

The Role of Tree Ring Drought Atlases in Climate Change Research: State of the Art and Future Developments

Edward R. Cook
Tree-Ring Laboratory
Lamont-Doherty Earth Observatory
of Columbia University

PAGES2k-PMIP3: Comparing Data and Model Estimates of
Hydroclimate Variability and Change over the Common Era

Lamont-Doherty Earth Observatory
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Why Tree-Ring Drought Atlases?

We must better understand the causes of hydroclimatic variability during the **Common Era**.

Climate models project that subtropical drying is likely to occur due to greenhouse warming and this may be happening already in the American Southwest.

Changes are annual means for the period 2080–2099 relative to 1980–1999

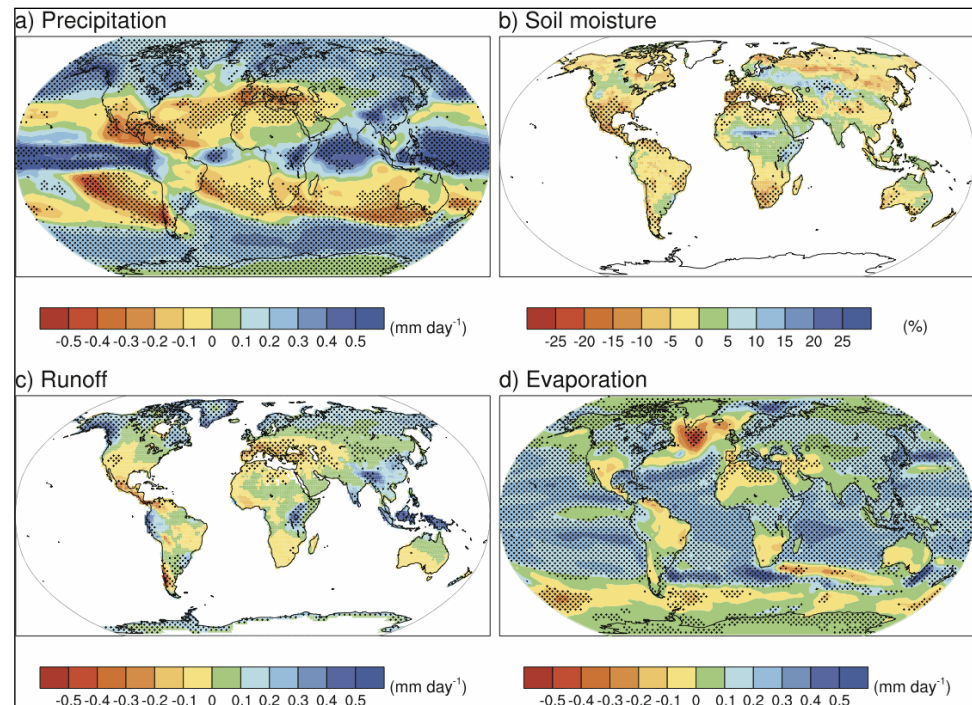
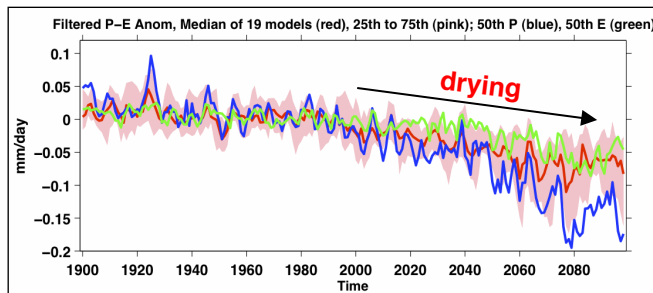


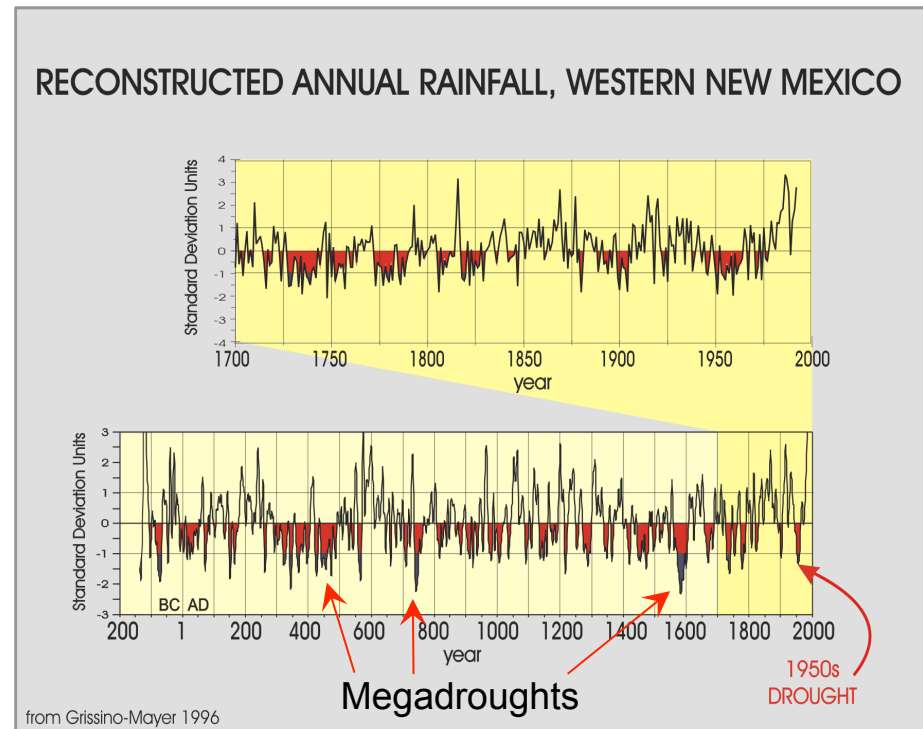
Figure courtesy of IPCC



Why Tree-Ring Drought Atlases?

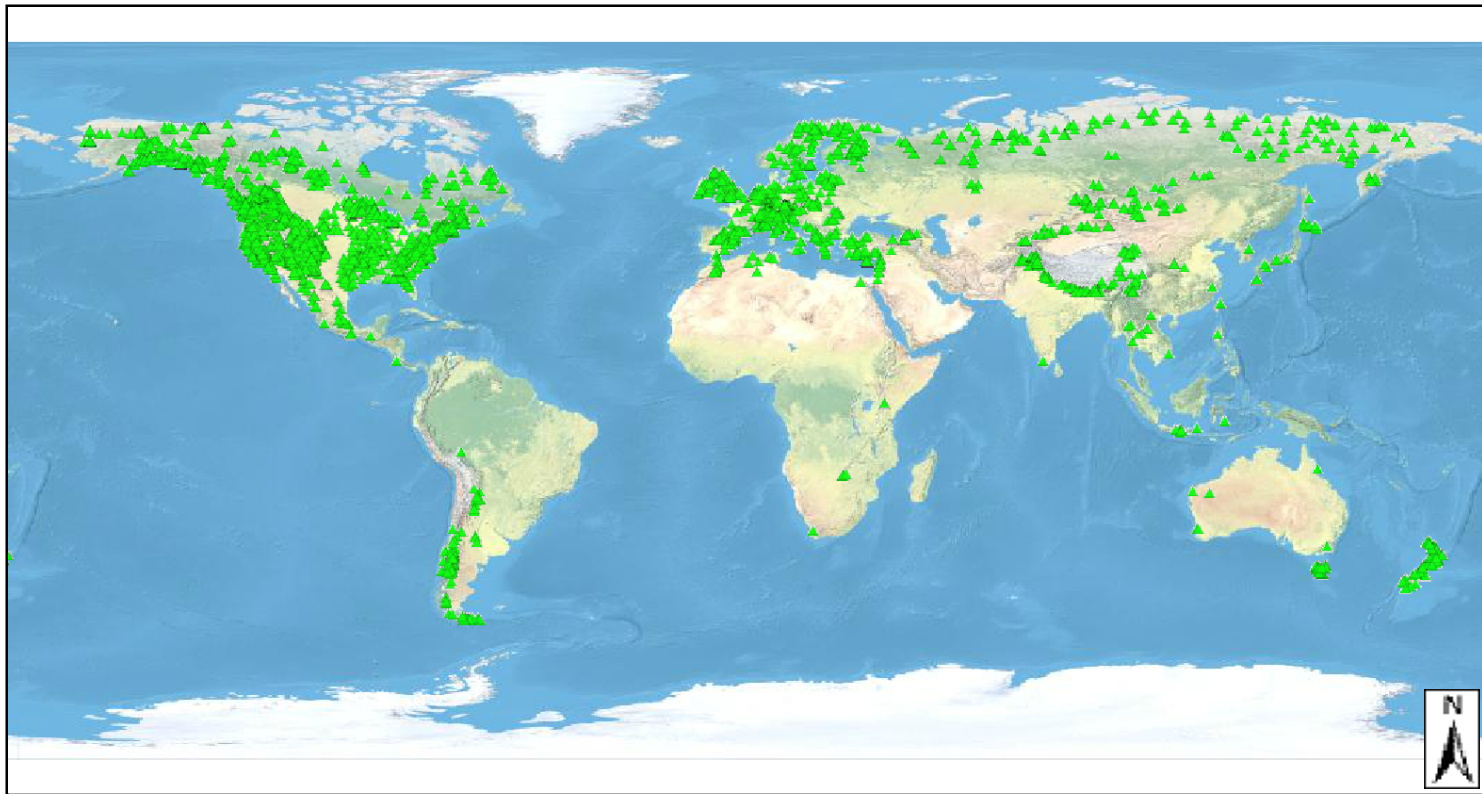
Yet, *ominously* we now know that droughts of unprecedented severity and duration occurred in the American West and elsewhere long before raising atmospheric CO₂. Thus, these past *megadroughts* must be viewed as “natural” phenomena.

Knowing how such “natural” megadroughts occurred in the pre-industrial low-CO₂ era is necessary for predicting how likely future megadroughts in the anthropocene will be.



How are Tree-Ring Drought Atlases Produced?

From the generous contributions of tree-ring data by the *global tree-ring research community* and archival support of the *NOAA International Tree-Ring Data Bank (ITRDB)*



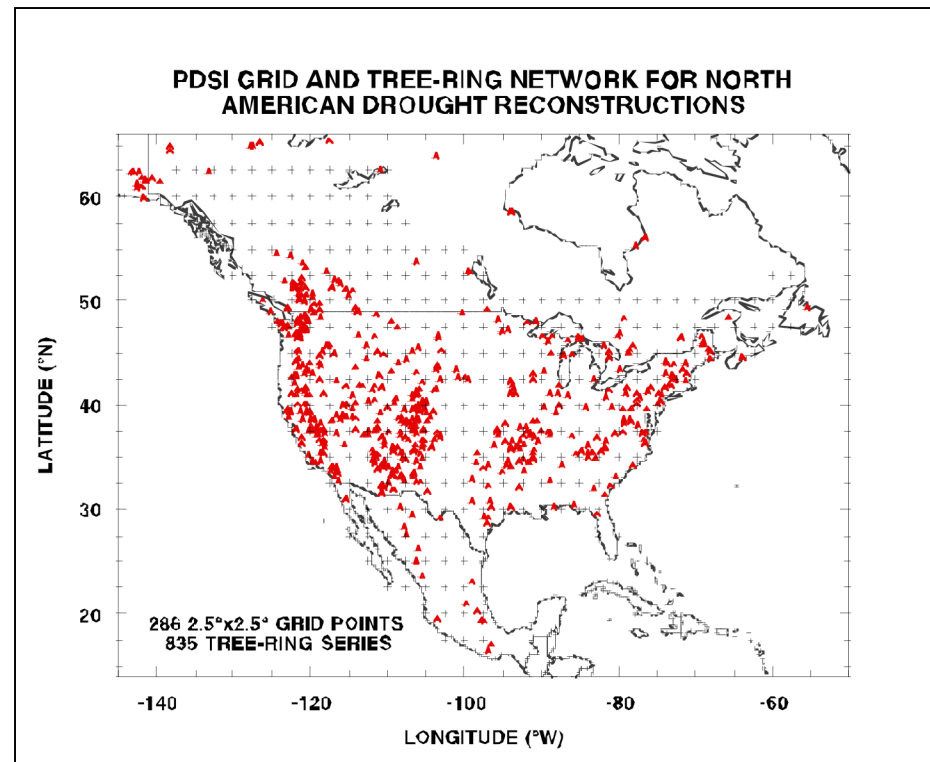
How are Tree-Ring Drought Atlases Produced?

(At least the way I do them!)

