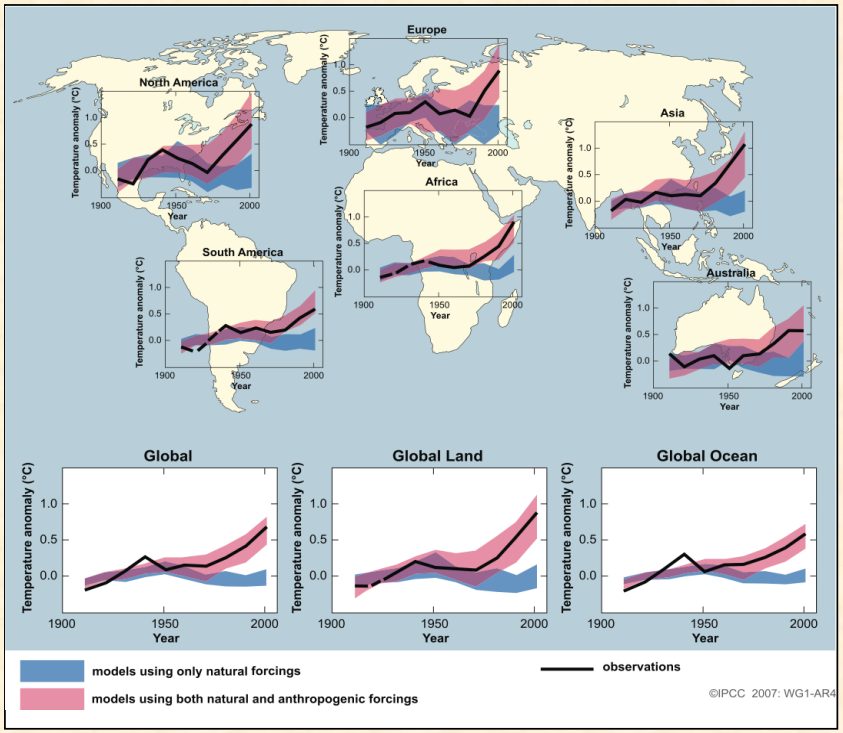
Decadal Climate Variability (DCV) During the Last Millennium from High-Resolution Proxies

Edward R. Cook
Tree-Ring Laboratory
Lamont-Doherty Earth Observatory
Palisades, New York 10964 USA

CLIVAR-ICTP Workshop on Past and Future Climate Shifts: Decadal Climate Variability and Predictability

November 16-20, 2015
Trieste, Italy

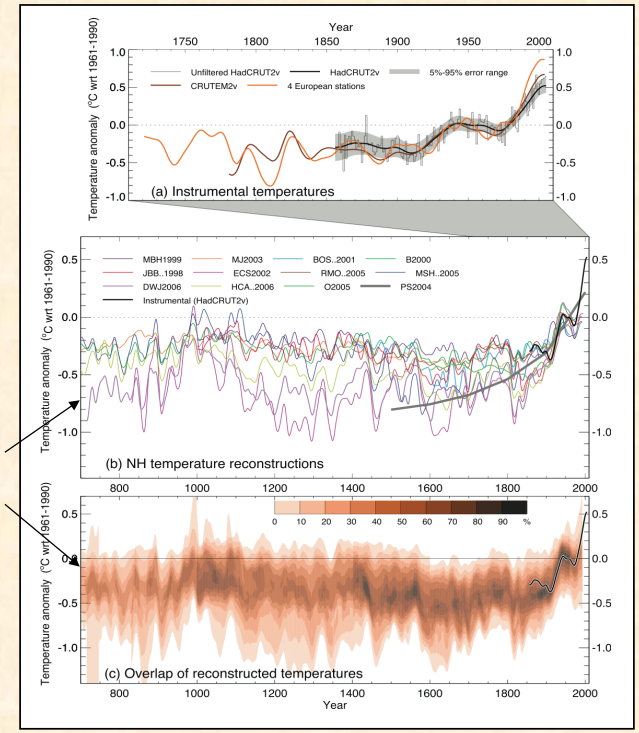
20th Century temperature change is increasingly dominated by GHG forcing since ~1970 - both globally and regionally.



http://ipcc-wg1.ucar.edu/wg1/wg1-figures.html

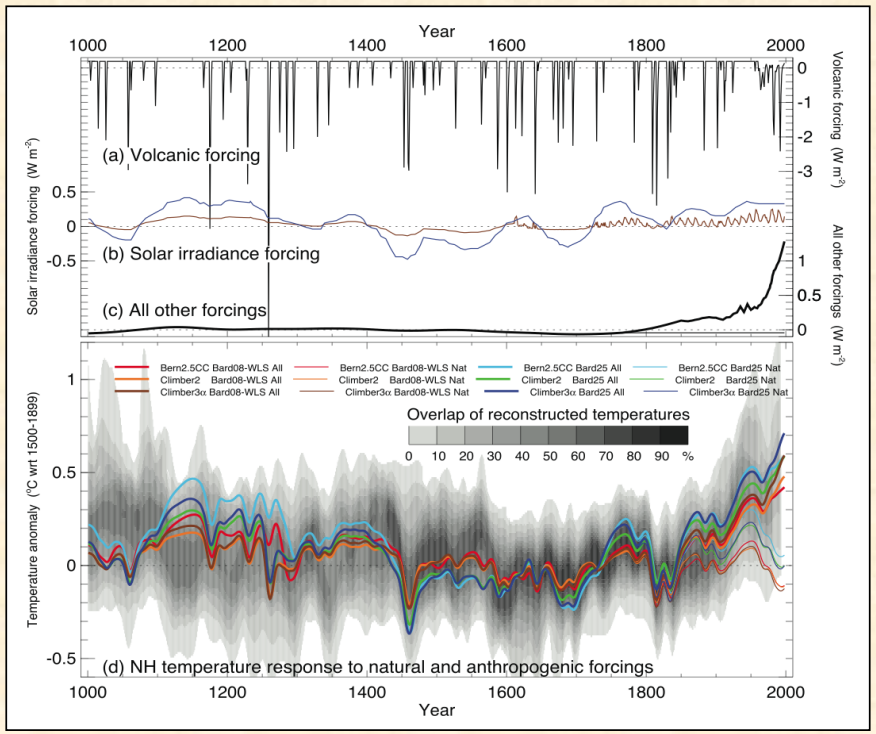
However, a lot of decadal (to centennial) variability (DCV) in paleoclimate data may not be accounted for by the models

A lot of DCV, but also a lot of uncertainty!



http://ipcc-wg1.ucar.edu/wg1/wg1-figures.html

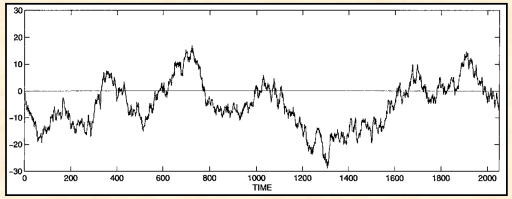
Over the past millennium, solar and volcanic forcing may explain some of this "natural" variability.



http://ipcc-wg1.ucar.edu/wg1/wg1-figures.html

But the simplest explanation for most DCV takes an "Occam's Razor" approach

- A low-order stochastic (e.g., a simple Hasselman-style **red noise** or low-order **ARMA** model) appears to be sufficient to explain **multi-year** variability apparent in (*typically*) short instrumental climate records.
- Wunsch (1999) argued that multi-year variability in instrumental records could be simply be modeled and simulated by low-order **ARMA** models (Wunsch, 1999, "The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations", *BAMS*).



