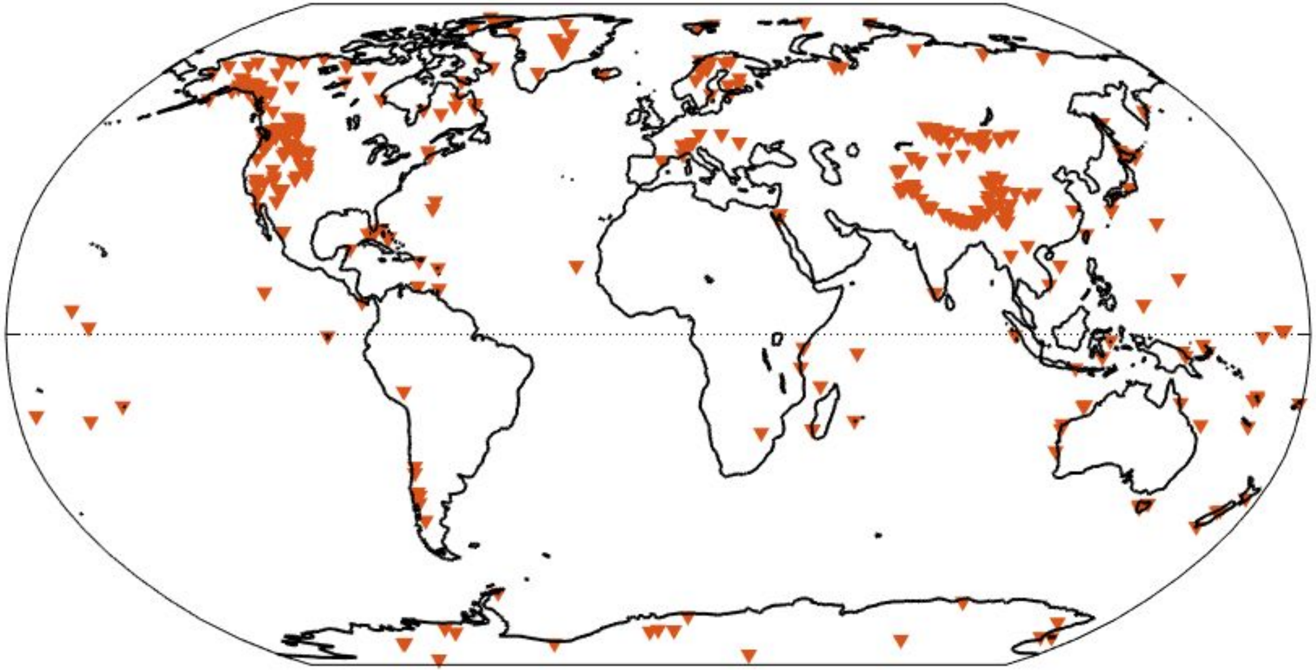


- **Limited SH Proxies**

Fewer SH Proxies

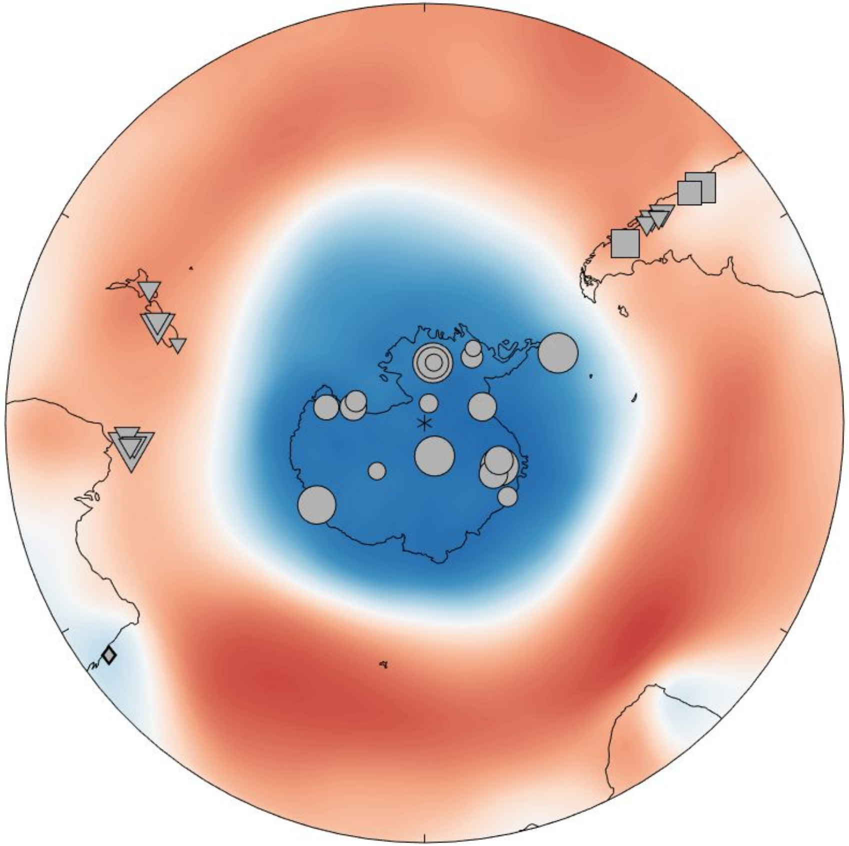
481

89

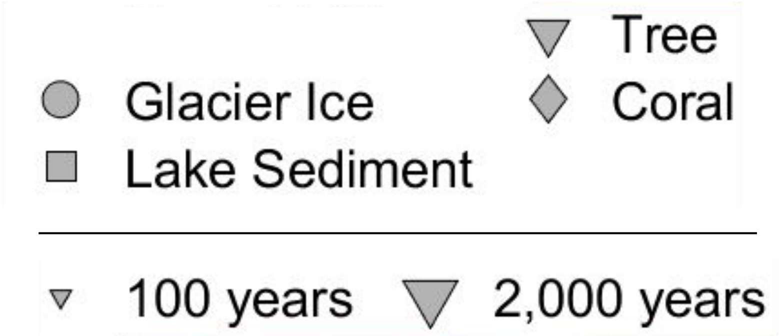


PAGES2k, annual resolution or greater