NADA Climate Grid and Tree-Ring Network

To produce *paleo-drought atlases* with the necessary spatio-temporal resolution, we use grids of instrumental drought data (e.g. *PDSI*) and networks of annual *tree-ring chronologies*.

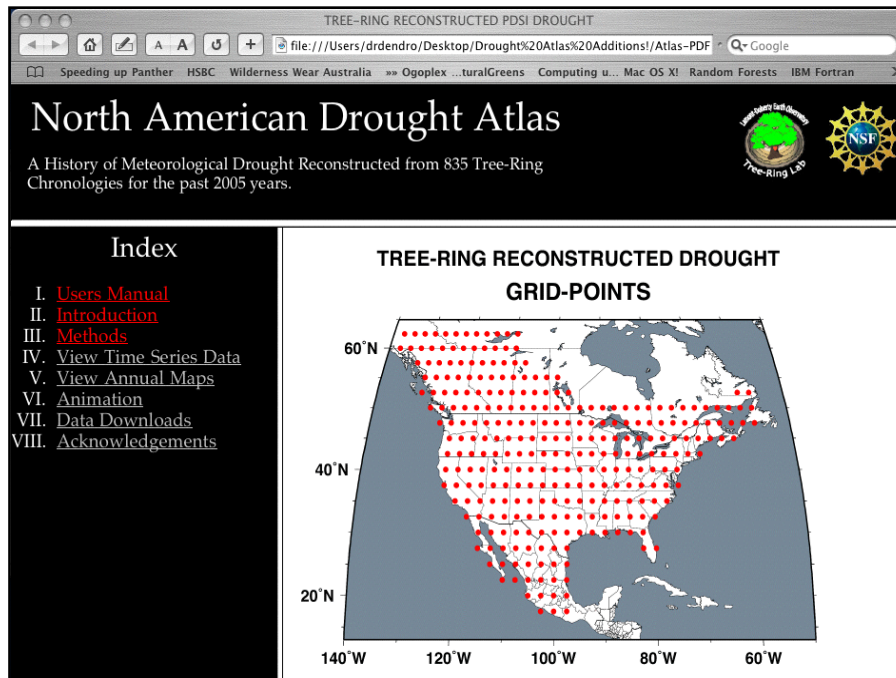
*Point-By-Point Regression** (*PPR*) is then used for reconstruction.



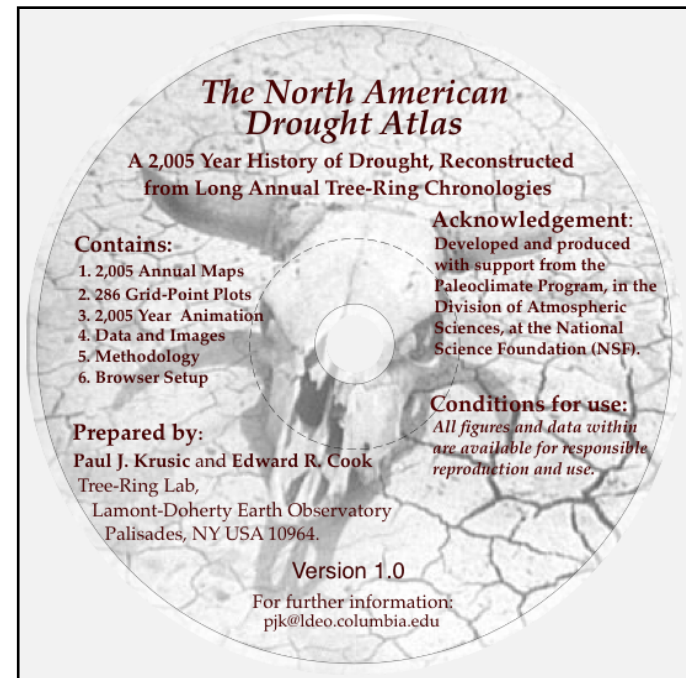
*See: Cook, E.R., Meko, D.M., Stahle, D.W., and Cleaveland, M.K. 1999. Drought reconstructions for the continental United States. *Journal of Climate* 12:1145-1162.

To this end, the *North American Drought Atlas (NADA)* was developed and released to the public in 2004

E. R. Cook, C. A. Woodhouse, C. M. Eakin, D. M. Meko, D. W. Stahle, 2004. Long-term aridity changes in the western United States. *Science* 306, 1015–1018.



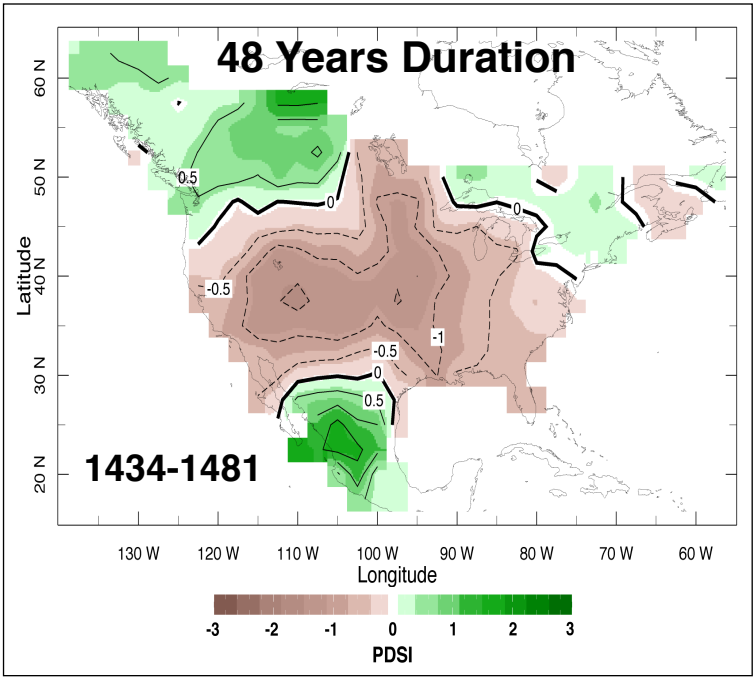
The screenshot shows a web browser window with the title "TREE-RING RECONSTRUCTED PDSI DROUGHT". The address bar shows a file path. The main content area features the title "North American Drought Atlas" and a subtitle "A History of Meteorological Drought Reconstructed from 835 Tree-Ring Chronologies for the past 2005 years." Below the title is an "Index" with links to: I. Users Manual, II. Introduction, III. Methods, IV. View Time Series Data, V. View Annual Maps, VI. Animation, VII. Data Downloads, and VIII. Acknowledgements. To the right of the index is a map of North America titled "TREE-RING RECONSTRUCTED DROUGHT GRID-POINTS" showing a grid of red dots across the continent. The map includes latitude and longitude markers (20°N to 60°N and 140°W to 60°W).



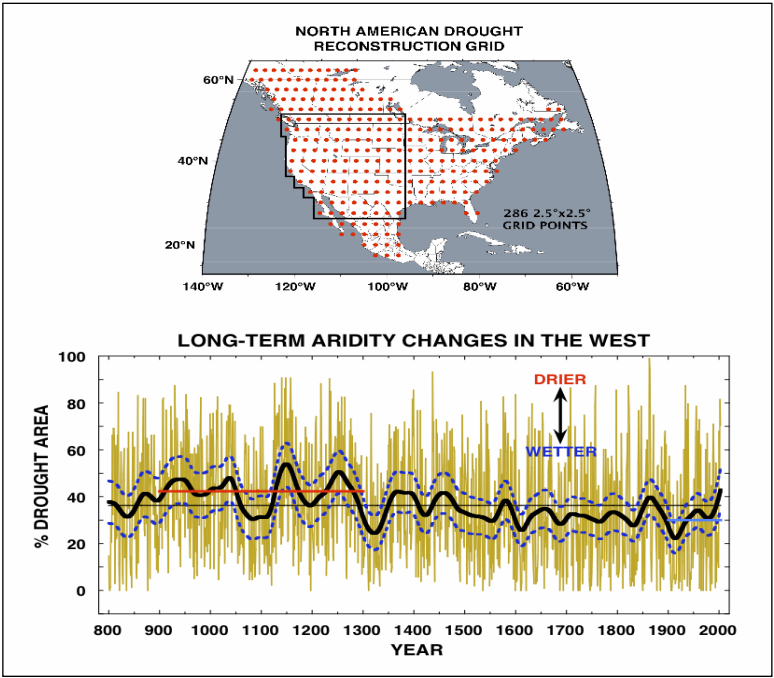
The CD-ROM cover features the title "The North American Drought Atlas" and the subtitle "A 2,005 Year History of Drought, Reconstructed from Long Annual Tree-Ring Chronologies". It lists the contents: 1. 2,005 Annual Maps, 2. 286 Grid-Point Plots, 3. 2,005 Year Animation, 4. Data and Images, 5. Methodology, and 6. Browser Setup. The cover also includes an "Acknowledgement" section, "Conditions for use" (stating that figures and data are available for responsible reproduction and use), and the preparers: Paul J. Krusic and Edward R. Cook, Tree-Ring Lab, Lamont-Doherty Earth Observatory, Palisades, NY USA 10964. The version is listed as "Version 1.0" and contact information is provided: "For further information: pjk@ldeo.columbia.edu".

What has the NADA been used for?

Documenting and Mapping Large-Scale Megadroughts



Revealing Long-Term Aridity Changes in the Western U.S. since AD 800



Adapted from Cook et al., 2004

What else has the NADA been used for?

Data For Comparing Forest Fire Histories To Past Droughts

“Multi-Millennial Fire History Of Giant Forest, Sequoia National Park, California, USA” (Swetnam et al., 2009, *Fire Ecology*)

Giant Sequoia Fire Scars

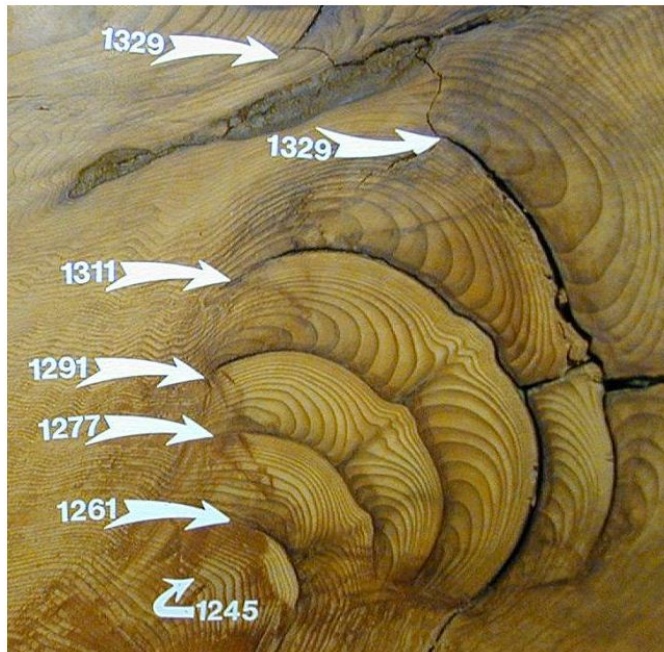
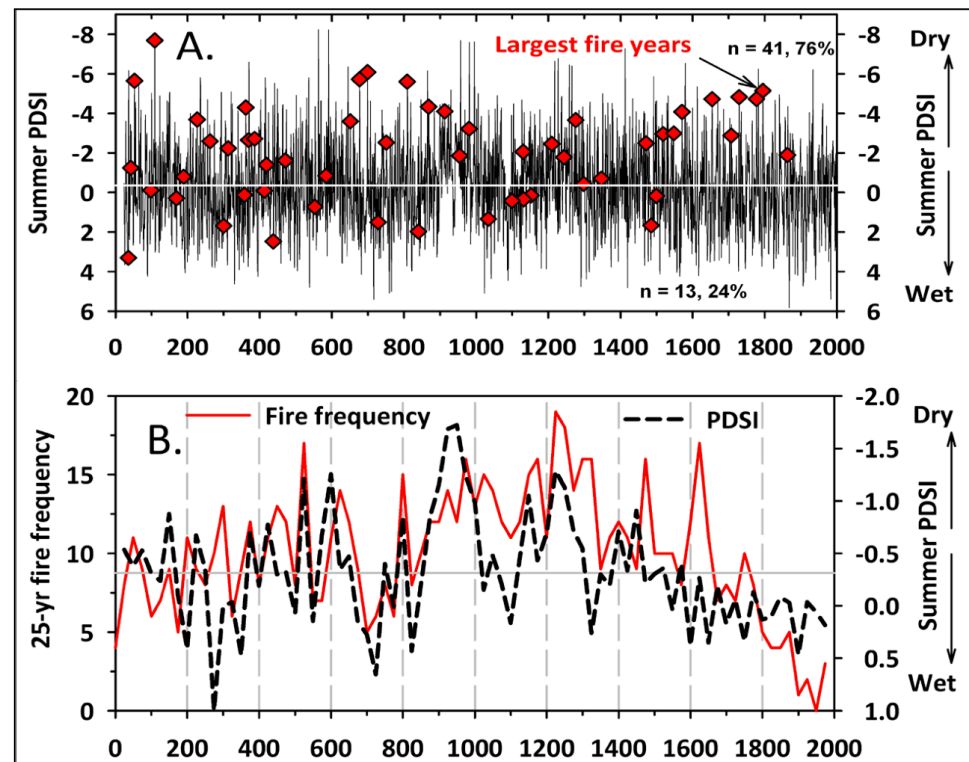