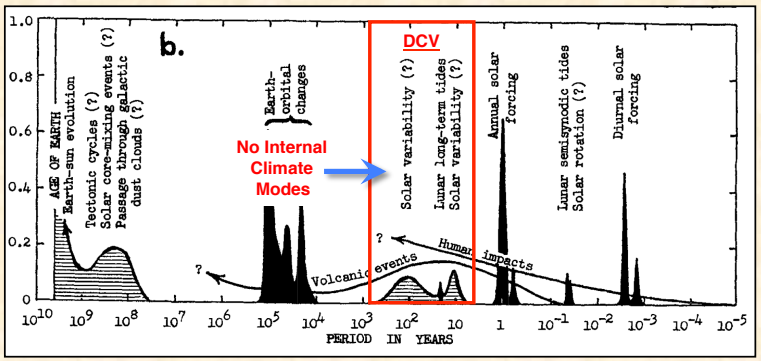
Synthetic "red noise" process from normally distributed white noise:

$x_t = 0.999x_{t-1} + e_t$ (Wunsch, 1999).

DCV by chance alone is readily apparent.

- This realization led to the ***null hypothesis*** that simple stochastic (e.g., low-order **ARMA** models are sufficient to describe, if not explain, **multi-year** climate variability.
- ***So what are the alternate hypotheses?***

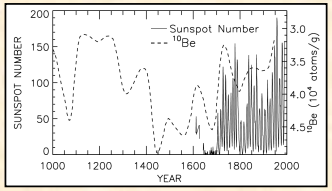
Solar variability at multiple time scales (punctuated by explosive volcanism, lunar tidal forcing too) have long been thought to contribute to DCV.



Mitchell, J.M. 1976. An overview of Climatic Variability and its causal mechanisms. *Quaternary Research* 6:481-493.

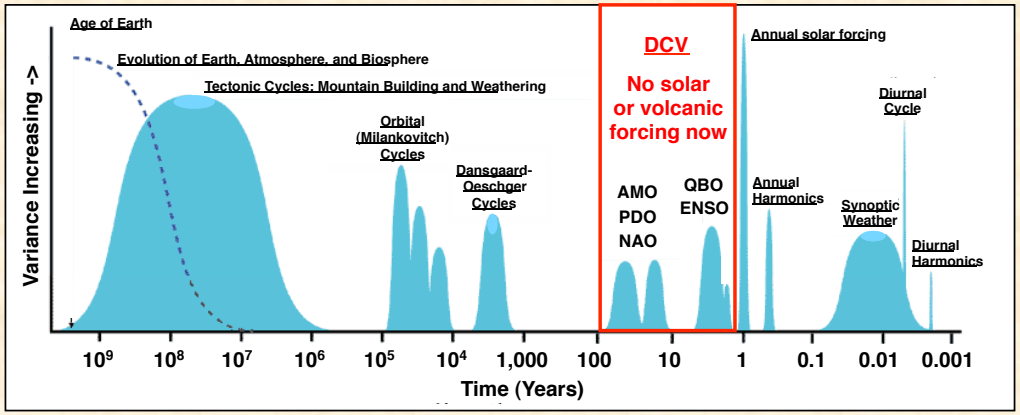
Some proposed time scales of solar forcing:

- ~11-yr "Schwabe" Cycle
- ~22-yr "Hale" Cycle
- ~87-yr "Gleissberg" Cycle
- ~210-yr "De Vries" Cycle



All are really "quasi-periodic" at best

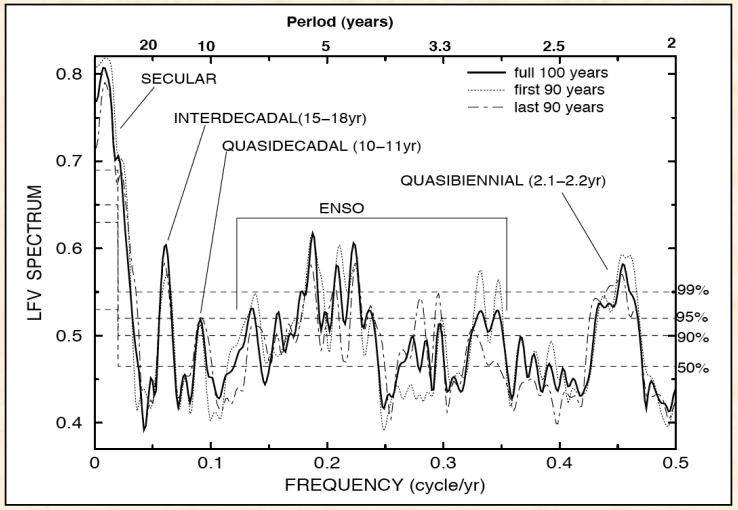
More recently, internal climate modes have been recognized as probably the most important contributors to DCV



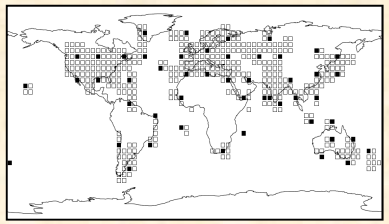
After: http://www.ncdc.noaa.gov/paleo/ctl/about1.html

- **El Niño/Southern Oscillation (ENSO) -- 2-7 yrs (+ LF modes)**
- **North Atlantic Oscillation (NAO) -- 7-8 yrs (+ LF modes)**
- **Pacific Decadal Oscillation (PDO) -- 20-40 yrs**
- **Atlantic Multidecadal Oscillation (AMO) -- 60-80 yrs**
- **NAM, SAM, and the modes goes on . . .**

Global-scale oscillatory modes of temperature variability (1891-1990) have also been identified using MTM-SVD spatiotemporal analysis