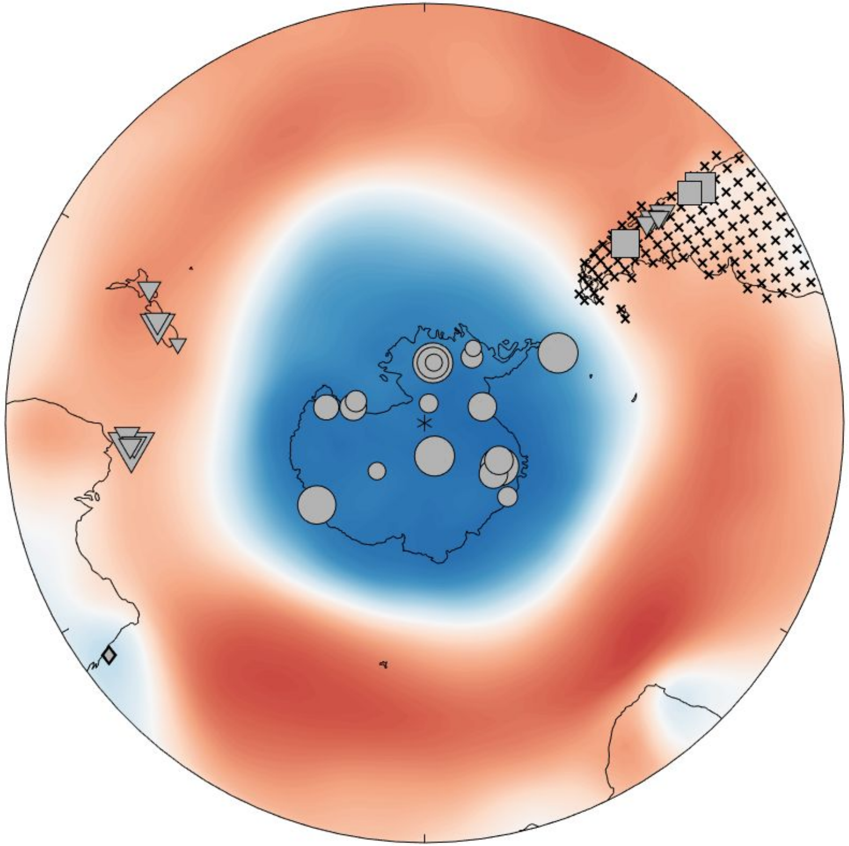
Proxy Network



PAGES2k



Proxy Network

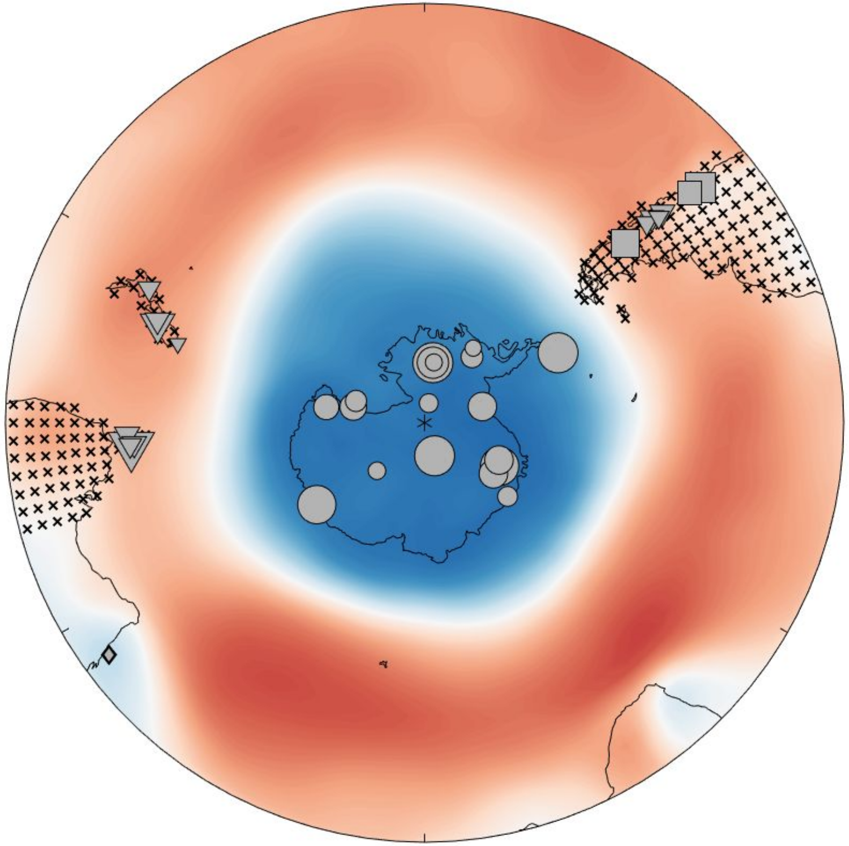


PAGES2k, SADA

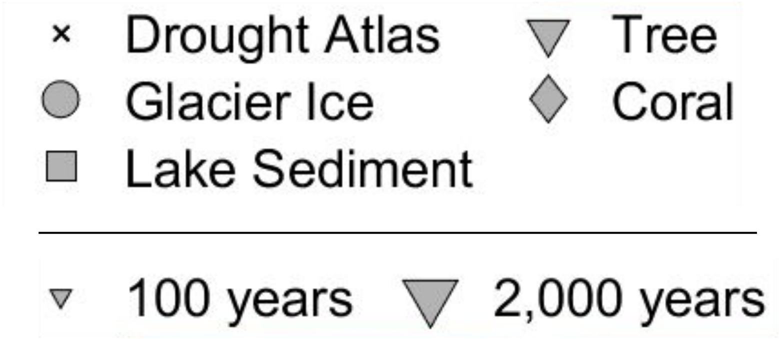
× Drought Atlas
▽ Tree
○ Glacier Ice
◇ Coral
□ Lake Sediment