Photo Courtesy of Tom Swetnam



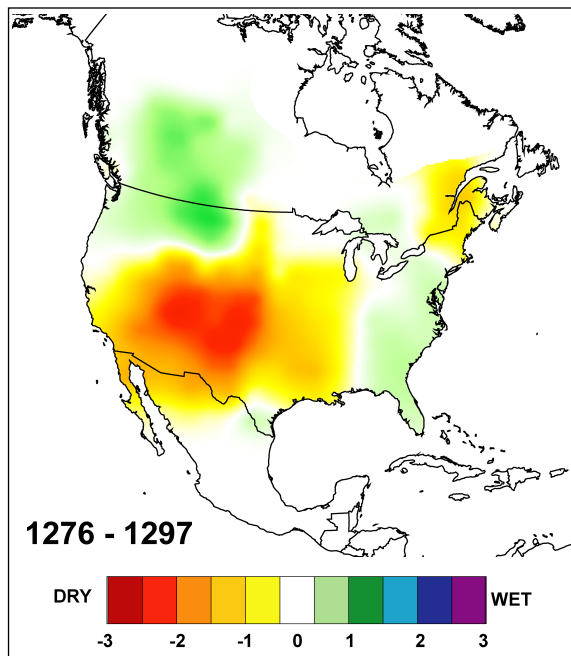
From Swetnam et al., 2009

One Last NADA Example

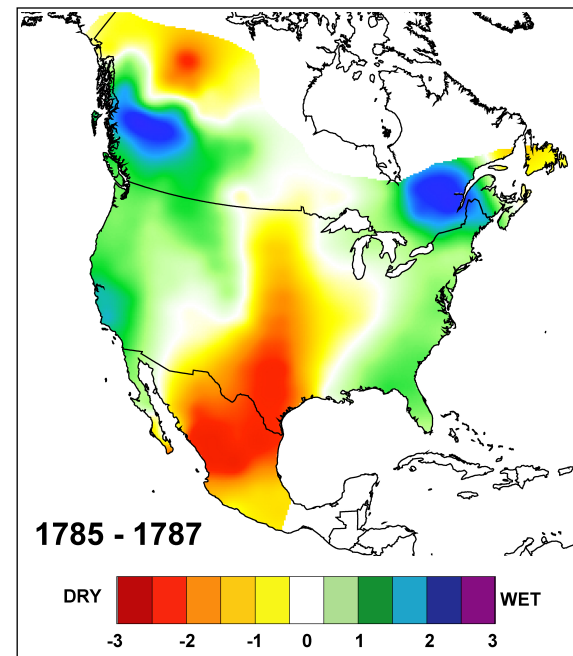
(There are many more that could be shown)

Suggested Links Between Droughts And Cultural Disasters

“Great Pueblo Drought”
Overpopulation/Overexploitation
Of Natural Resources
Social System Collapse
(Douglass, 1929)



“El Año de Hambre”
Famine and Disease Kill 300,000
“Most disastrous single event in the
history of colonial maize
agriculture” (Gibson, 1964)



Figures courtesy of David Stahle

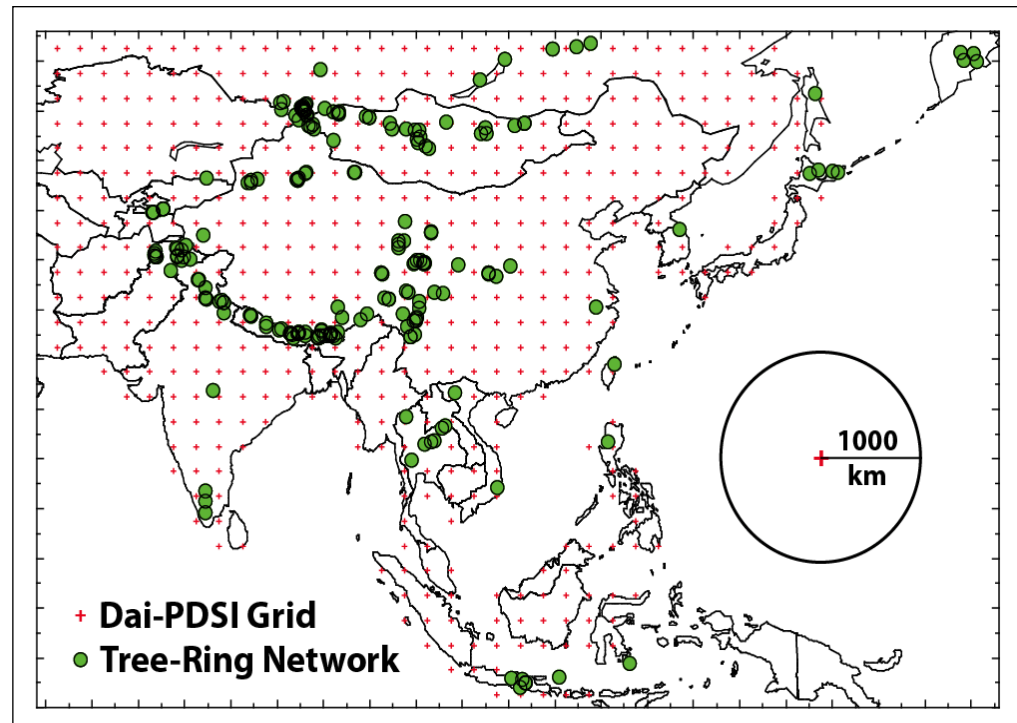
Another tree-ring drought atlas now: the *Monsoon Asia Drought Atlas (MADA)*

Cook, E.R., K.J. Anchukaitis, B.M. Buckley, R.D. D'Arrigo, G.C. Jacoby, and W.E. Wright. 2010. Asian monsoon failure and megadrought during the last millennium. *Science* 328(5977):486-489.

As with the **NADA**, a grid of instrumental **drought indices** and a network of annual **tree-ring chronologies** were used to produce the **MADA**.

An ensemble version of **Point-By-Point Regression** was used for reconstruction. See Cook et al. (2010) for details.

MADA Climate Grid and Tree-Ring Network

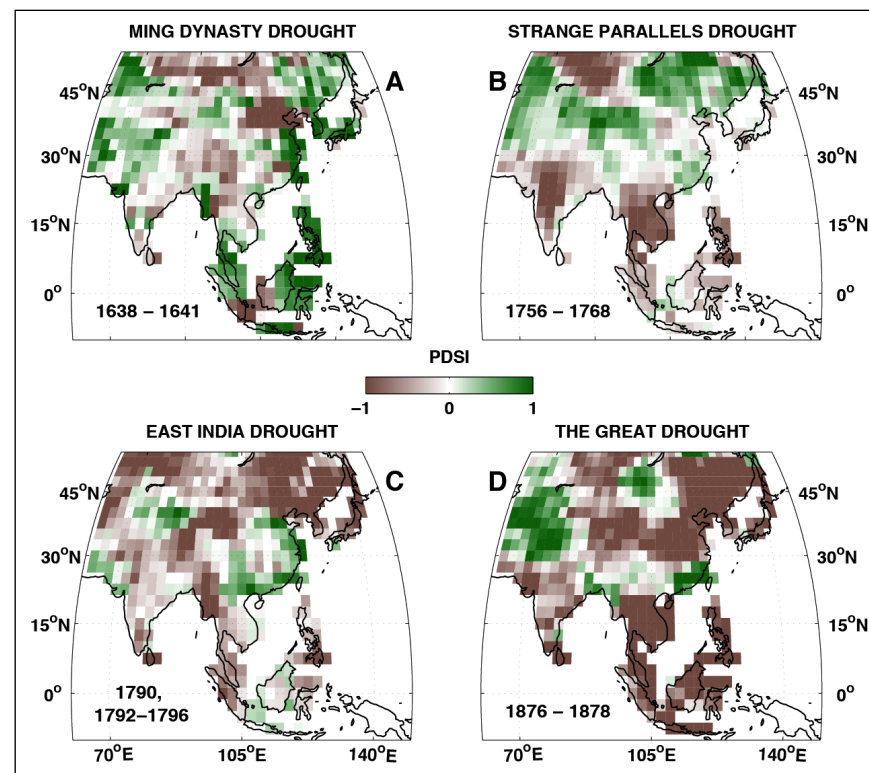


From Cook et al., 2010

What has the MADA been used for?

Mapping 'Historical' Monsoon Failures in Full Spatial Detail

“Asian Monsoon Failure and Megadrought During the Last Millennium”
(Cook et al., 2010, *Science*)



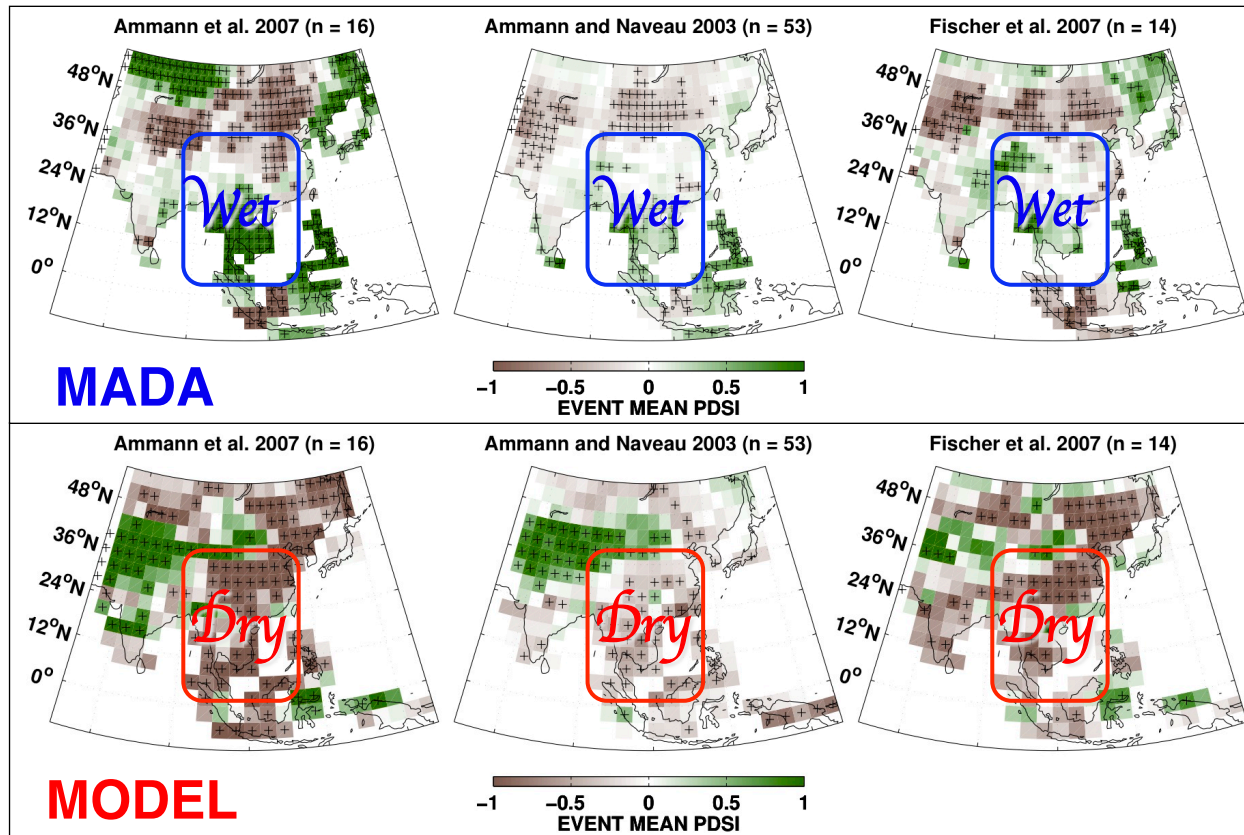
From Cook et al., 2010

Using MADA for data/model comparisons

“The Influence of Volcanic Eruptions on the Climate of the Asian Monsoon Region” (Anchukaitis et al., 2010, *Geophys. Res. Lett.*)

Superposed
Epoch
Analysis:
MADA vs.
CSM 1.4

Three
published
key year
lists.