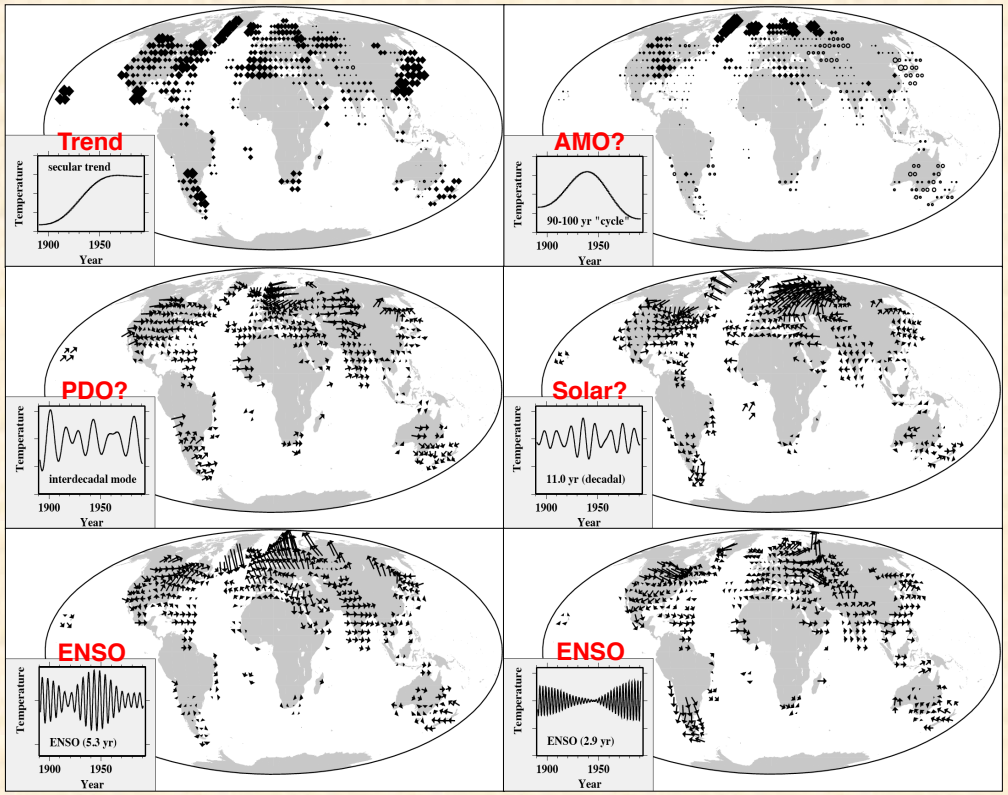


Mann, M.E. and J. Park. 1994. Global-scale modes of surface temperature variability on interannual to century timescales. *JGR* 99:25,819-25,833.



Mann, M.E. and J. Park. 1999. Oscillatory spatiotemporal signal detection in climate studies: a multiple-taper spectral domain approach. *Advances in Geophysics* 41.

Band-limited phase-coherent modes of temperature variability
(Mann & Park, 1994)



Some comments now

- There appears to be little doubt that some form of **band-limited DCV** exists in **instrumental climate records**. The sources of this oscillatory variability are not always clear. ENSO, NAO, PDO, AMO, etc. forcing is highly likely, maybe even SOLAR too, punctuated by volcanic forcing
- The question now is *"Is this apparent oscillatory variability just a **short-term** expression of stochastic (e.g., red noise or low-order ARMA) variability that arose mostly by chance in the mostly 20th century instrumental observations?"* (the previous ***null hypothesis***)
- Or *"Is this apparent oscillatory variability indicative of **long-term band-limited** forcing of the coupled climate system?"* (a generic ***alternate hypothesis***)
- At **DCV** time scales, like those associated with the **PDO** and **AMO**, it is **extremely difficult** to tell which hypothesis is more likely to be correct given the relatively short instrumental records . . . and theory is that not much help either.
- This puts us in an uncomfortable situation described by Wright (1971) as "**Two Rules of Climate Change**."

Two Rules of Climate Change

Wright, P.B. 1971. Quasi-biennial oscillations in the atmosphere. ***Weather*** 26:69-76.

1. ***"Some feature of the atmosphere can always be found that will oscillate in accordance with your hypothesis."***
2. ***"Shortly after its discovery the oscillation will disappear."***

To investigate the ***longer-term*** existence of oscillatory DCV climate modes

1. We need ***longer records*** of the climate modes thought to be responsible for Dec-Cen climate variability.
2. Annually resolved, exactly dated, ***tree-ring reconstructions*** of climate modes (ENSO, PDO, NAO, AMO) can be used to determine if oscillatory variability seen in the instrumental climate records occurred in the past.
3. ***Null hypothesis***: *Band-limited variability exists in the observations by chance alone due to internal stochastic forcing in the coupled climate system and should not be expected to have persisted over time.*

   The disappearance of observed oscillatory behavior in the long climate mode reconstructions would support this ***null hypothesis***.
4. ***Alternate hypothesis***: *Observed band-limited variability persists back in time in the reconstructions in ways that suggest some form of intrinsic or extrinsic quasi-periodic forcing that is not easily explained by simple stochastic forcing.*

   The presence of such oscillatory behavior in long climate mode reconstructions would support this ***alternate hypothesis***.

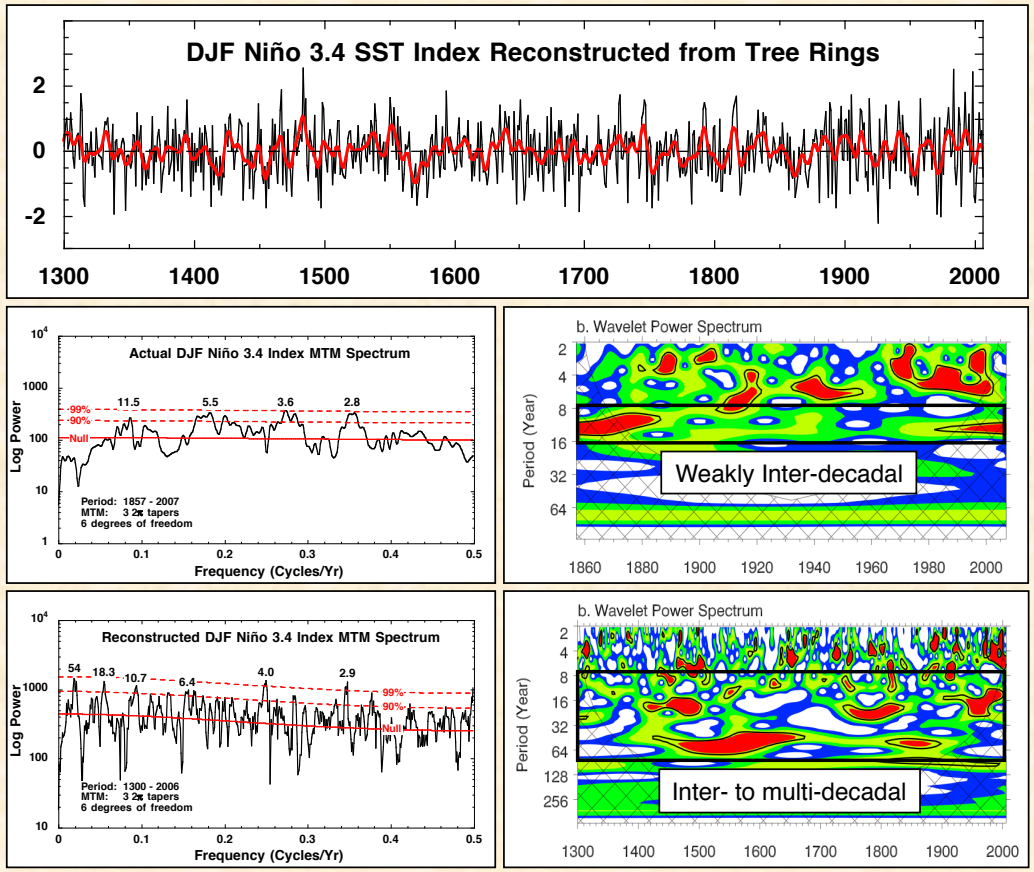
Six climate mode reconstructions by tree rings will be examined for existence of long-term oscillatory behavior