▽ 100 years
▽ 2,000 years

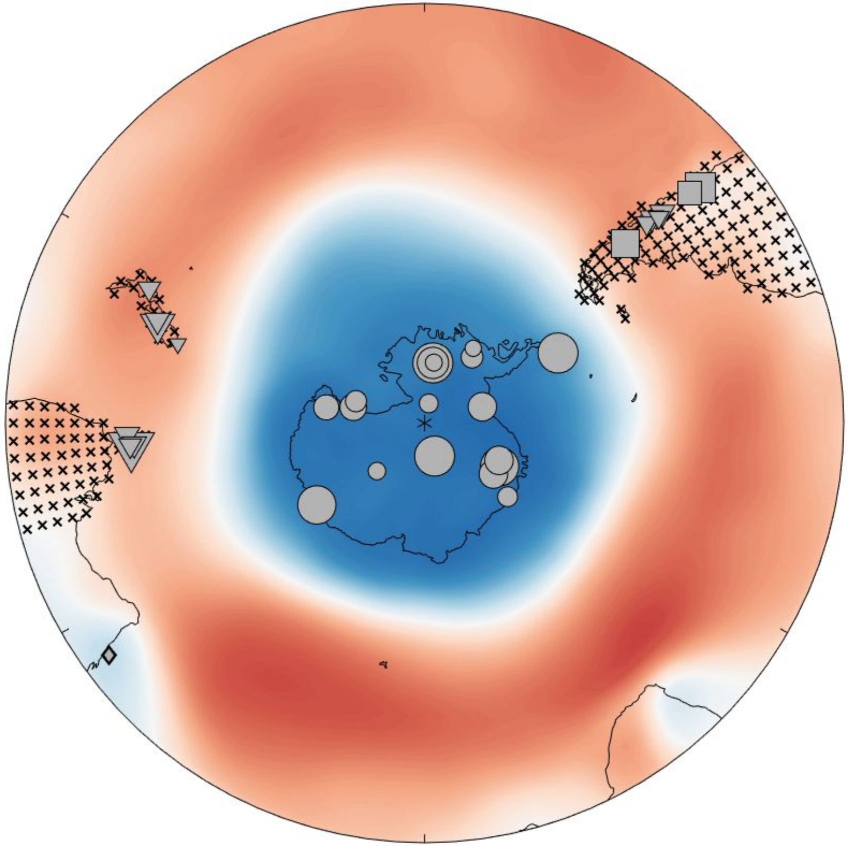
Proxy Network



PAGES2k, SADA, ANZDA



Proxy Network



SADA: 286 records

ANZDA: 177 records

New Reconstruction

A. Data Assimilation

1. Method: Offline ensemble Kalman filter
2. Prior: Stationary multi-model
3. Proxy system models:

B. Advantages

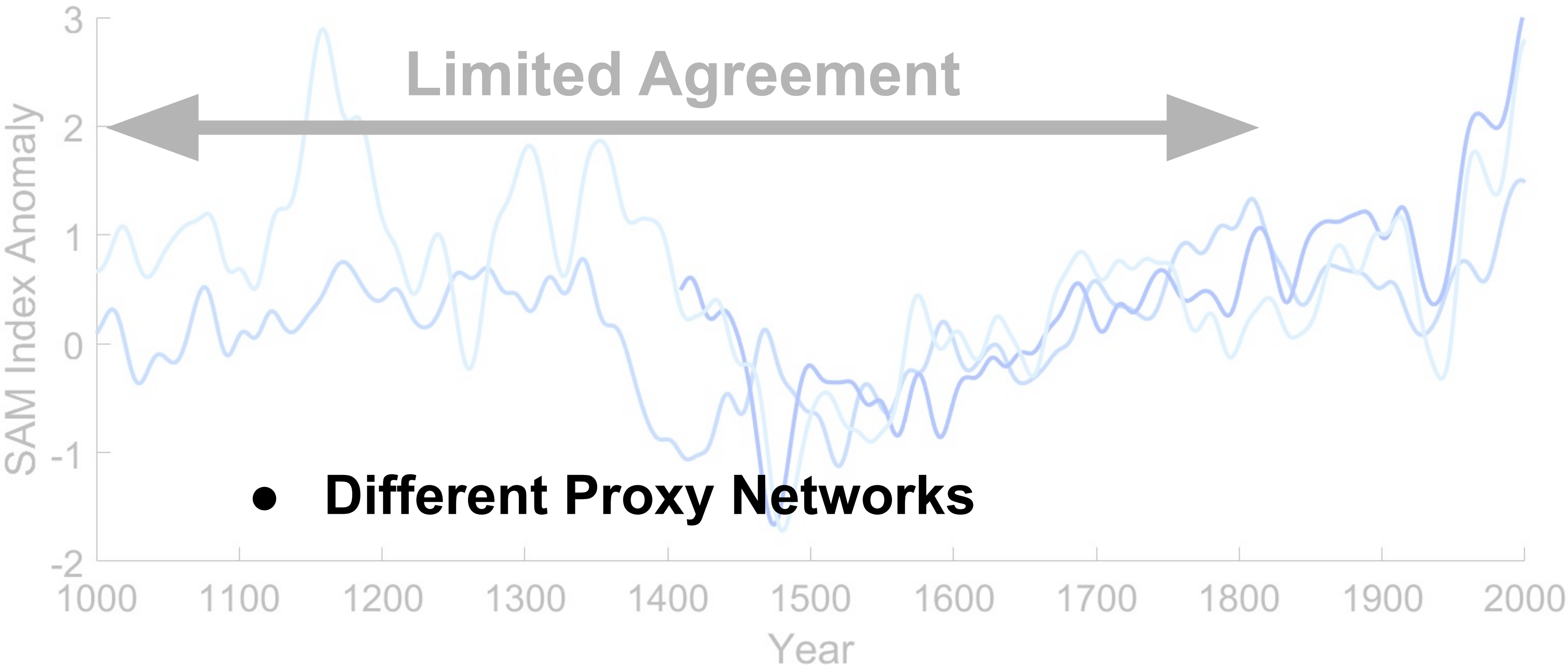
1. Not calibrated to SAM index
2. More proxy information (drought atlases)
3.

New Reconstruction

1. **Data Assimilation**
   a. Method: Offline ensemble Kalman filter
   b. Prior: Stationary multi-model
   c. Proxy system models: Linear seasonal temperature, $\mathbf{PDSI_{Thornthwaite}}$

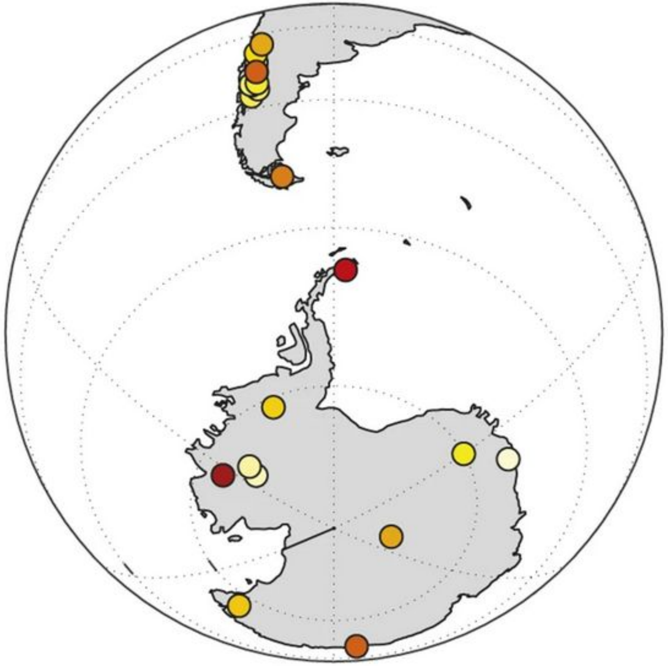
- Evans et al., (2013)