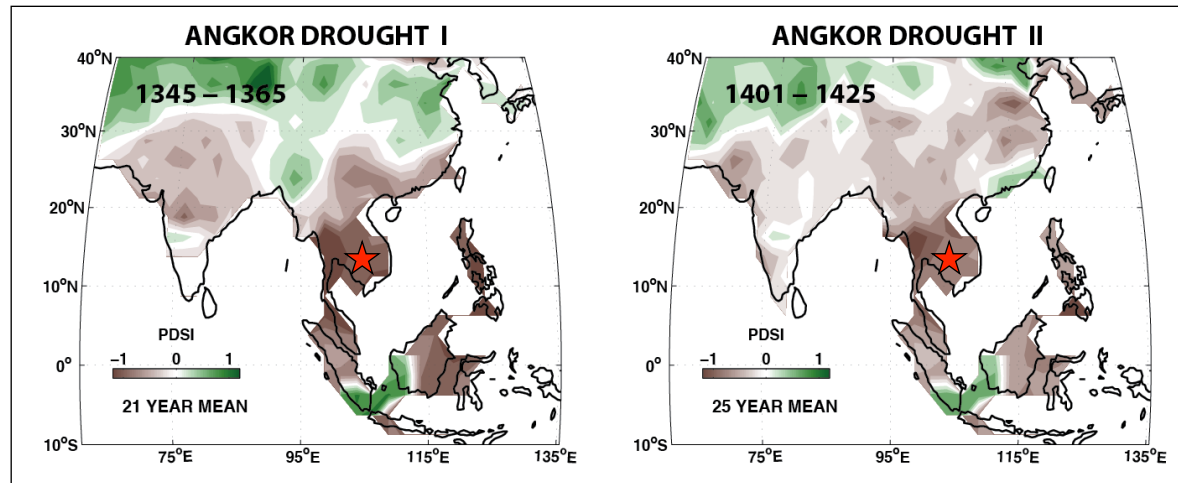
From
Anchukaitis
et al., 2010.

Almost opposite results. Who's right? I'll bet on the trees because they were there!

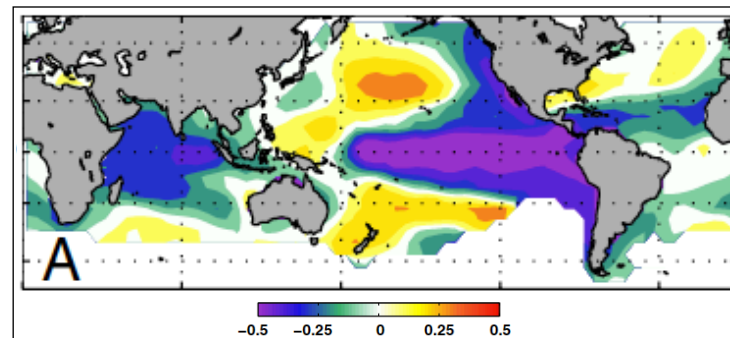
One Last MADA Example

Megadroughts and ENSO linked to cultural demise in Southeast Asia!

“Climate as a Contributing Factor in the Demise of Angkor, Cambodia” (Buckley et al., 2010, *Proc. Nat. Acad. Sci.*)



Correlations
between SE Asia
drought and SSTs



From Buckley
et al., 2010

The Scientific Impact of the NADA and MADA

-- Evidence from Citation Indices --

"Long-term aridity changes in the western United States", Science, 2004 - The NADA: **Google Scholar: 1126, Web of Science: 767**

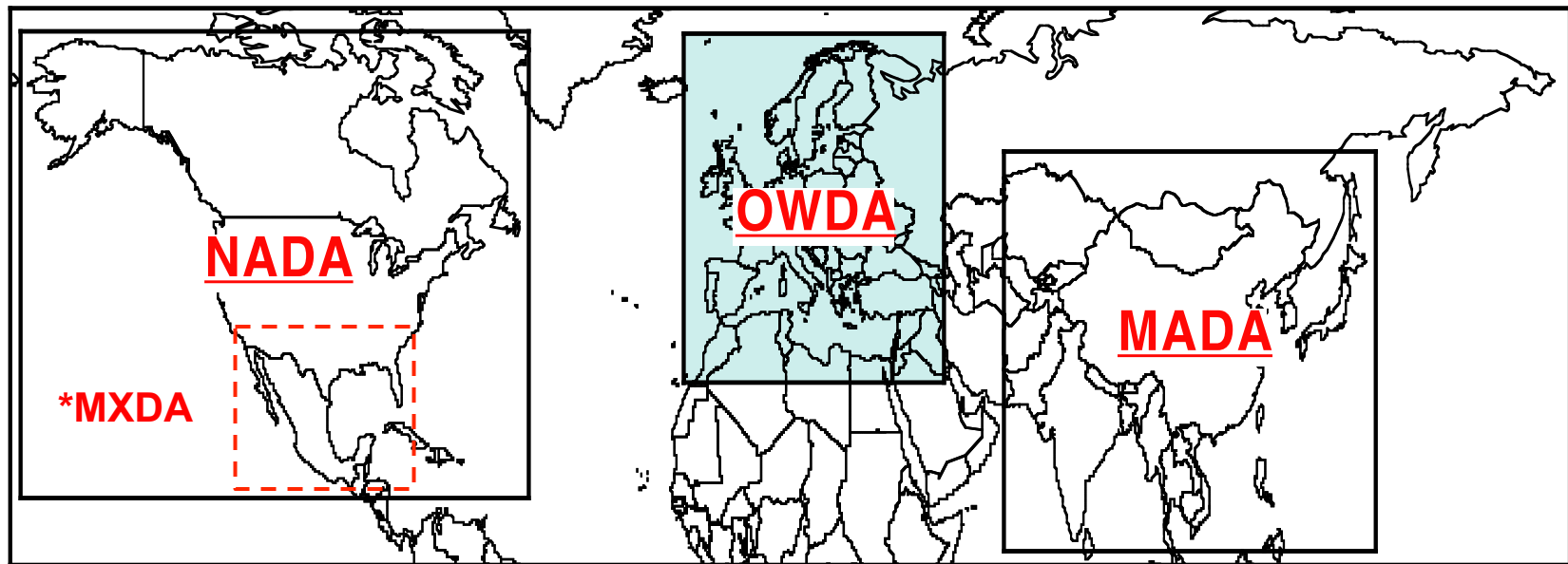
"Asian monsoon failure and megadrought during the last millennium", Science, 2010 – The MADA: **Google Scholar: 446, Web of Science: 346**

These citation indices objectively reveal the considerable scientific impact the NADA and MADA have had in general and help justify the continuing development of tree-ring drought atlases elsewhere in the world.

With this segue, here is what has happened more recently.

A 3rd NH tree-ring drought atlas has been published now: The “Old World Drought Atlas” (OWDA)

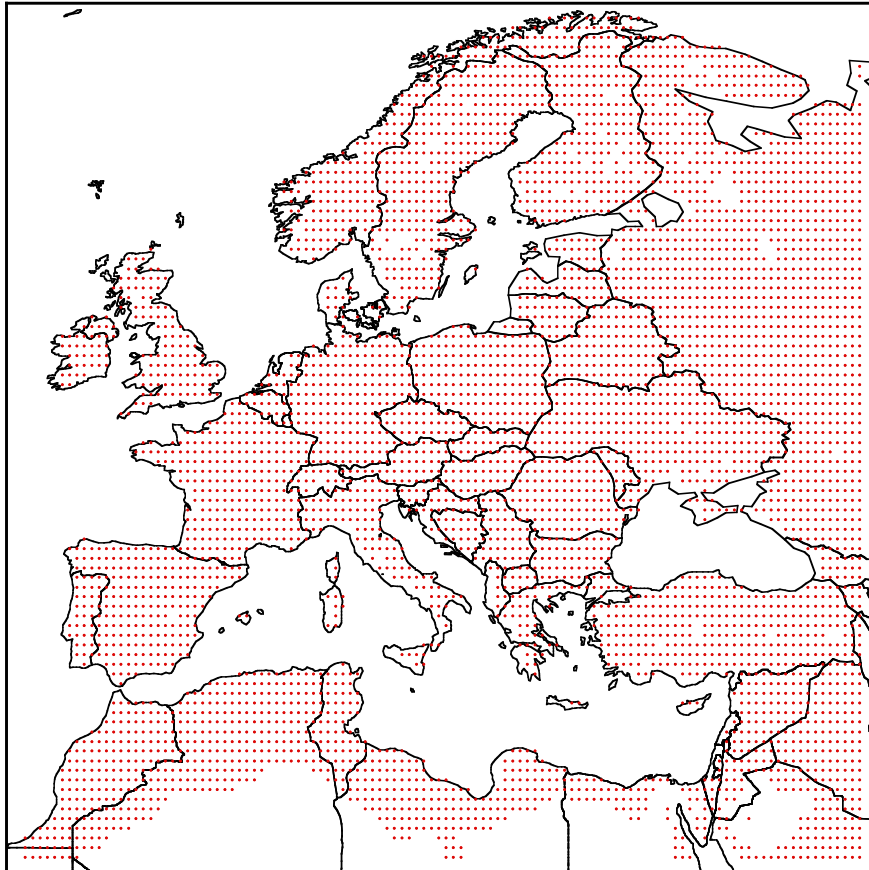
Cook, E. R., et al. 2015. Old World Megadroughts and Pluvials during the Common Era. *Science Advances* 1(10), e1500561, doi:10.1126/sciadv.1500561.



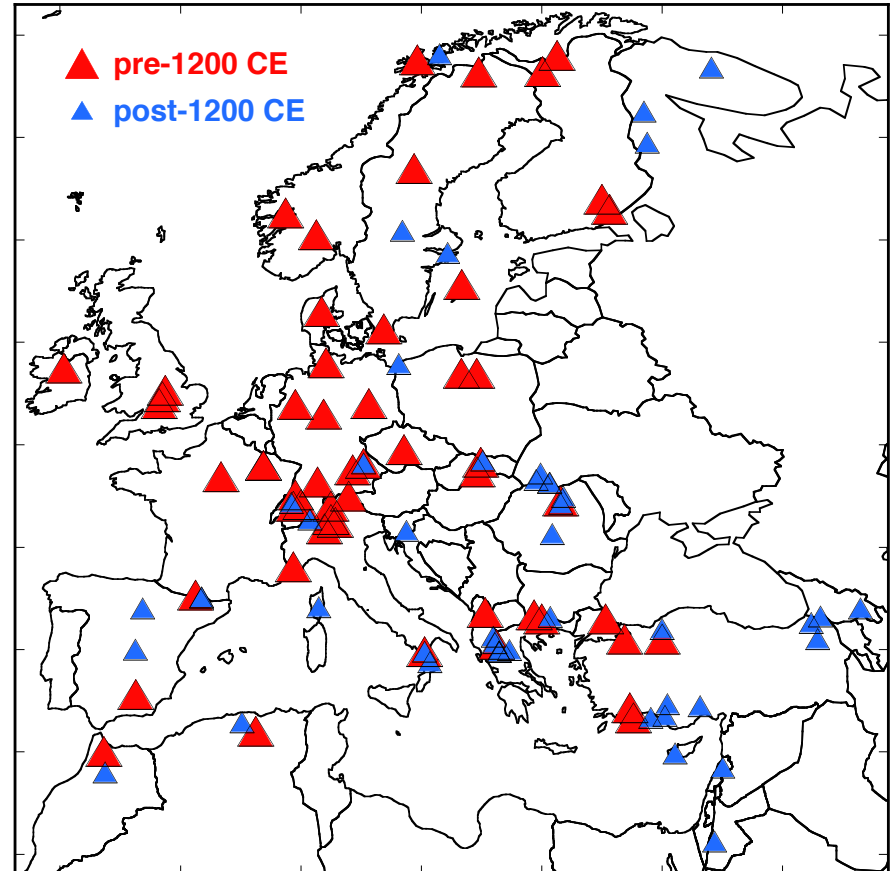
*The “Mexican Drought Atlas” (**MXDA**) is in review at *Quaternary Science Reviews*.