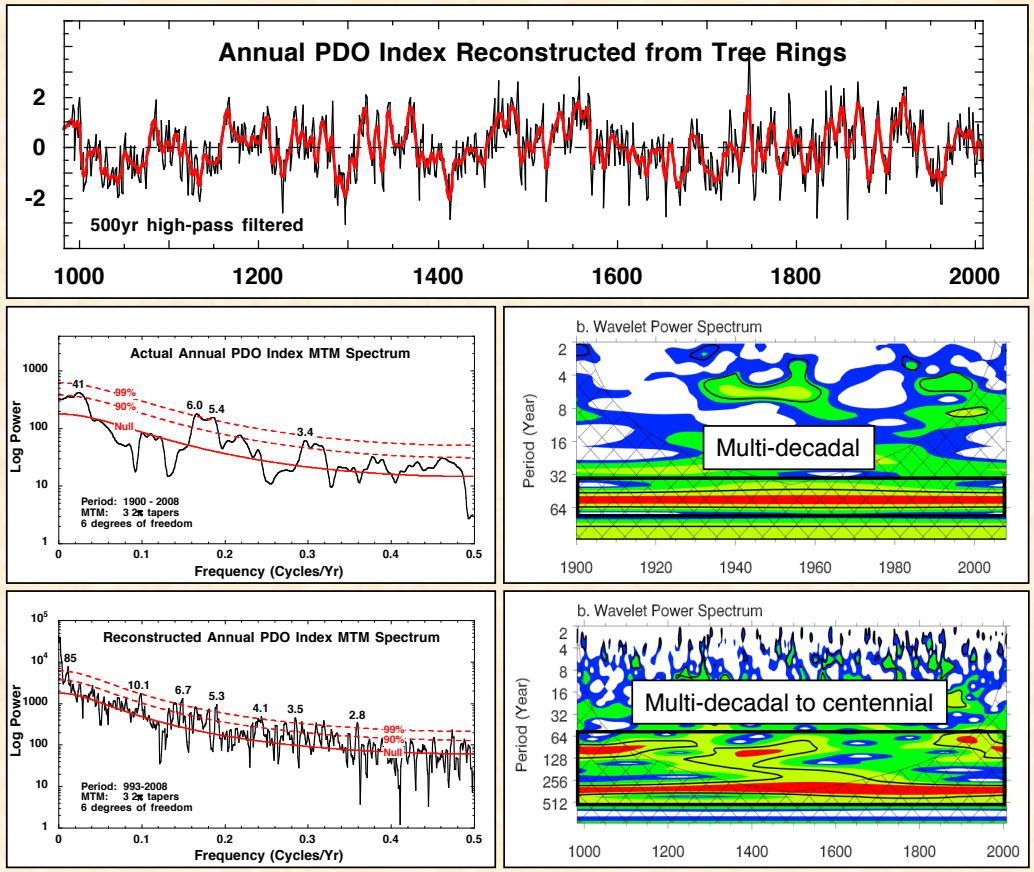
1. **Dec-Feb ENSO Niño 3.4 SST Reconstruction - A.D. 1300-2006 -** Cook et al. 2008. ENSO reconstructions from long tree-ring chronologies: Unifying the differences? Contributed talk presented at a special workshop on "Reconciling ENSO Chronologies for the Past 500 Years", held in Moorea, French Polynesia on April 2-3, 2008.
2. **Annual PDO reconstruction - A.D. 993-1996 -** MacDonald and Case. 2005. Variations in the Pacific Decadal Oscillation over the past millennium. *Geophysical Research Letters* 32, L08703, doi:10.1029/2005GL022478.
3. **Apr-Aug PDO reconstruction - A.D. 1479-2001 -** Cook. 2002. Reconstructions of Pacific decadal variability from long tree-ring records. Invited talk (GC42A-04) presented at Special Session GC 1600: "Pacific Decadal Variability", Spring AGU, N. Mantua and E. Sarachik (conveners).
4. **Dec-Mar NAO reconstruction - A.D. 1400-2008 -** Cook et al. 2002. A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation index since A.D. 1400. *Journal of Climate* 15:1754-1764.
5. **Annual AMO reconstruction - A.D. 1567-2008 -** Gray et al. 2004. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. *Geophysical Research Letters* 31, L12205, doi:10.1029/2004GL019932.
6. **Jun-Aug NAM (AO) SLP reconstruction - A.D. 1650-2007** - D'Arrigo et al. 2003. Tree-ring reconstructions of temperature and sea-level pressure variability associated with the warm-season Arctic Oscillation since AD 1650. *Geophysical Research Letters* 30, 1549,doi: 10.1029/2003GL017250.

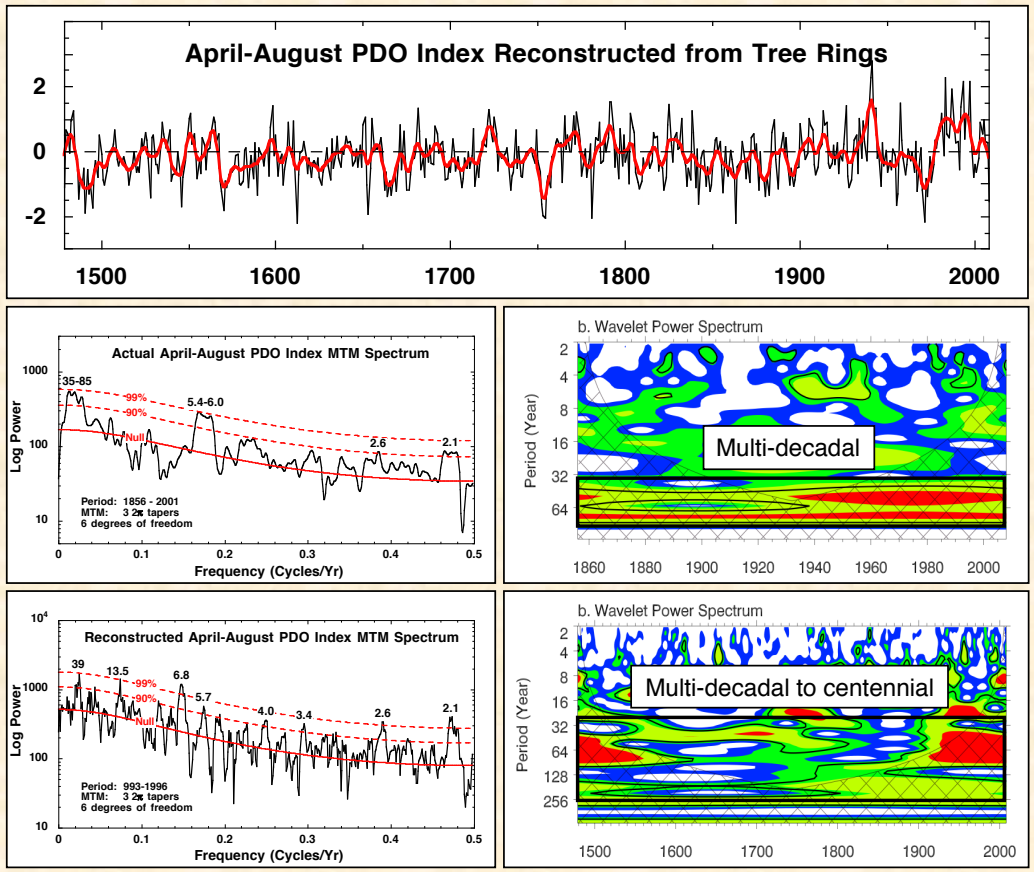
This list is illustrative, not comprehensive.