SAM Reconstructions

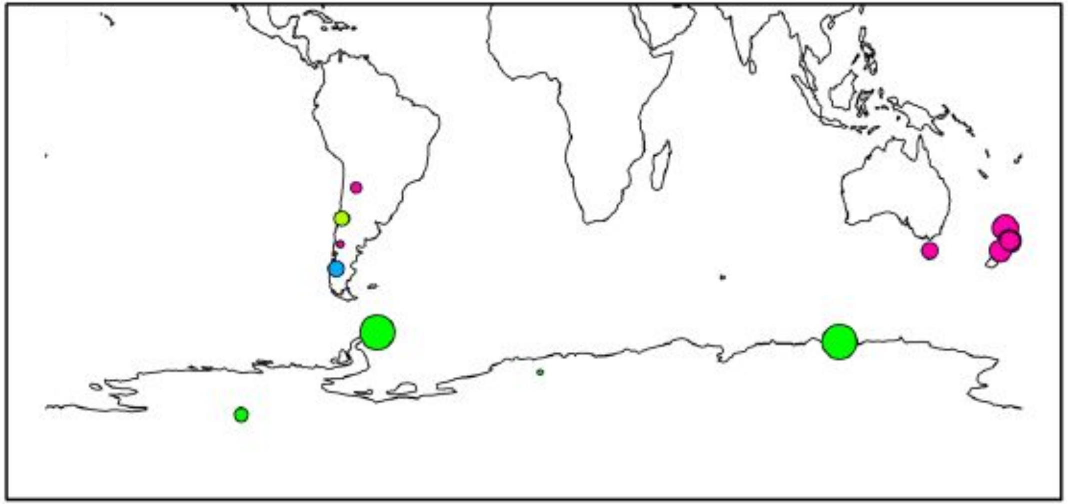


- **Different Proxy Networks**

Different Proxy Networks

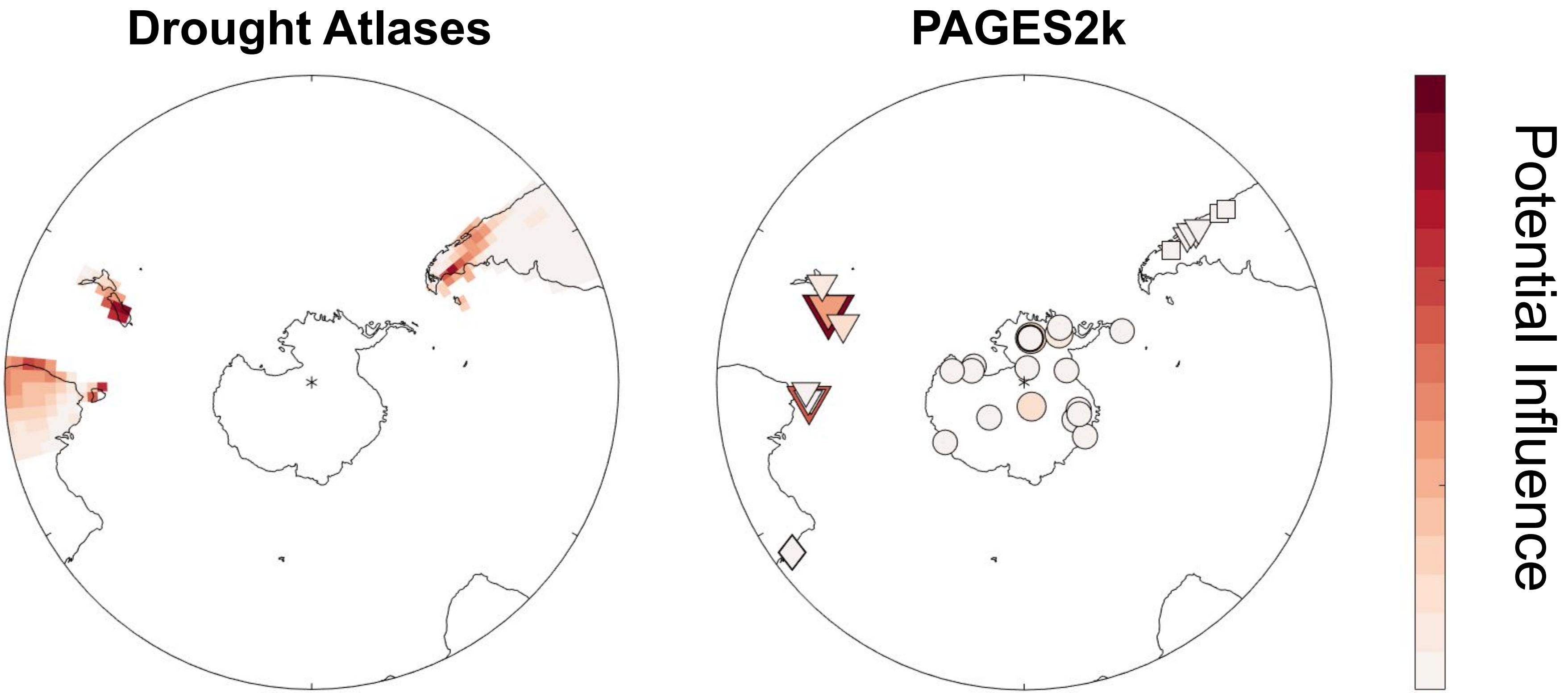


Abram et al., (2014). Figure 2a

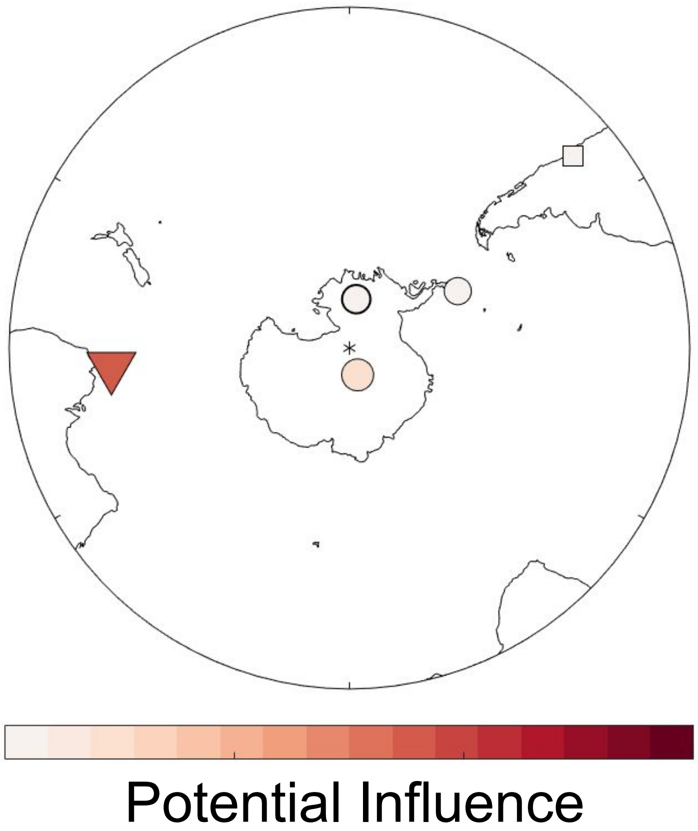


Datwyler et al., (2018). Figure 7b

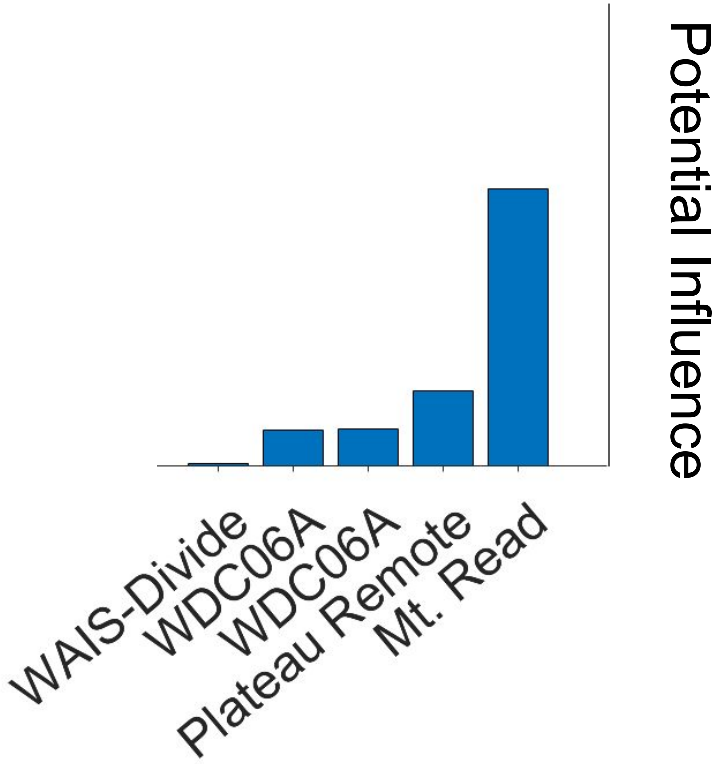
Optimal Sensor



8 - 165 CE

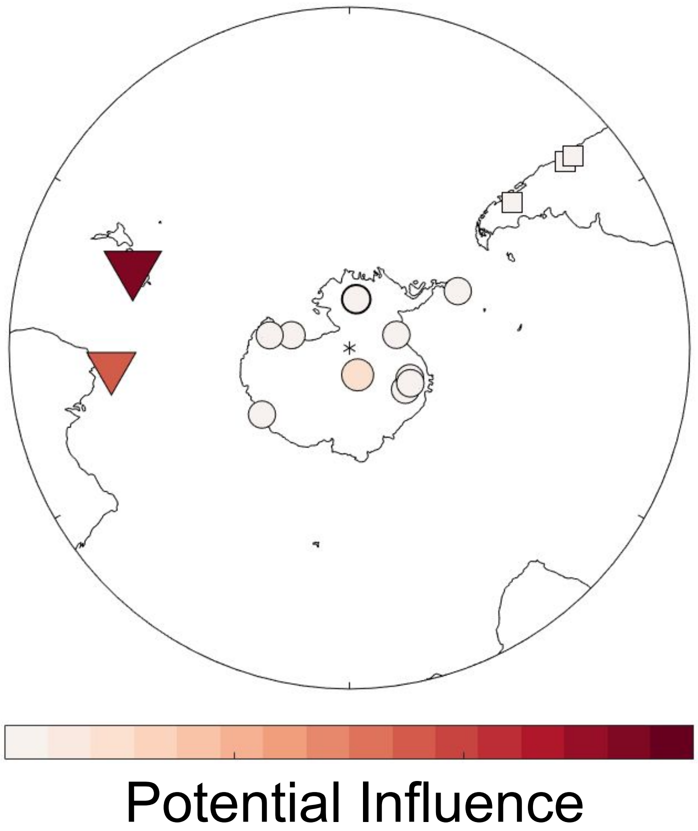


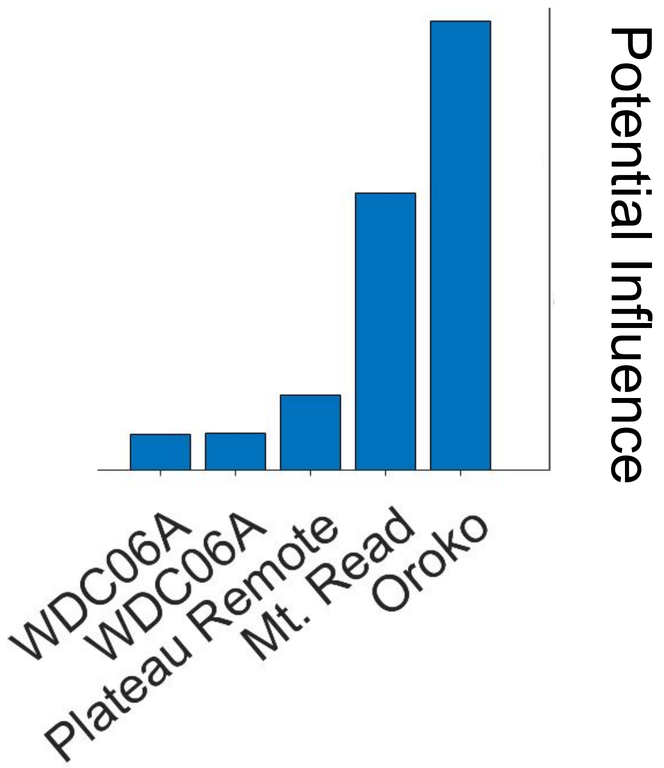
Potential Influence



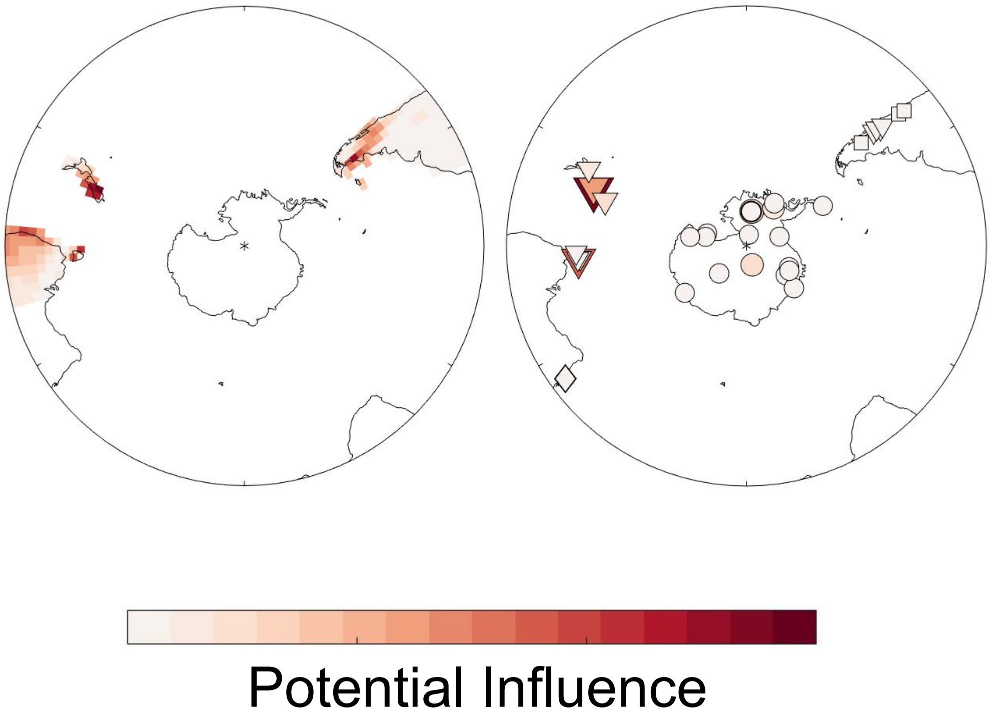