The OWDA Target Field and Tree-Ring Network

OWDA Target: 5414 0.5° JJA scPDSI Grid Points



OWDA Tree-Ring Network: 106 Chronologies



Historical Climatology Studies in Europe Allow for Comparisons with of the OWDA – Example 1

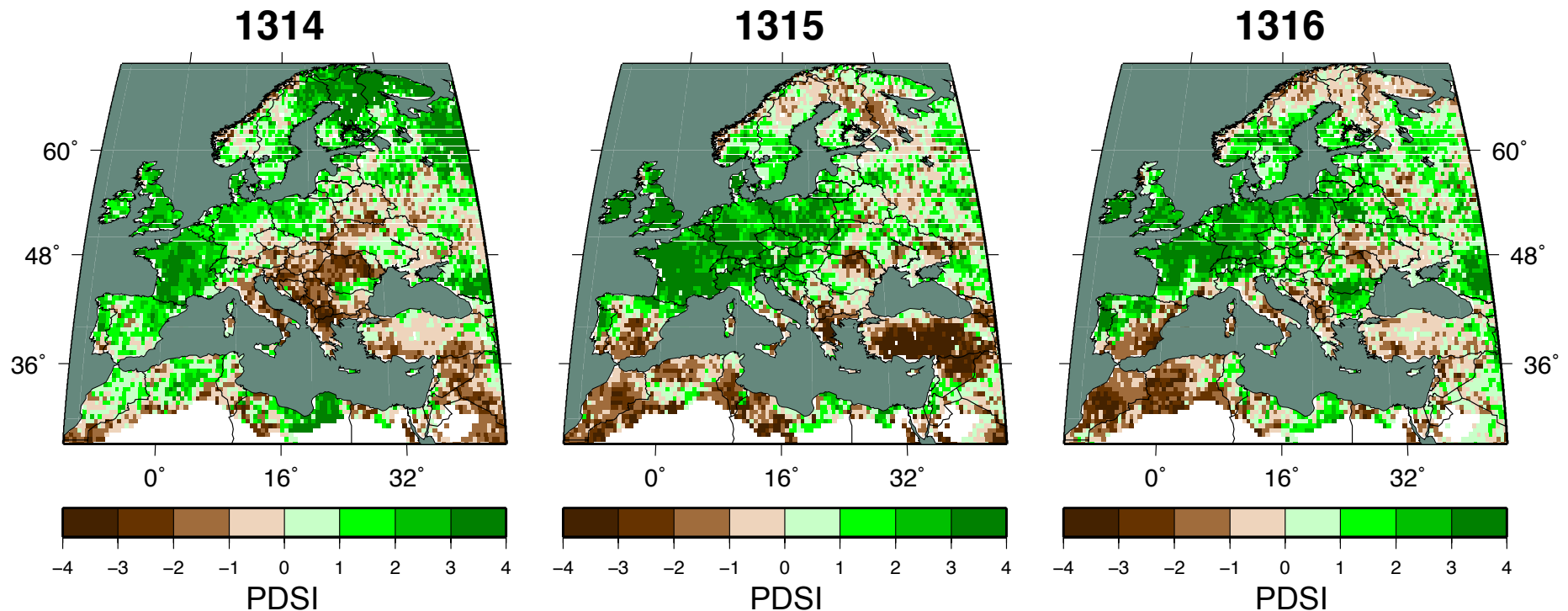
“The Great European Famine of 1315, 1316, and 1317”

Lucas, H.S. 1930. *Speculum – A Journal of Medieval Studies*.

The Great Famine – Northern Europe in the Early Fourteenth Century

Jordon, W.C. 1996. Princeton University Press.

Caused by too much spring-summer rain beginning in 1314.



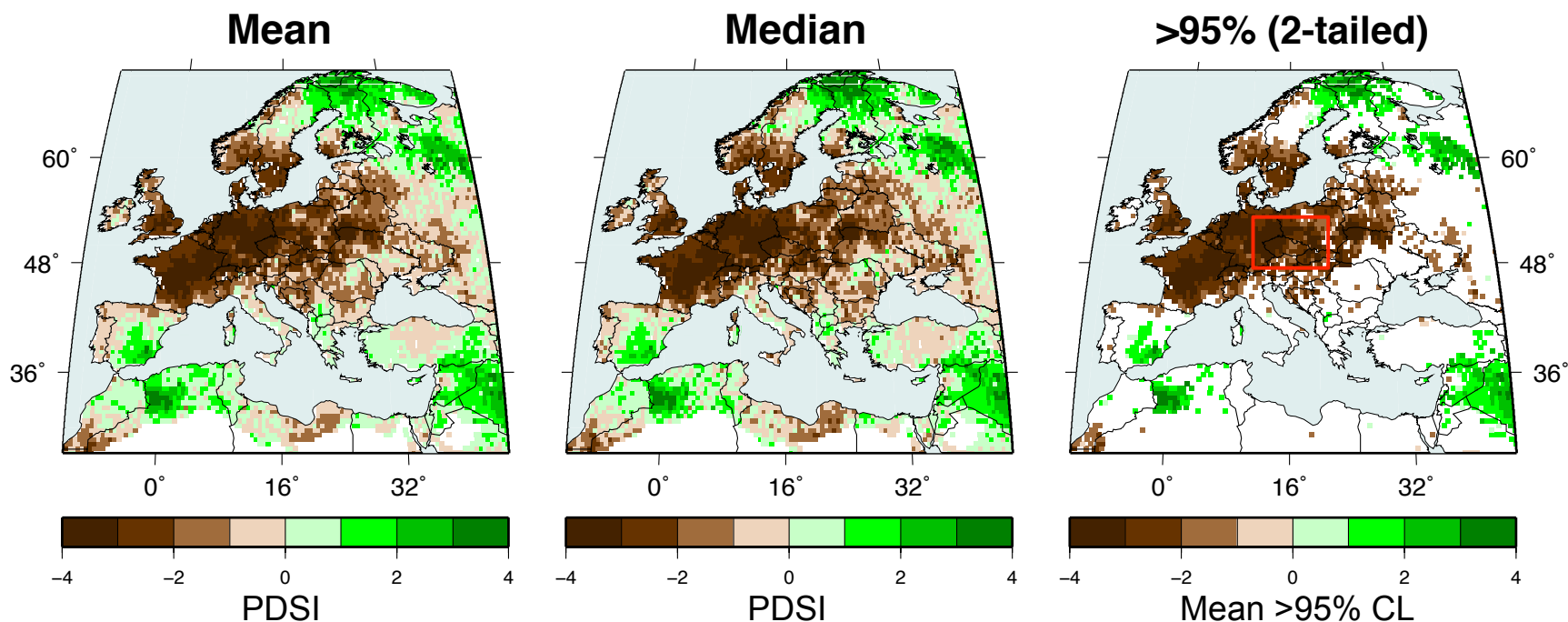
Historical Climatology Studies in Europe Allow for Comparisons with of the OWDA – Example 2

“Droughts in the Czech Lands, 1090–2012 AD”

R. Brazdil et al. 2013. *Climate of the Past* 9:1985-2002.

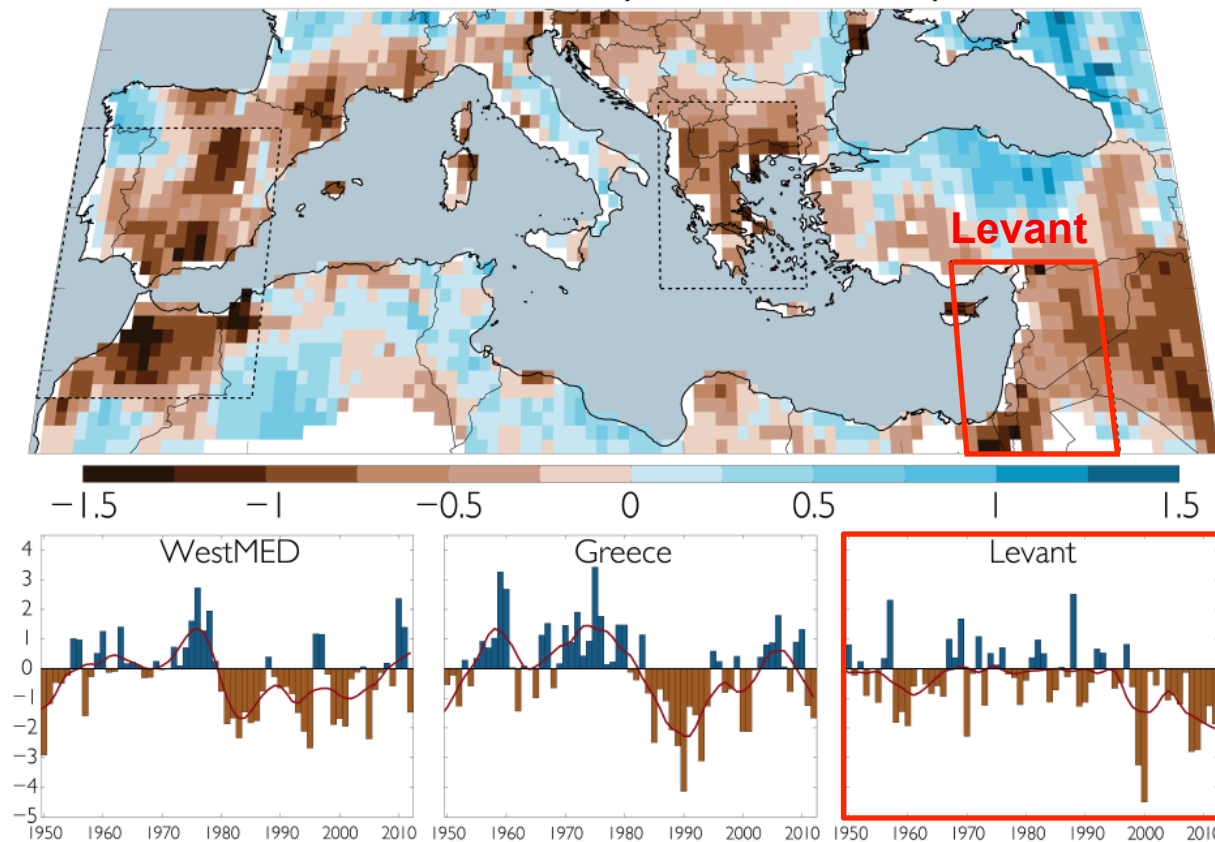
Mean of Eight Noteworthy Czech Lands Droughts:

1442, 1471, 1473, 1540, 1590, 1616, 1718, 1719



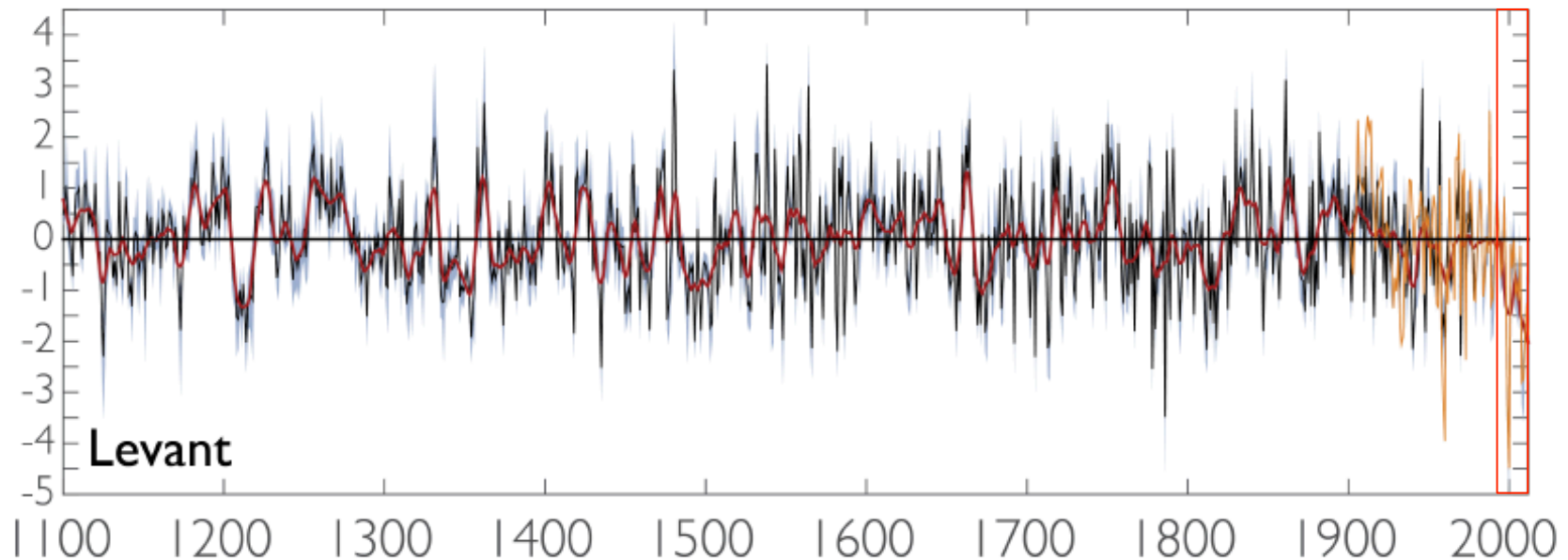
The OWDA also allows us to investigate the recent Mediterranean drying trend – the Levant is drying most. How unusual is it compared to the past 900 years?