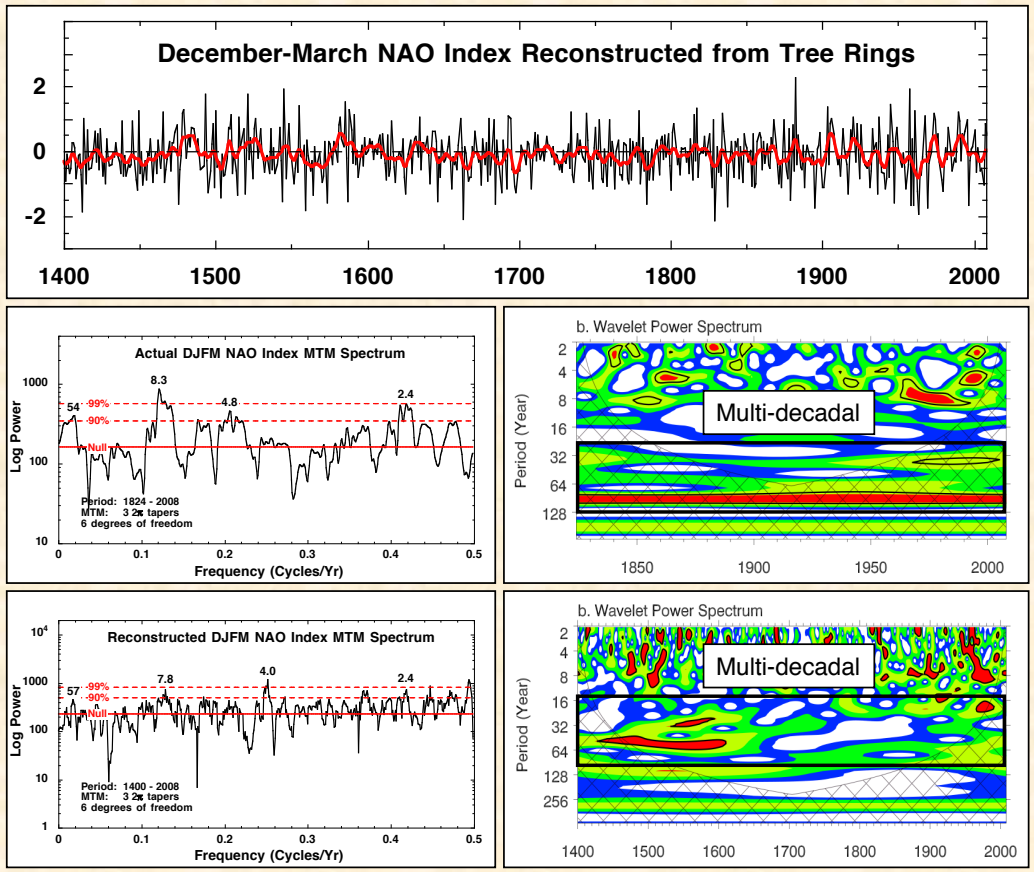
Methods of analysis

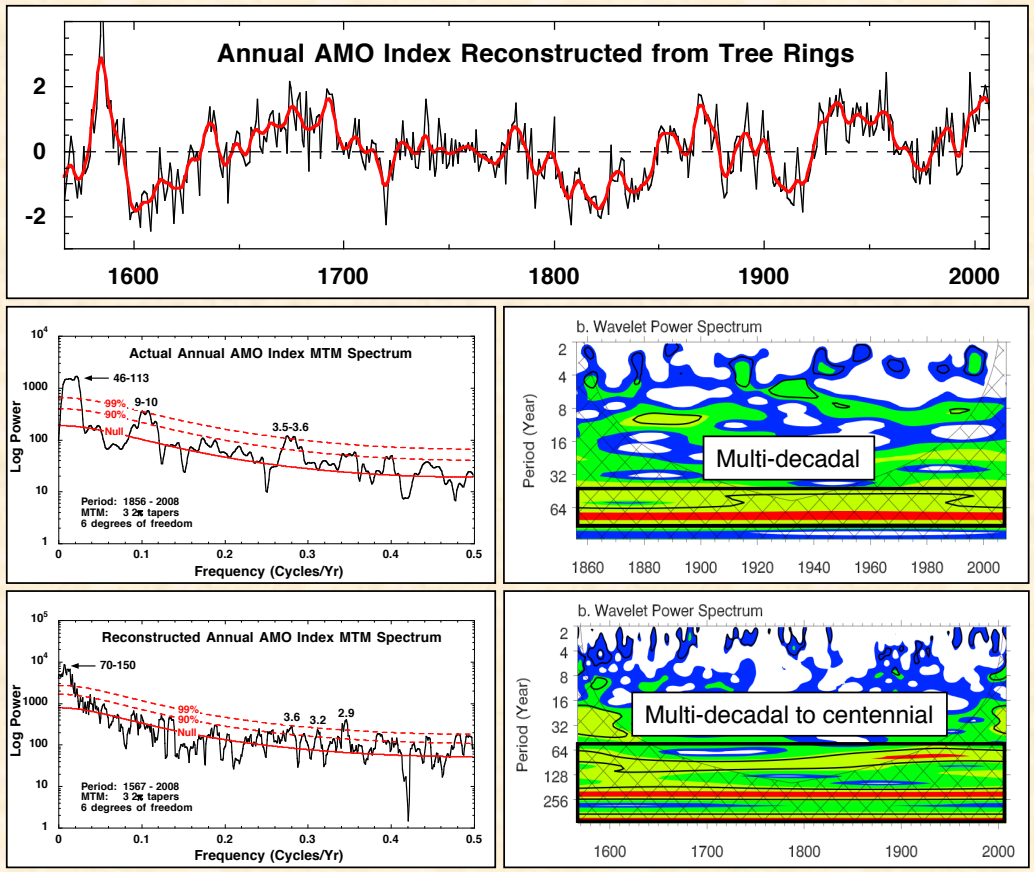
- Spectral analyses of the actual and reconstructed climate modes will be conducted using **multi-taper (MTM) and wavelet methods** to describe the band-limited properties of the data.
- Significance tests of spectral peaks will be based on ***a priori* probabilities** and a **red noise null continuum** model (see Gilman et al. 1963. "On the power spectrum of red noise", *JAS* 20; Mann & Lees. 1996. "Robust estimation of background noise and signal detection in climate time series", *Climatic Change* 33).
- The **superior leakage resistance and consistency** of **MTM** over other methods of spectral analysis will provide robust tests of the overall presence of band-limited variability.
- The **wavelet spectrum** (Torrence and Campo. 1998. "A practical guide to wavelet analysis", *BAMS* 79) will reveal the degree to which the band-limited variability in the actual data is present back in time in the reconstructions.