Potential Influence
WAIS-Divide
WDC06A
WDC06A
Plateau Remote
Mt. Read

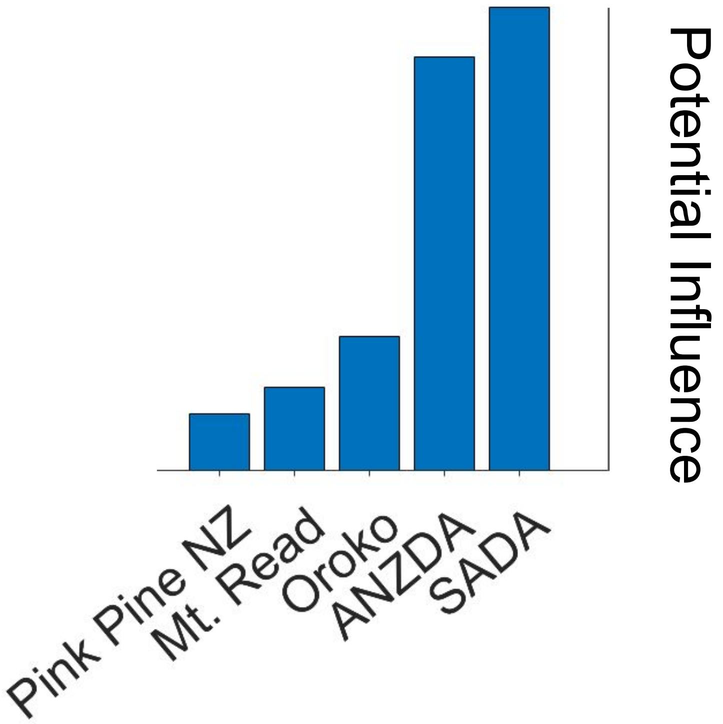
1232 - 1399 CE


Potential Influence


Potential Influence
WDC06A
WDC06A
Plateau Remote
Mt. Read
Oroko

1848 - 1983 CE


Potential Influence


Pink Pine NZ
Mt. Read
Oroko
ANZDA
SADA
Potential Influence

New Reconstruction

A. Data Assimilation

1. Method: Offline ensemble Kalman filter
2. Prior: Stationary multi-model
3. Proxy system models: Linear seasonal temperature, $PDSI_{Thornthwaite}$