OWDA PDSI (1980–2012)



From: Cook, B.I., et al. 2016. Spatiotemporal drought variability in the Mediterranean over the last 900 years. *J. Geophys. Res. Atmos.*, 121, doi:10.1002/2015JD023929.

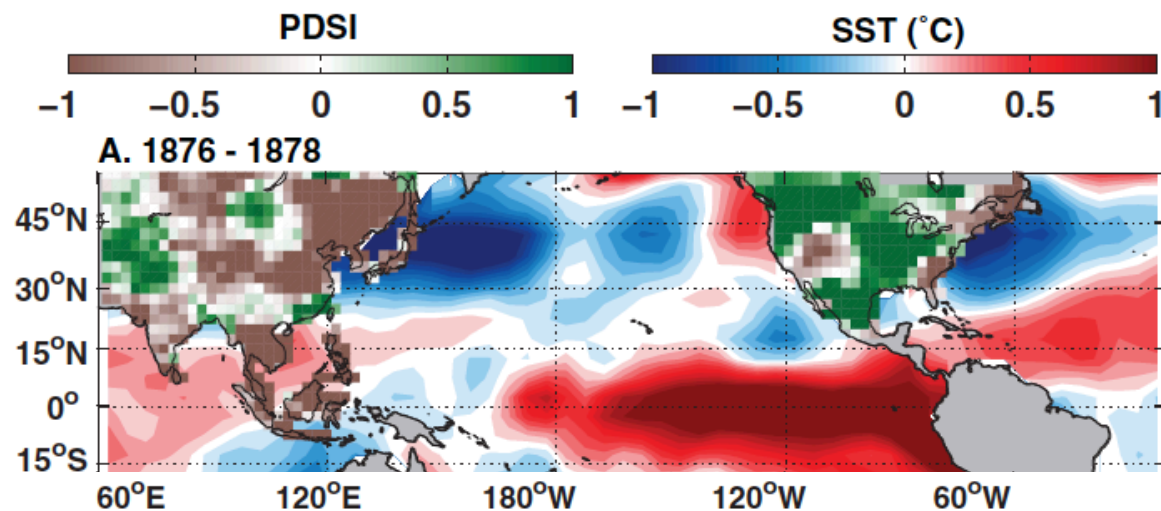
Here is the average reconstruction back to 900 CE over the Levant. So, how unusual is it compared to the past 900 years? Pretty unusual. Anthropogenically forced?



“Estimating uncertainties using a resampling approach, we conclude that there is an 89% likelihood that this drought is drier than any comparable period of the last 900 years and a 98% likelihood that it is drier than the last 500 years.” (Cook et al. 2016).

Individual drought atlases are good, but multiple drought atlases are better because they can be jointly used to search for coupled modes of climate forcing:

This can be done because, as constructed, the drought atlases are based on ***completely independent data***. Below is an example from the MADA (2010) publication: the MADA and NADA are “connected” by an tropical Pacific El Niño “bridge” in 1876-78 that produced dry conditions in Asia and wet conditions in North America as expected.



Another example of how multiple drought atlases can be used to identify coupled modes of climate forcing:

ENSO and PDSI (1901-1978) Drought Atlas Correlations

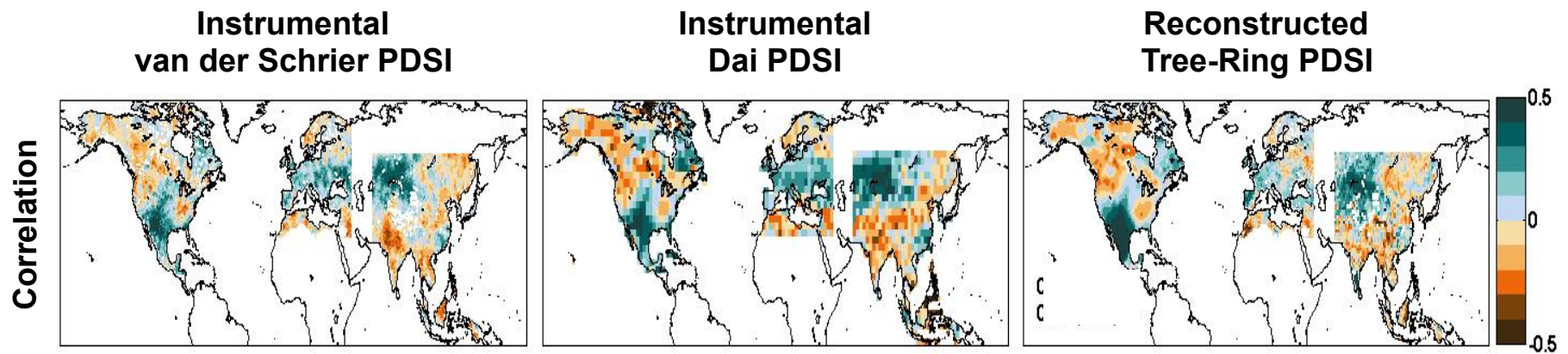


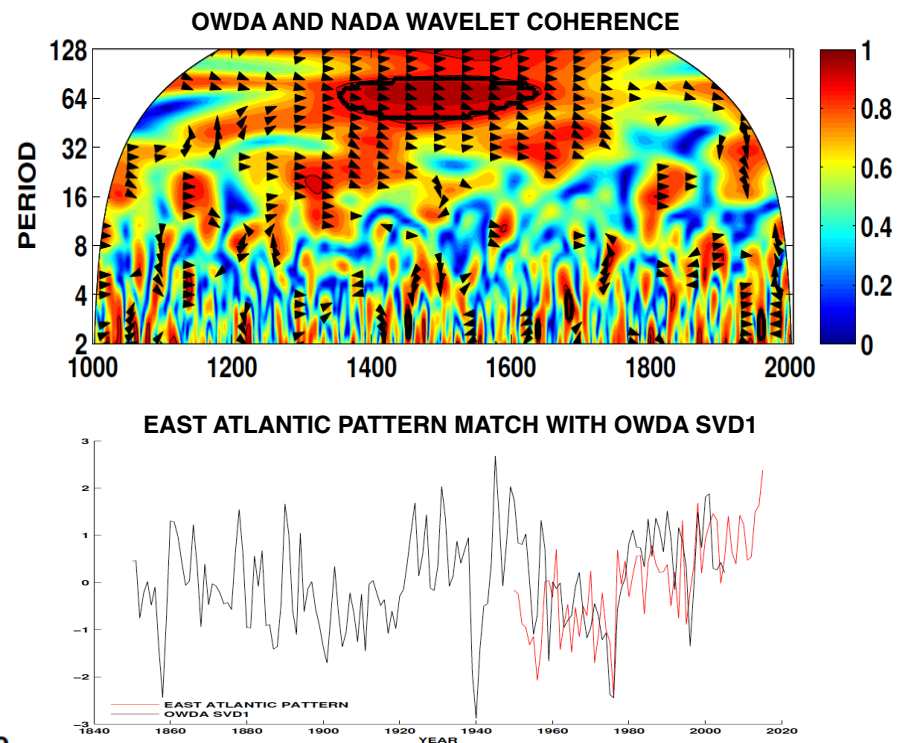
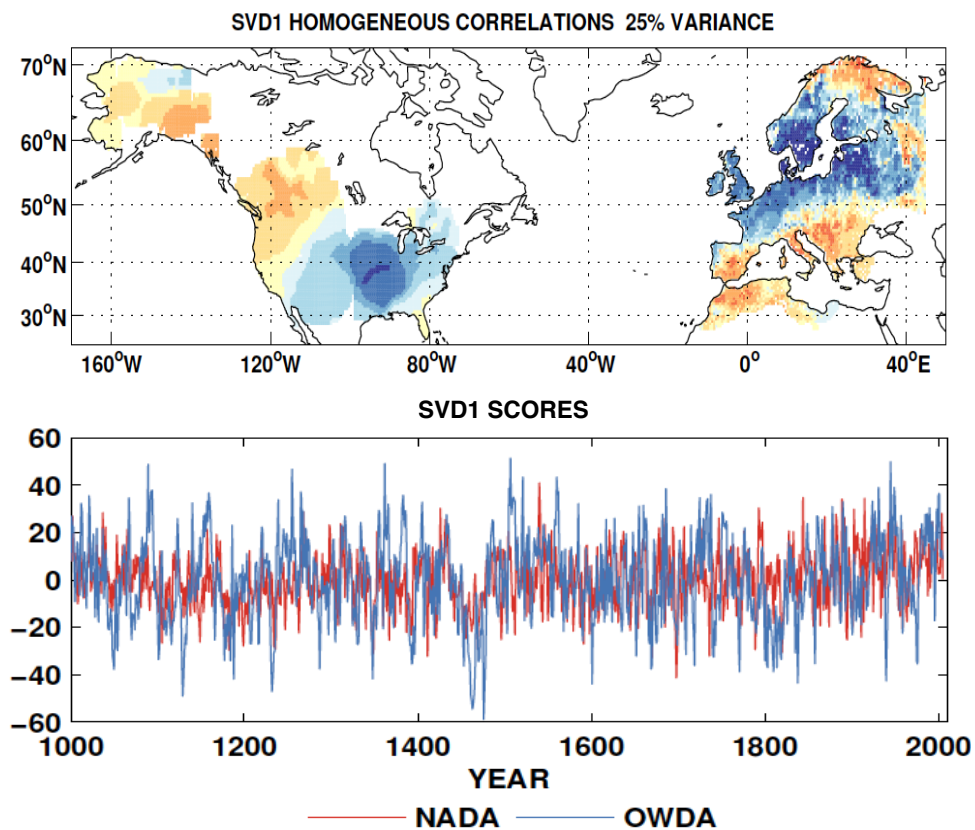
Figure courtesy of Hun Baek and Jason Smerdon

The patterns of correlation between ENSO and the instrumental and tree-ring drought atlases are remarkably similar!

This suggests that a ENSO-forced coupled mode of hydroclimatic variability exists in the independent drought atlases, but the sign of forcing differs by region within and between atlases.

A more sophisticated “coupled mode” analysis can also be conducted: NADA vs. OWDA here

Using the Singular Value Decomposition (SVD) method of Bretherton, a search for coupled modes in the NADA and OWDA has revealed an amazing degree of coupling: the leading two modes SVD1 & SVD2 explained 25% & 19% of the joint variance, 44% in total (Anchukaitis and Cook, in prep.). SVD1 results are shown here:

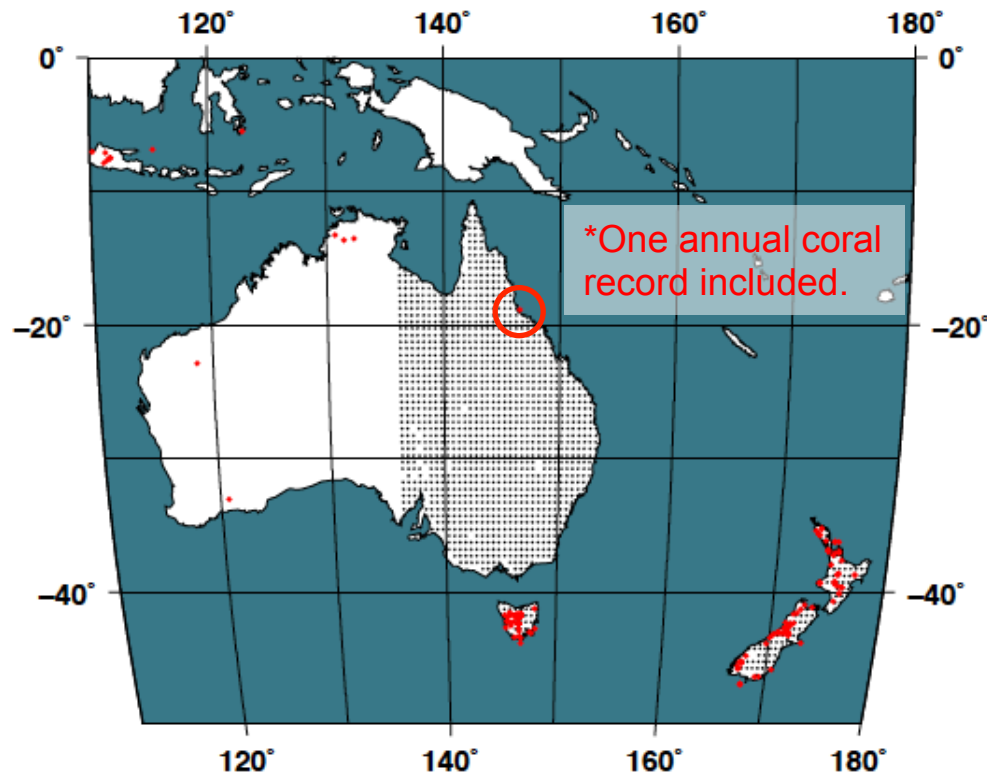


Figures courtesy of Kevin Anchukaitis

Now for a recently published SH tree-ring* drought atlas: Australia-New Zealand Drought Atlas (ANZDA):