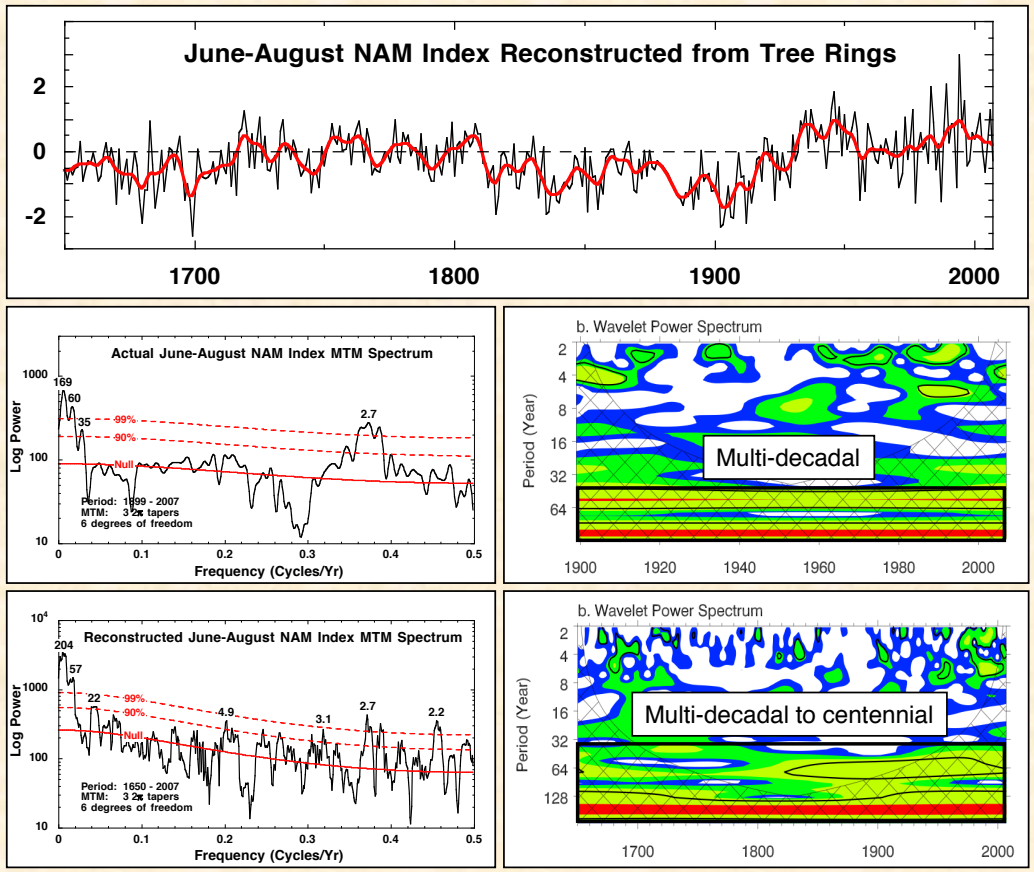

DJF Niño 3.4 SST Index Reconstructed from Tree Rings
2
0
-2
1300
1400
1500
1600
1700
1800
1900
2000
Actual DJF Niño 3.4 Index MTM Spectrum
Log Power
Frequency (Cycles/Yr)
11.5
5.5
3.6
2.8
99%
90%
Null
Period: 1857 - 2007
MTM: 3 2π tapers
6 degrees of freedom
b. Wavelet Power Spectrum
Period (Year)
Weakly Inter-decadal
Reconstructed DJF Niño 3.4 Index MTM Spectrum
54
18.3
10.7
6.4
4.0
2.9
Period: 1300 - 2006
MTM: 3 2π tapers
6 degrees of freedom
Inter- to multi-decadal


Annual PDO Index Reconstructed from Tree Rings
2
0
-2
500yr high-pass filtered
1000
1200
1400
1600
1800
2000
Actual Annual PDO Index MTM Spectrum
Log Power
41
99%
90%
Null
6.0
5.4
3.4
Period: 1900 - 2008
MTM: 3 2π tapers
6 degrees of freedom
Frequency (Cycles/Yr)
b. Wavelet Power Spectrum
Period (Year)
Multi-decadal
Reconstructed Annual PDO Index MTM Spectrum
85
10.1
6.7
5.3
4.1
3.5
2.8
Period: 993-2008
MTM: 3 2π tapers
6 degrees of freedom
Multi-decadal to centennial


April-August PDO Index Reconstructed from Tree Rings
2
0
-2
1500
1600
1700
1800
1900
2000
Actual April-August PDO Index MTM Spectrum
Log Power
1000
100
10
35-85
-99%
-90%
5.4-6.0
Null
2.6
2.1
Period: 1856 - 2001
MTM: 3 2π tapers
6 degrees of freedom
0
0.1
0.2
0.3
0.4
0.5
Frequency (Cycles/Yr)
b. Wavelet Power Spectrum
Period (Year)
2
4
8
16
32
64
Multi-decadal
1860
1880
1900
1920
1940
1960
1980
2000
Reconstructed April-August PDO Index MTM Spectrum
10⁴
1000
100
10
39
13.5
-99%
-90%
6.8
5.7
4.0
3.4
Null
2.6
2.1
Period: 993-1996
MTM: 3 2π tapers
6 degrees of freedom
Frequency (Cycles/Yr)
b. Wavelet Power Spectrum
Period (Year)
2
4
8
16
32
64
128
256
Multi-decadal to centennial
1500
1600
1700
1800
1900
2000


December-March NAO Index Reconstructed from Tree Rings
2
0
-2
1400
1500
1600
1700
1800
1900
2000
Actual DJFM NAO Index MTM Spectrum
Log Power
1000
100
10
8.3
4.8
2.4
54
99%
90%
Null
Period: 1824 - 2008
MTM: 3 2π tapers
6 degrees of freedom
0
0.1
0.2
0.3
0.4
0.5
Frequency (Cycles/Yr)
b. Wavelet Power Spectrum
Period (Year)
2
4
8
16
32
64
128
Multi-decadal
1850
1900
1950
2000
Reconstructed DJFM NAO Index MTM Spectrum
Log Power
10^4
1000
100
10
1
7.8
4.0
2.4
57
99%
90%
Null
Period: 1400 - 2008
MTM: 3 2π tapers
6 degrees of freedom
0
0.1
0.2
0.3
0.4
0.5
Frequency (Cycles/Yr)
b. Wavelet Power Spectrum
Period (Year)
2
4
8
16
32
64
128
256
Multi-decadal
1400
1500
1600
1700
1800
1900
2000

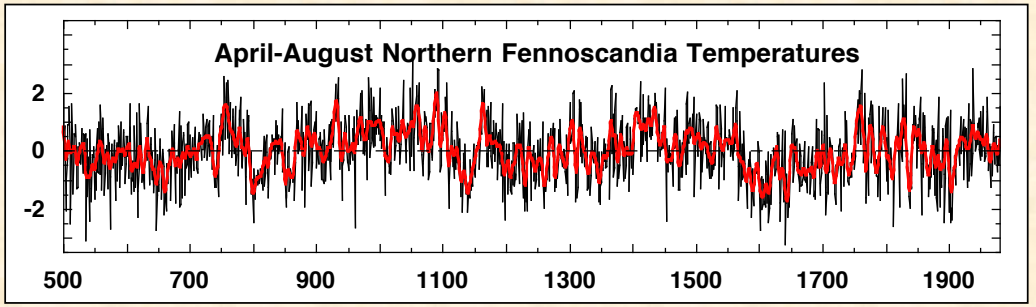

Annual AMO Index Reconstructed from Tree Rings
2
0
-2
1600
1700
1800
1900
2000
Actual Annual AMO Index MTM Spectrum
46-113
9-10
3.5-3.6
99%
90%
Null
Period: 1856 - 2008
MTM: 3 2π tapers
6 degrees of freedom
Log Power
Frequency (Cycles/Yr)
b. Wavelet Power Spectrum
Period (Year)
Multi-decadal
Reconstructed Annual AMO Index MTM Spectrum
70-150
3.6
3.2
2.9
Period: 1567 - 2008
MTM: 3 2π tapers
6 degrees of freedom
Multi-decadal to centennial