B. Advantages

1. Not calibrated to SAM index
2. More proxy information (drought atlases)
3. Assess proxy influence (optimal sensor)

Context

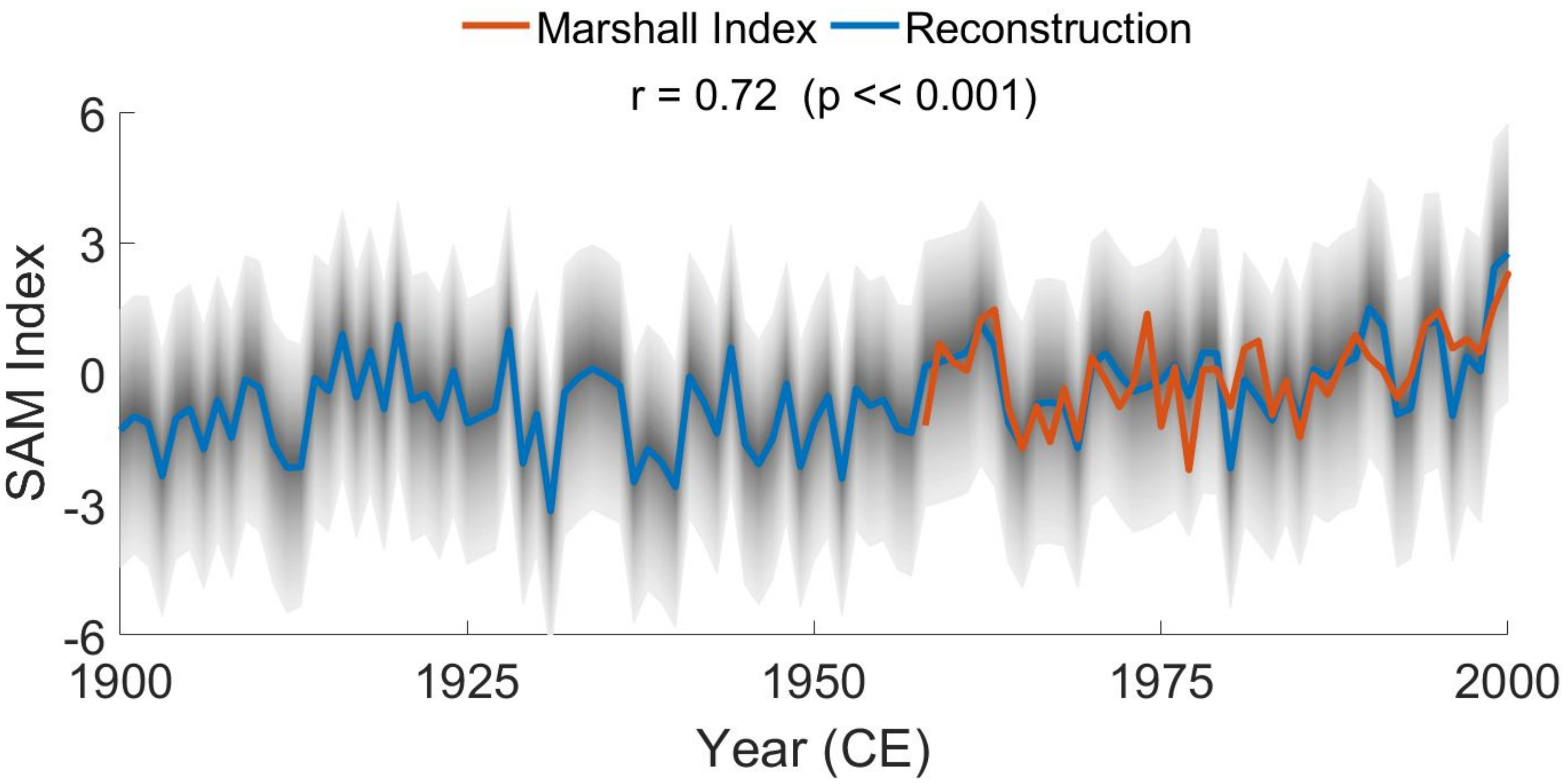
Data Assimilation Method

Results

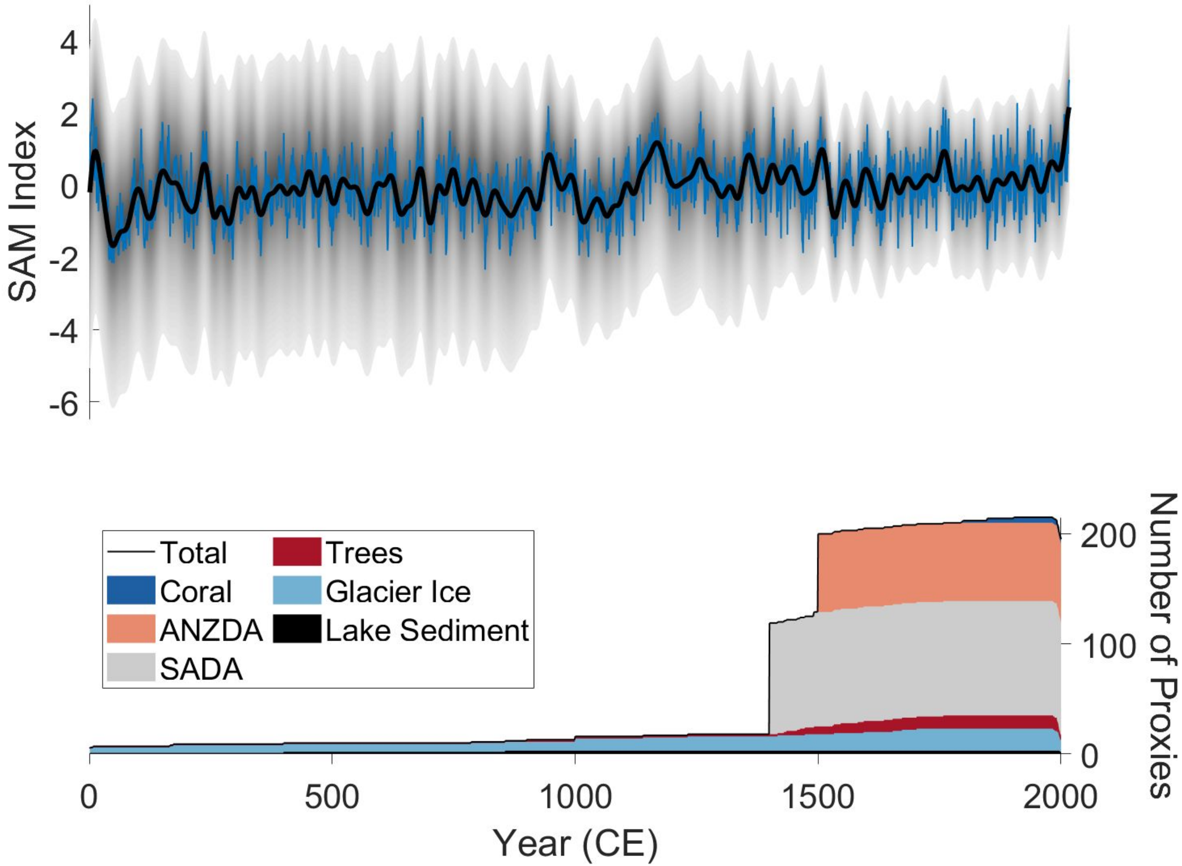
Results

A. New reconstruction

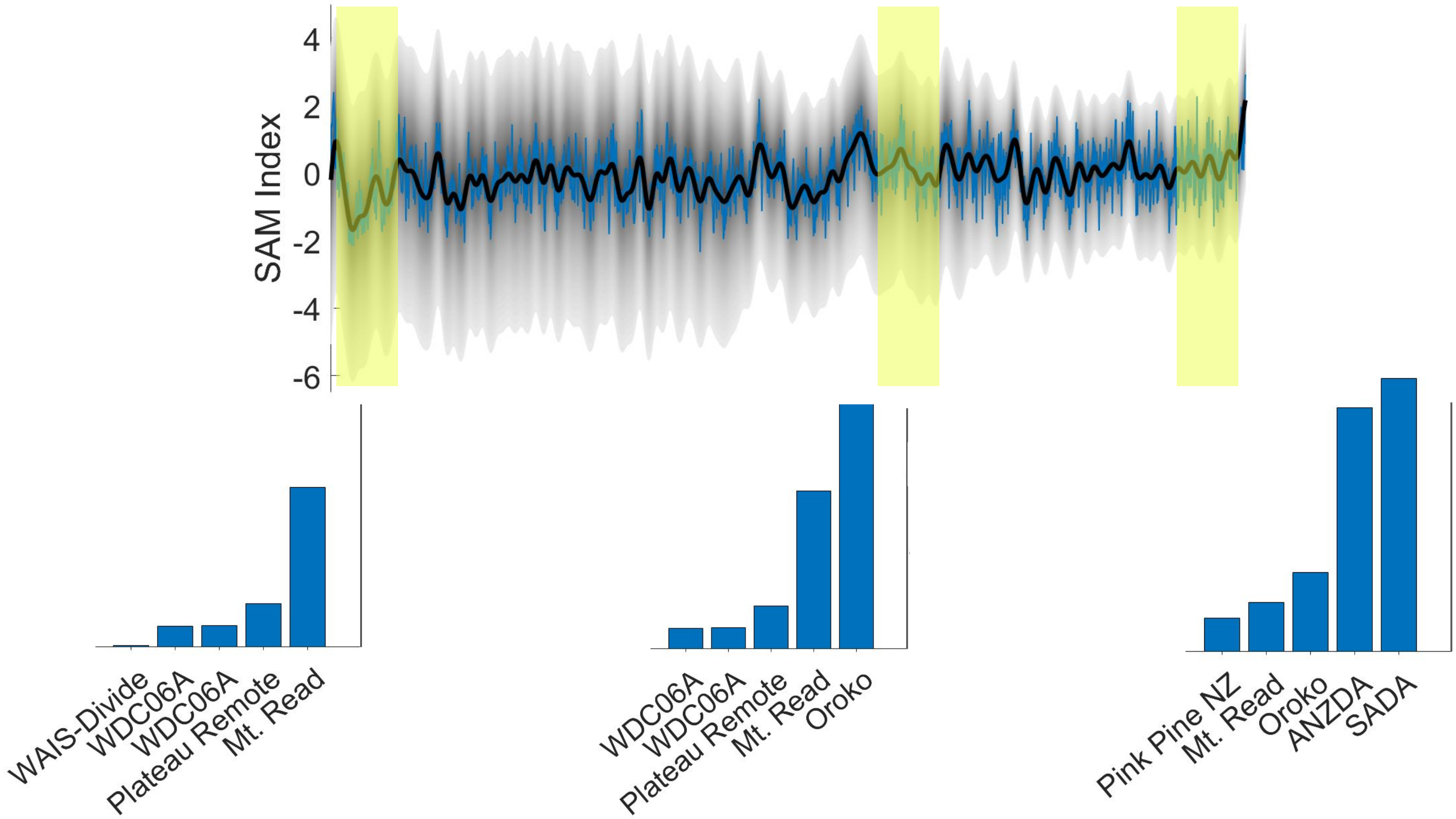
Reconstruction



Reconstruction



Reconstruction



Results