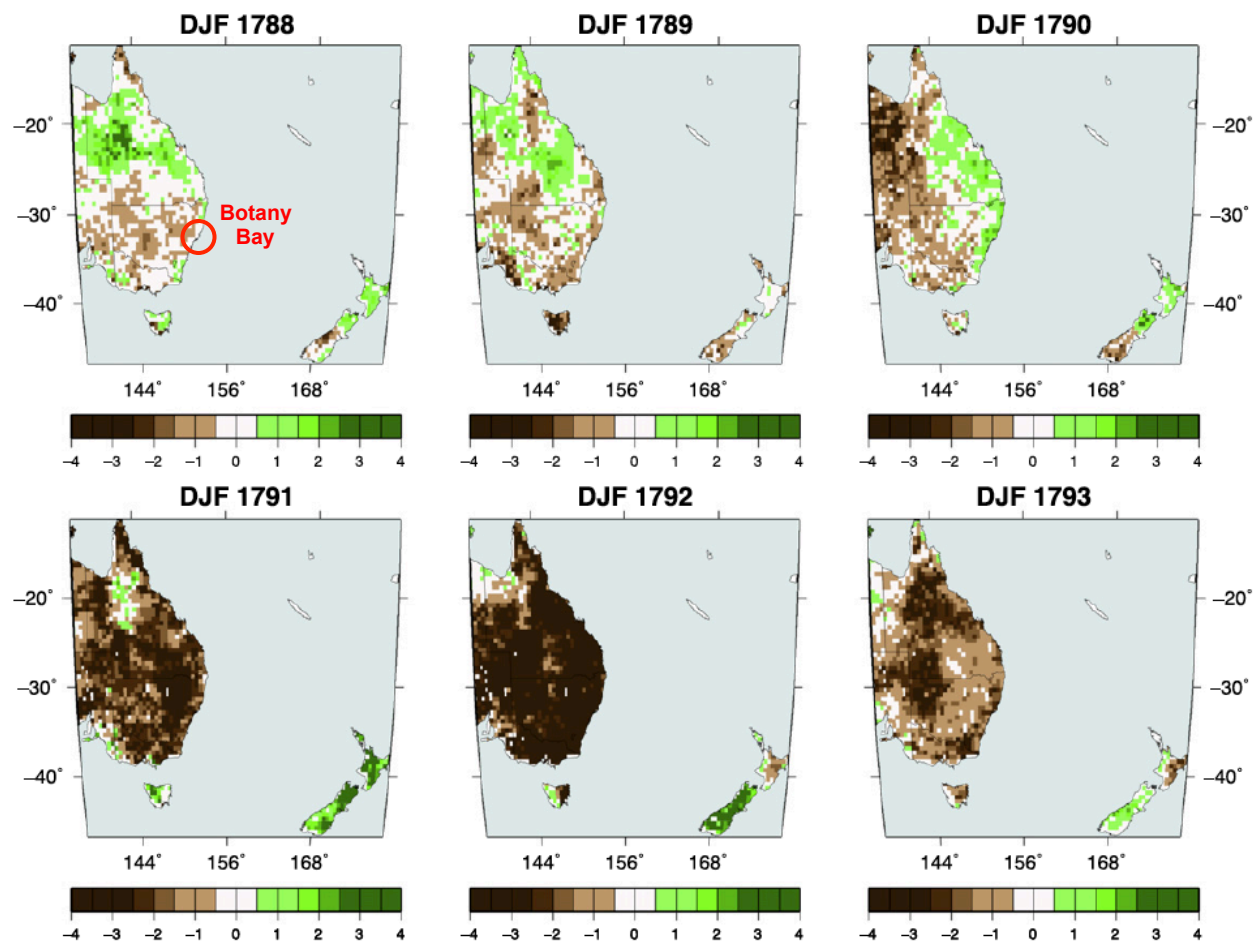
Palmer, J.G. et al. 2015. Drought variability in the eastern Australia and New Zealand summer drought atlas (ANZDA, CE 1500–2012) modulated by the Interdecadal Pacific Oscillation. *Environmental Research Letters* 10, doi:10.1088/1748-9326/10/12/124002.

1375 0.5° DJF scPDSI points reconstructed from 177 tree-ring and one coral-proxy records using PPR.



From: Palmer et al. 2015.

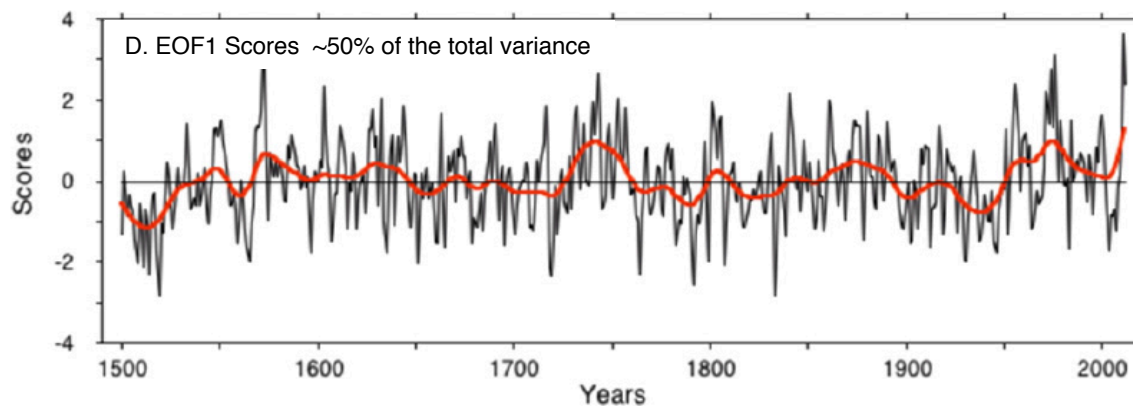
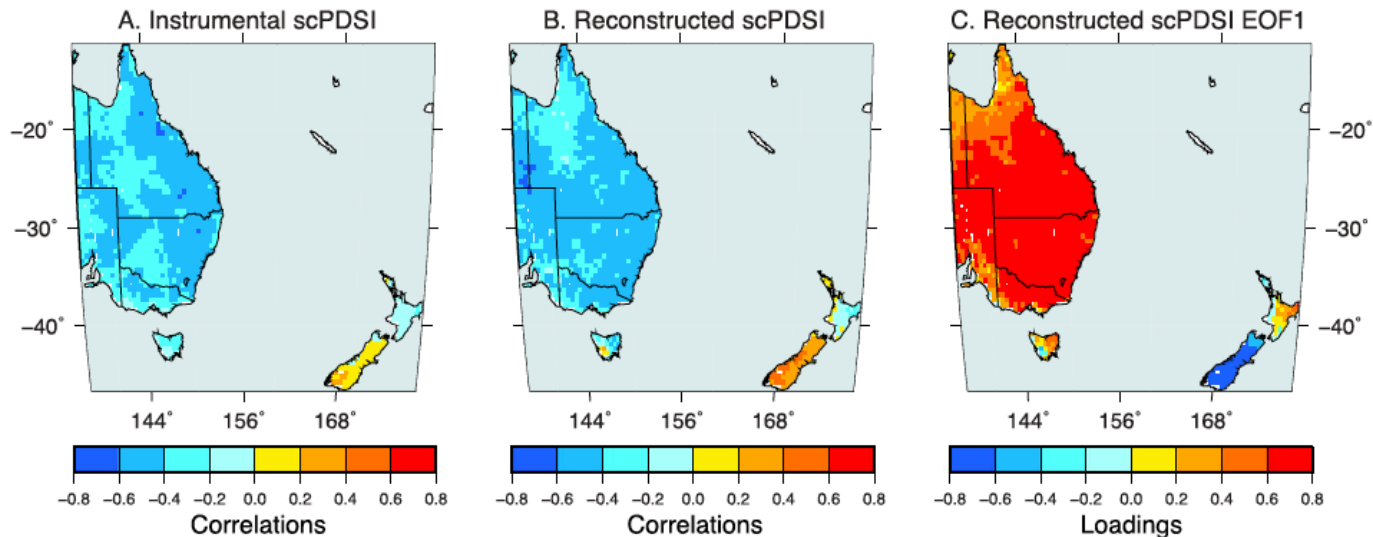
The ANZDA: European arrival in 1788 was greeted by overall fine conditions, followed by severe drought a few years later (agrees with historical records).



From: Palmer et al. 2015.

Variability in wet and dry over ANZDA is tightly coupled with the phase of the Interdecadal Pacific Oscillation (IPO) as measured by the Tripole Index (TPI) (Henley et al. 2015).

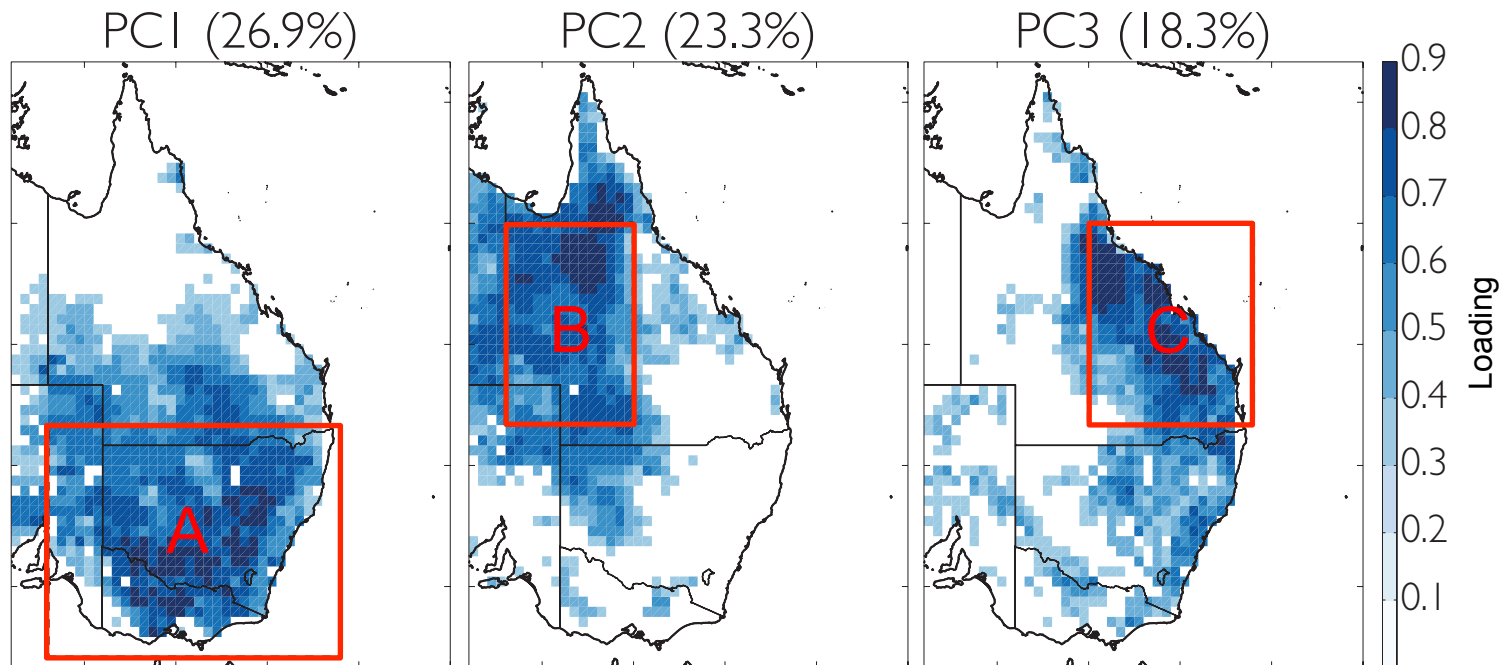
1902-1975 correlations with DJF TPI



From the ANZDA, this is effectively a reconstruction of the DJF Tripole Index

From: Palmer et al. 2015.