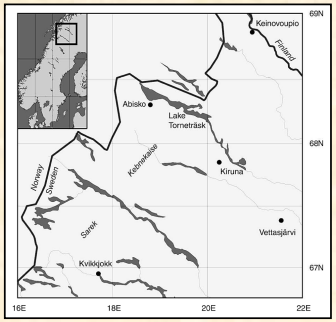

June-August NAM Index Reconstructed from Tree Rings
2
0
-2
1700
1800
1900
2000
Actual June-August NAM Index MTM Spectrum
Log Power
1000
100
10
169
60
35
99%
90%
Null
2.7
Period: 1699 - 2007
MTM: 3 2π tapers
6 degrees of freedom
0
0.1
0.2
0.3
0.4
0.5
Frequency (Cycles/Yr)
b. Wavelet Power Spectrum
Period (Year)
2
4
8
16
32
64
Multi-decadal
1900
1920
1940
1960
1980
2000
Reconstructed June-August NAM Index MTM Spectrum
Log Power
10^4
1000
100
10
204
57
22
99%
90%
Null
4.9
3.1
2.7
2.2
Period: 1650 - 2007
MTM: 3 2π tapers
6 degrees of freedom
0
0.1
0.2
0.3
0.4
0.5
Frequency (Cycles/Yr)
b. Wavelet Power Spectrum
Period (Year)
2
4
8
16
32
64
128
Multi-decadal to centennial
1700
1800
1900
2000

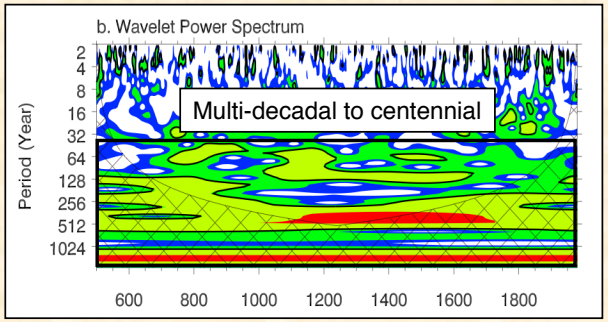
Results from spectral analyses

- All of the reconstructed climate modes have various degrees of band-limited **DCV** that **intermittently persists over time**.
- This variability commonly falls in the general **30-100 year band**.
- The December-March NAO reconstruction has the **weakest expression** of long-term band-limited **multi-decadal** variability.
- The PDO, AMO, and NAM reconstructions all show the **long-term presence** of band-limited **multi-decadal** variability, but much of it resides in the **"cone of influence"** of the wavelet spectrum.
- None of the climate mode reconstructions are really long enough to describe band-limited **centennial time scale variability** in a statistically robust way.
- For that I will use a 1,481 year long **April-August temperature reconstruction** from northern Sweden where climate should be influenced by the **AMO** and **NAM**.
- This is followed by a 1,276 year long **January-September temperature reconstruction** for the Gulf of Alaska that may have a connection to the **PDO**.

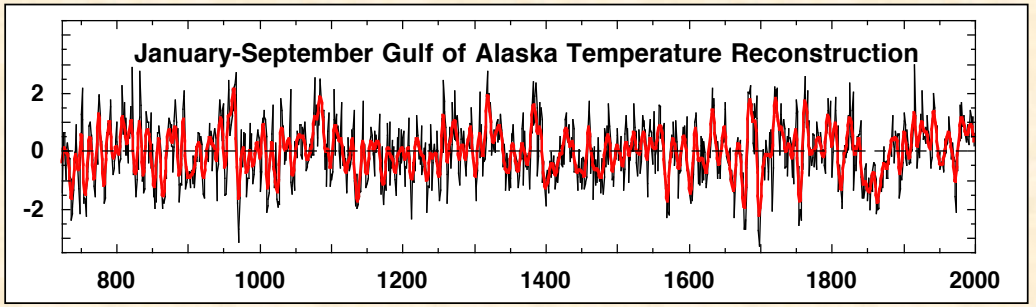
Briffa et al. 1992. "Fennoscandian summers from AD 500: temperature changes on short and long timescales", *Climate Dynamics* 7:111-119.

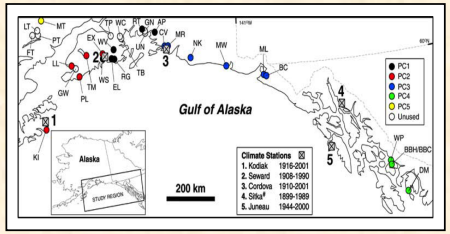


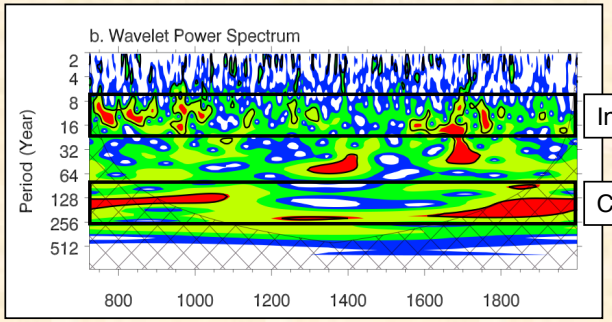




Wilson et al. 2007. "Cycles and shifts: 1,300 years of multi-decadal temperature variability in the Gulf of Alaska", *Climate Dynamics* 28:425-440.







Inter-decadal

Centennial

Some more comments now

- From the spectral analyses of the **climate mode reconstructions** and two very long **temperature reconstructions**, **intermittent band-limited DCV** appears to be a **common feature** over the past several centuries to millennium or more in the past.
- It does not appear to be a **transient phenomenon** restricted just to the 20th century. Wright's **"Two Rules of Climate Change"** does not apply in a strict sense. Rather, **DCV** oscillations appear to come and go over time in an **amplitude modulated** way.
- A preferred **DCV** band is difficult to define, but it often occurs in the **30-100 year** band. **PDO** and **AMO** forcing?
- Variability at **centennial time scales** is present in some of the reconstructions, but it is far **less robustly** identified due to the limited lengths of some reconstructions.
- These results allow for **internal stochastic forcing** to be the cause of **DCV**. However, the band-limited nature of the variability does not easily admit a simple **red noise** process as an explanation. Rather, the power spectra suggest a **mixture** of low-order ARMA forcing (with complex roots?) and other band-limited forcing.
- These results still permit the possibility that there could be an **external rhythmic forcing** of climate (e.g. by solar) that contributes to **DCV**.