A. New reconstruction

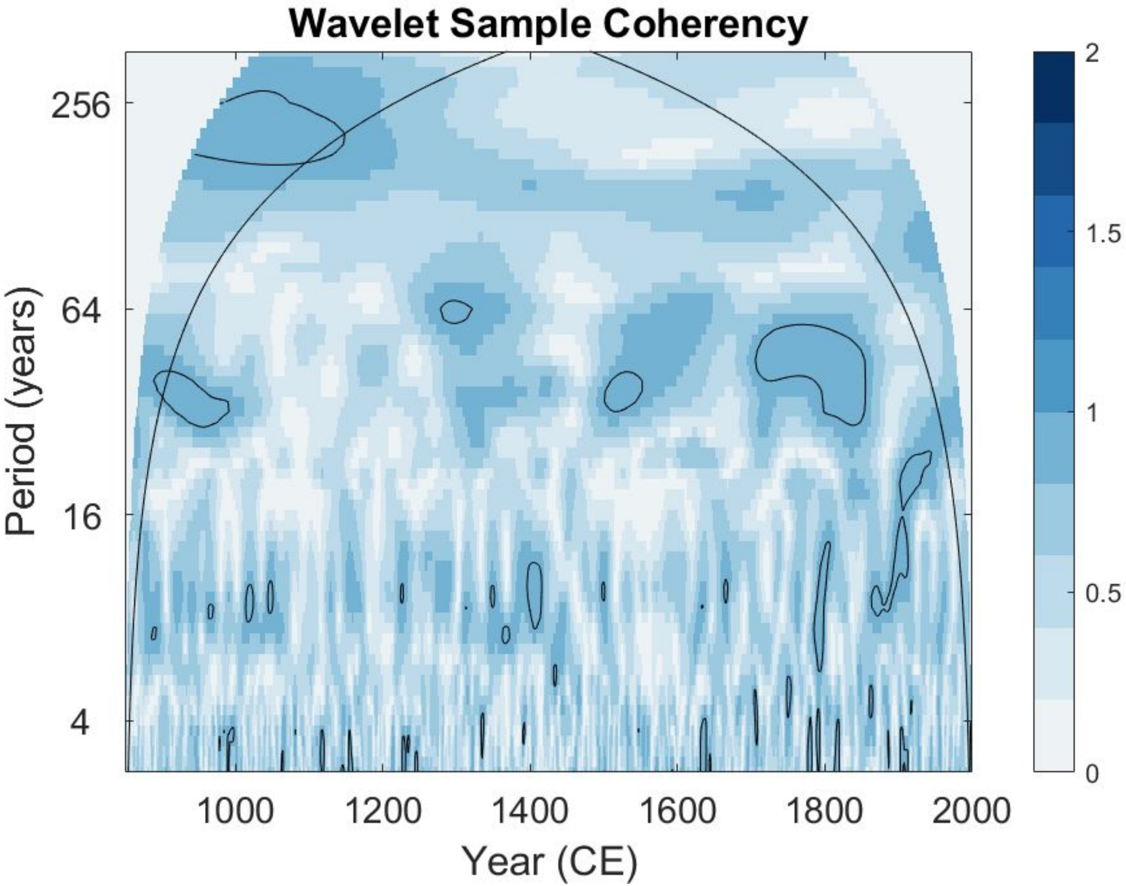
- Correlation with Marshall Index: 0.72 ($p \ll 0.001$)
- Quantified influential proxies

Results

A. **New reconstruction**
   - Correlation with Marshall Index: 0.72 ($p \ll 0.001$)
   - Quantified influential proxies

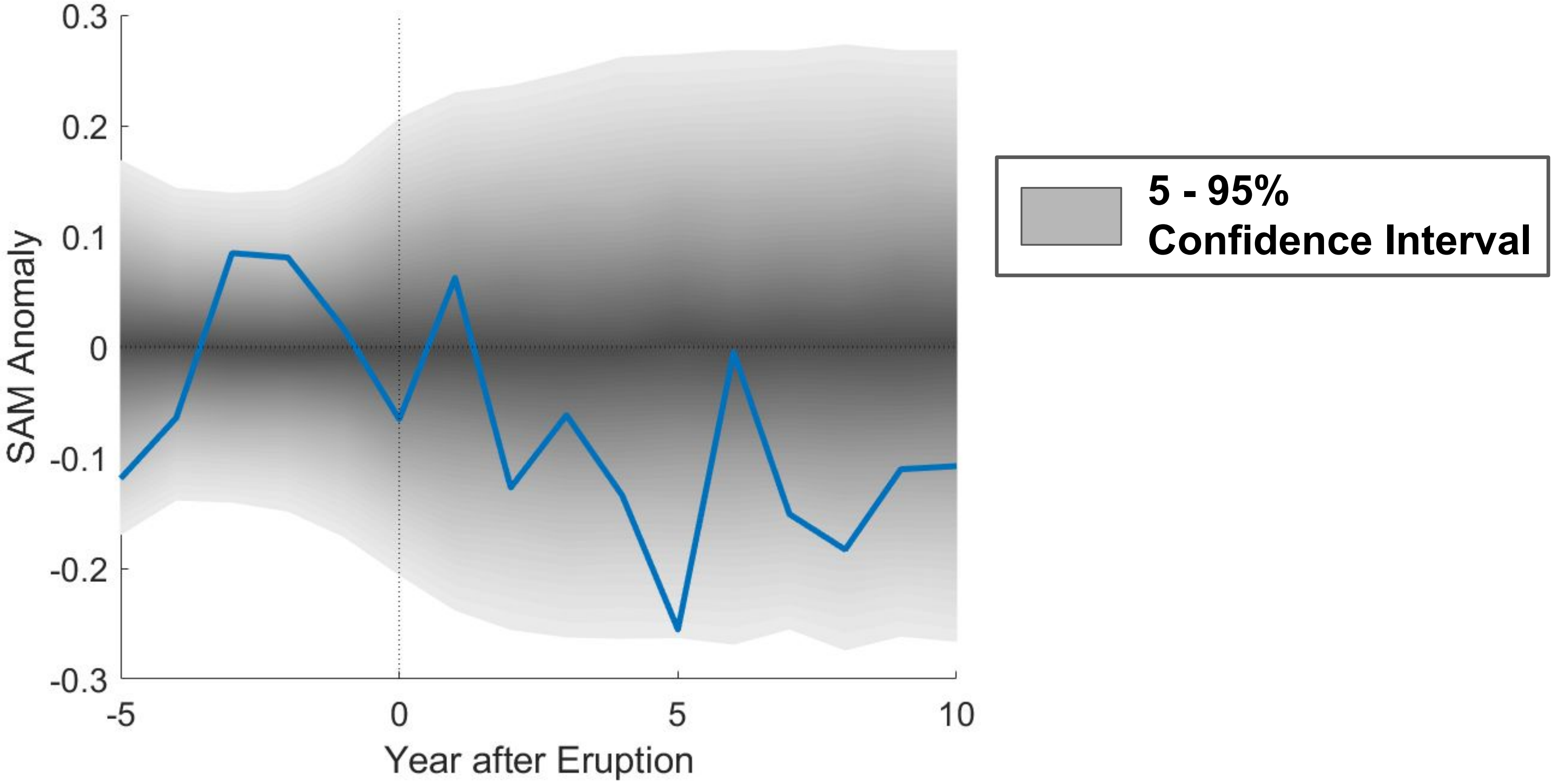
B. **Long-term drivers of the SAM**
   - Internal variability