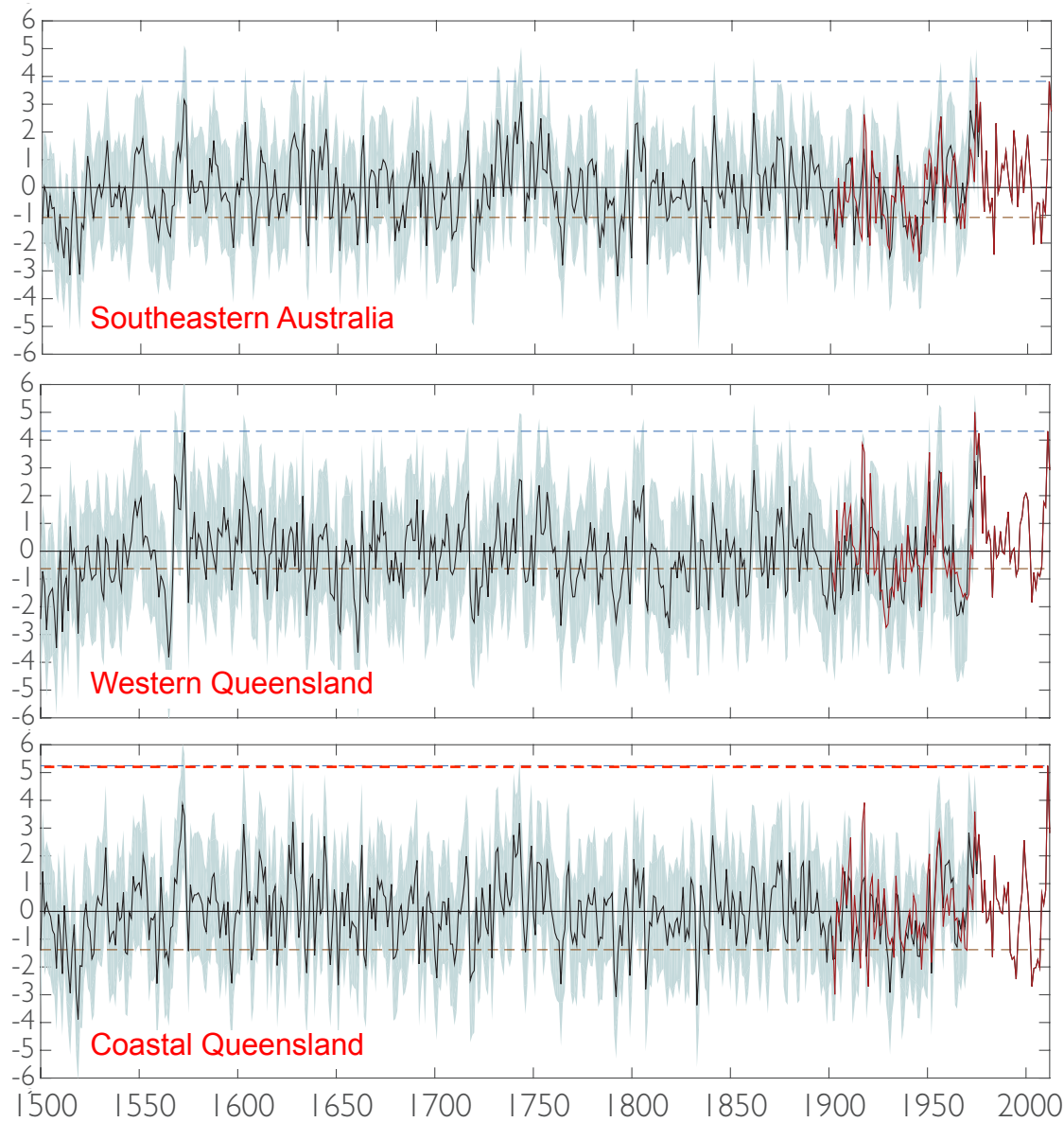
The ANZDA also allows us to investigate recent drying and wetting patterns over Australia. How unusual are they compared to the past 500 years?



A. Southeastern Australia B. Western Queensland C. Coastal Queensland

From: Cook, B.I., et al. 2016. The paleoclimate context and future trajectory of extreme hydroclimate events in eastern Australia. *J. Geophys. Res. Atmos.*, in revision.

The ANZDA: Consider the very wet 2011 year. How unusual?

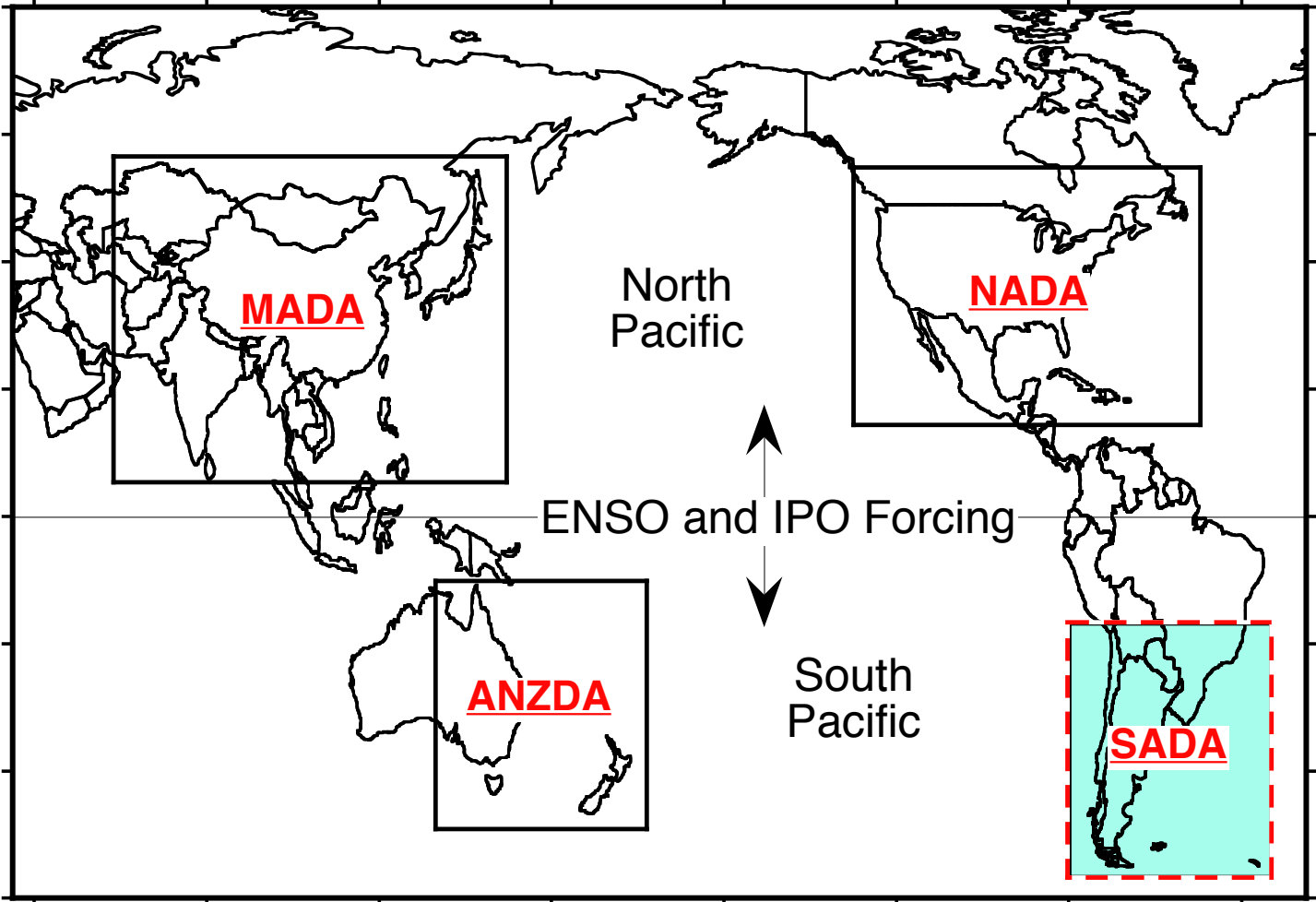


2011 exceeds all but one past event in Coastal Queensland at the 95% 1-tailed level compared to reconstruction prediction intervals.

From: Cook et al., 2016.

So what is the next proposed tree-ring drought atlas?

The South American Drought Atlas (SADA)!

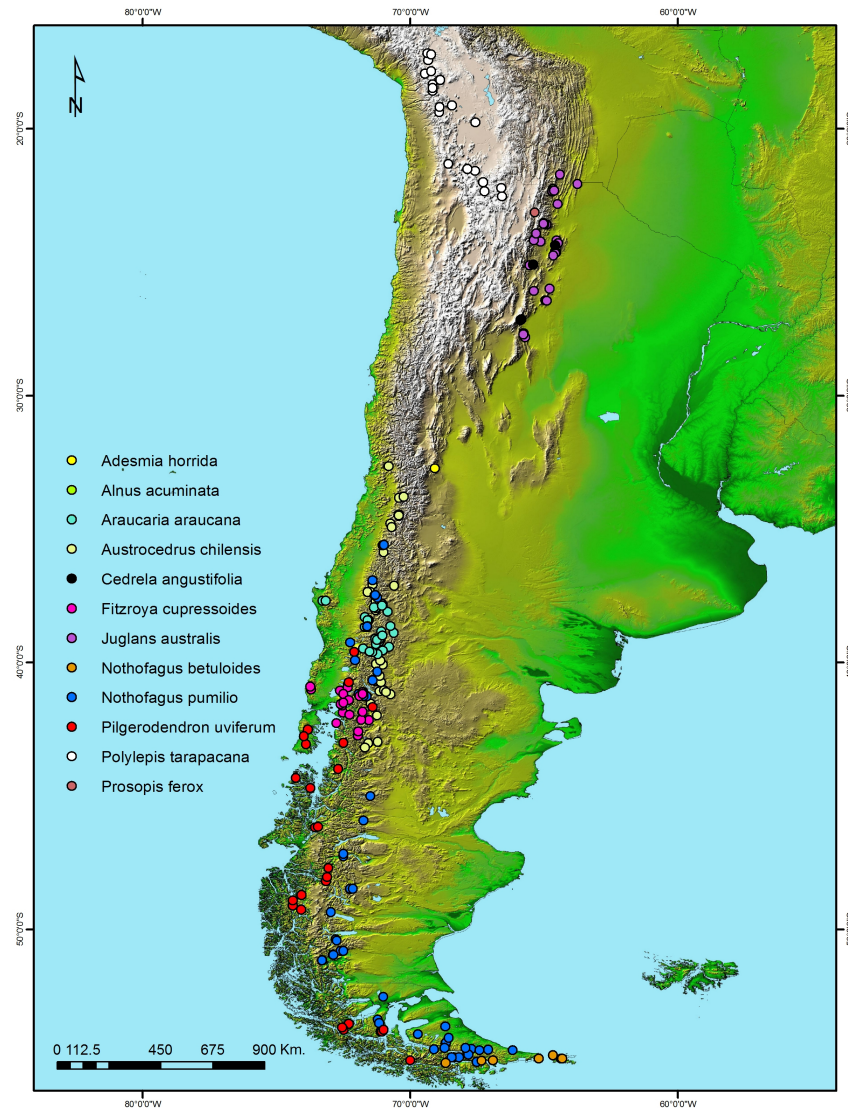


Potential for Producing the SADA

SADA Tree-Ring Network

The SADA is now possible through the long-time efforts of South American dendrochronologists who have jointly developed the 250+ site tree-ring network shown to the right.

With a target field of PDSI similar to the kind that has been used elsewhere, it is expected that PPR will produce a SADA with skill comparable to that found in the other drought atlases.



The SADA will fill in the circum-Pacific Basin land areas in all but the equatorial region of South America, thus allowing for important investigations such as:

- Using the new SADA jointly with the NADA, MADA, and ANZDA, it will be possible to identify coupled modes of inter- and intra-hemispheric variability of droughts, pluvials, and extremes in the Pacific Basin to understand and characterize their magnitude and geographic phasing.
- This in turn will lead to the identification of the climate forcings responsible for the coupled modes in terms of interhemispheric symmetries that might be expected from El Niño-Southern Oscillation/Interdecadal Pacific Oscillation (ENSO/IPO) forcing as it propagates poleward from the equatorial Pacific region (cf. Villalba et al. 2001, 2011). Other forcings as well (AMO, NAM, SAM, volcanism, etc.) may be identified.
- ***Tree-Ring Drought Atlases are a testimony to the enormous power of dendrochronology in paleoclimatic studies.***