Improving Our Understanding of Causes of DCV

- The development of spatial climate reconstructions from tree rings provides a vehicle for better understanding the properties and causes of DCV – an example here from three independent drought atlases

NADA

Long-Term Aridity Changes in the Western United States

Science 2004

MADA

Asian Monsoon Failure and Megadrought During the Last Millennium

Science 2010

OWDA

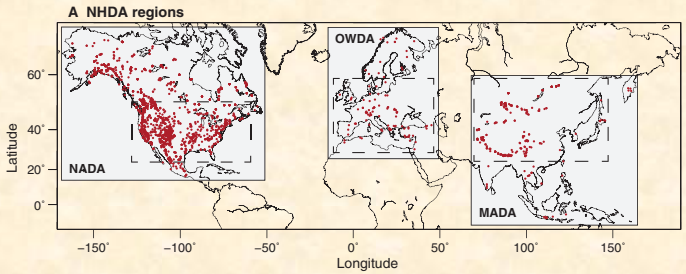
RESEARCH ARTICLE

CLIMATOLOGY

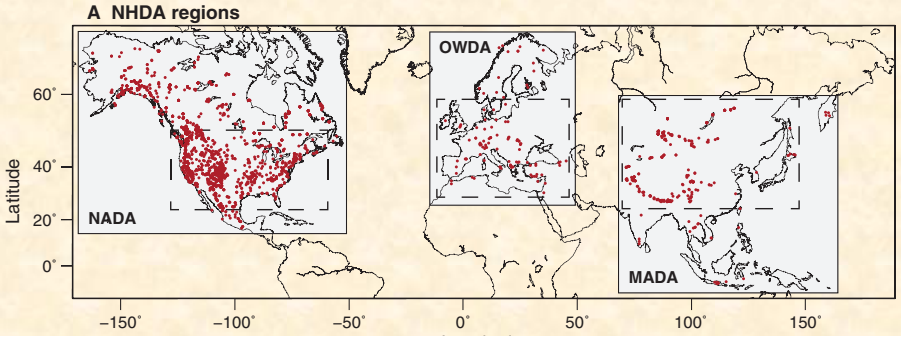
Old World megadroughts and pluvials during the Common Era

10.1126/sciadv.1500561

Science Advances 2015



Improving Our Understanding of Causes of DCV



Note the anti-phased behavior between drought atlases that persists over time.

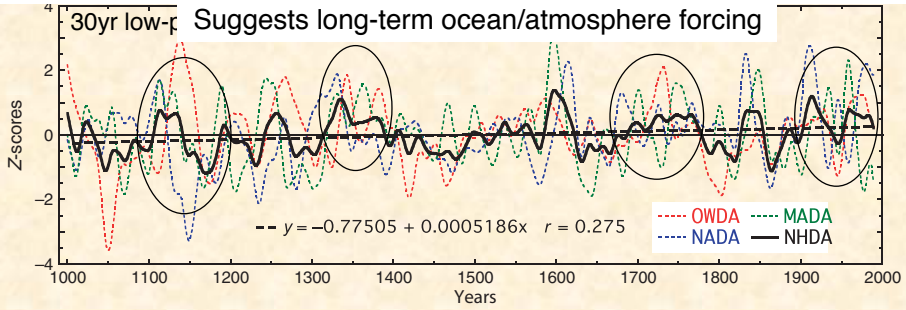


Figure from Cook et al. 2015. Science Advances.

Here is an example from the drought atlases: The hemispheric pattern of continential hydroclimatic variability during the Puebloan Great Drought period implies large-scale oceanic forcing as the cause

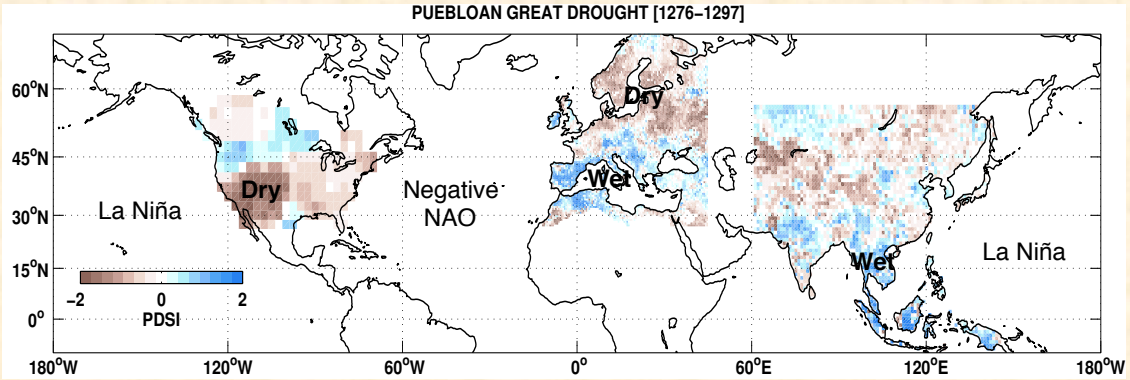
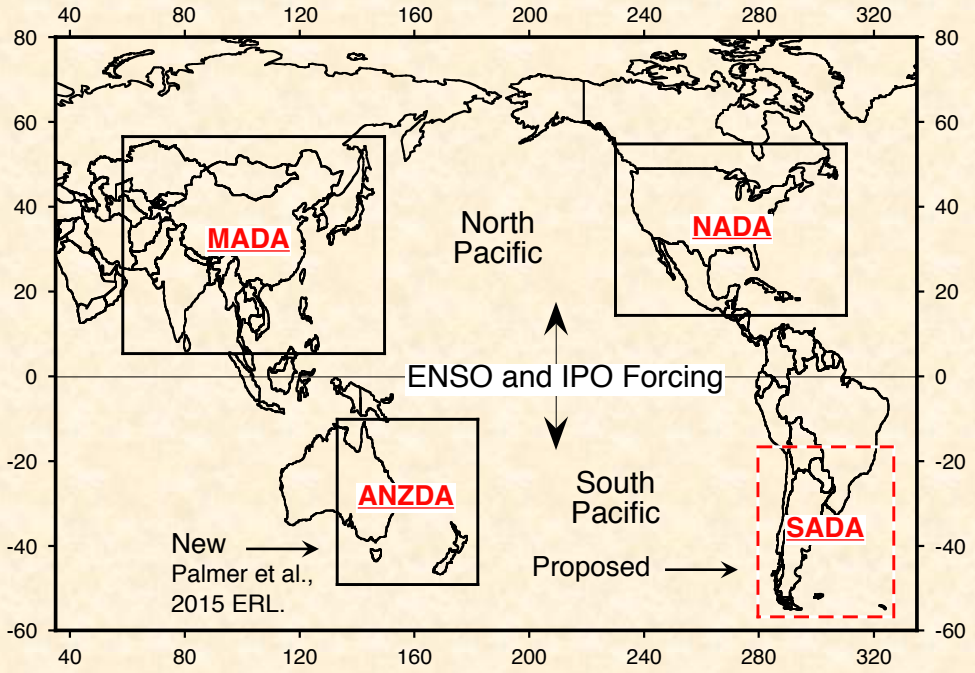


Figure courtesy of Kevin Anchukaitis

See also Coats et al., 2015: Are simulated megadroughts in the North American southwest forced? *Journal of Climate* 28:124-142.

Expanding drought atlas coverage to the full Pacific Ocean rim land areas:



With this said,

- **“I am finished!”** (The last line in the movie ***There Will Be Blood***.)