Solar



Wavelet Sample Coherency
256
64
16
4
Period (years)
1000
1200
1400
1600
1800
2000
Year (CE)
2
1.5
1
0.5
0

Volcanic



0.3
0.2
0.1
0
-0.1
-0.2
-0.3
SAM Anomaly
-5
0
5
10
Year after Eruption
5 - 95%
Confidence Interval

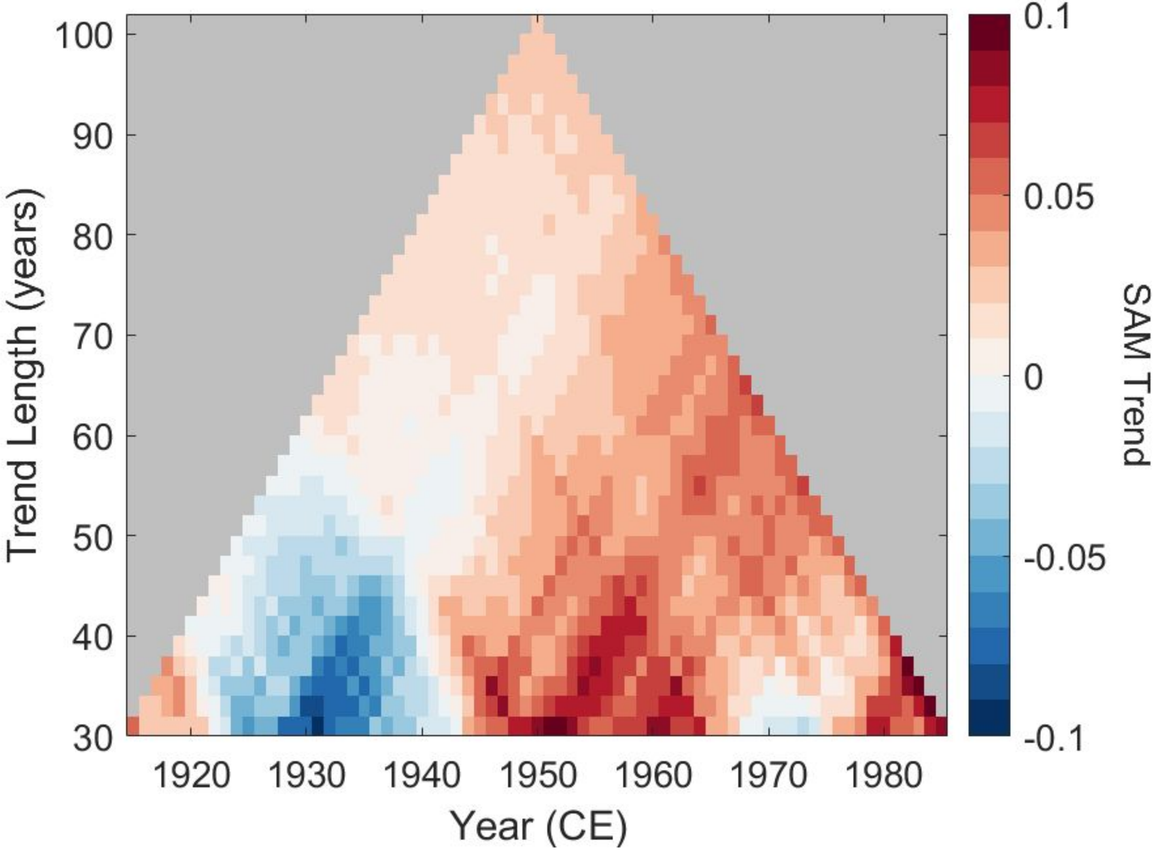
Results

A. **New reconstruction**
   - Correlation with Marshall Index: 0.72 ($p \ll 0.001$)
   - Quantified influential proxies

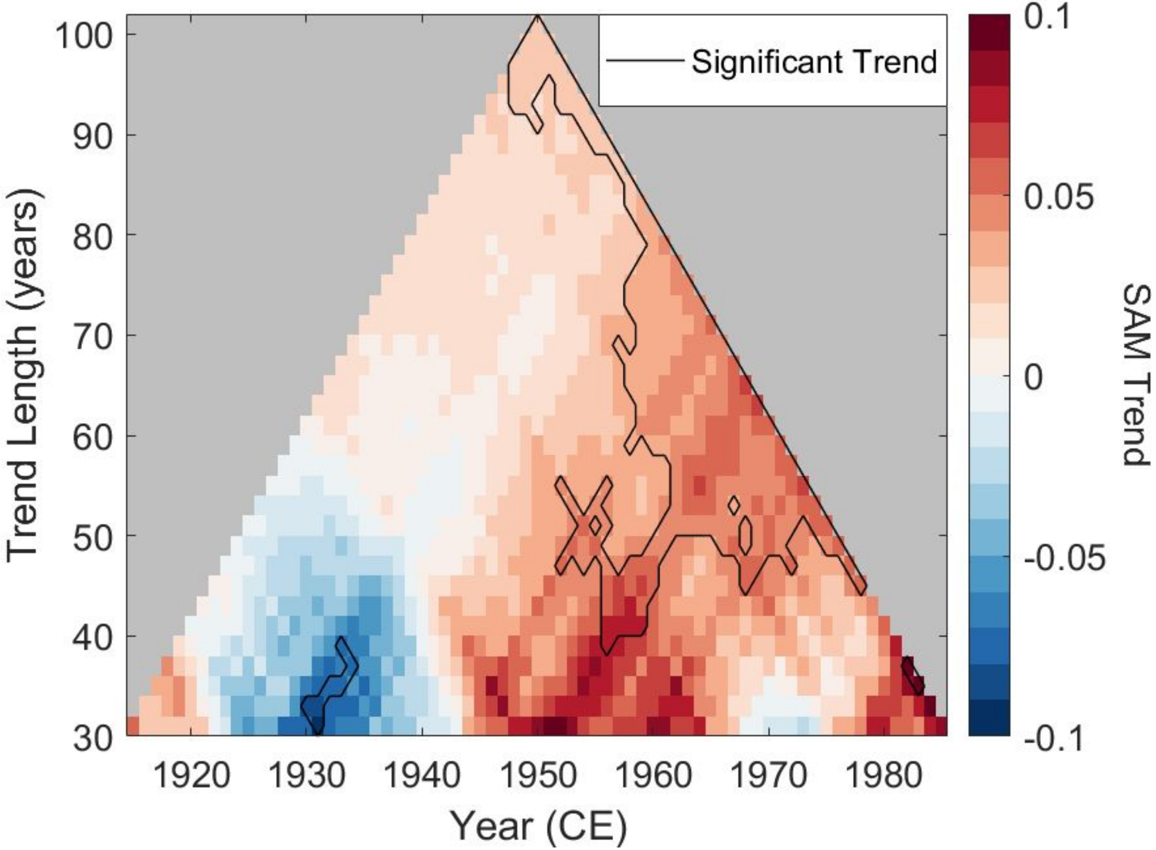
B. **Long-term drivers of the SAM**
   - Internal variability

C. **Modern Trend**

Modern Trends



Modern Trends



Results

A. New reconstruction
- Correlation with Marshall Index: 0.72 ($p \ll 0.001$)
- Quantified influential proxies

B. Long-term drivers of the SAM
- Internal variability

C. Modern Trend
- Outside range of natural variability (5% - 95%)
- Significance depends on trend length
- 45+ years, most recent interval

Caveats and Future Work

A. **Climate model covariance biases**
   - Multi-model ensemble

B. **Proxy system model biases**
   - Reduces proxy influence
   - Develop more sophisticated models

C. **Equally weighted climate models**
   - Models are not fully independent
   - Develop more accurate weighting scheme

DASH Package

DASH Public

A package for paleoclimate data assimilation workflow.

data-assimilation ensemble-kalman-filter paleoclimate particle-filter optimal-sensor

MATLAB

https://github.com/JonKing93/DASH

Thank you!

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B. **National Science Foundation**
- P2C2 AGS-1803946

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