GBYTES, MDROUGHTS, AND 2 KYEARS OF CLIMATE HISTORY

Jason E. Smerdon

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Motivation
2-KYR CLIMATE RECONSTRUCTIONS
PLACE OBSERVATIONS IN CONTEXT

NORTHERN HEMISPHERE MEAN TEMPERATURE

PROXY RECONSTRUCTIONS
INSTRUMENTAL ESTIMATES

ANOMALY (°C WRT 1881-1980)

TIME (YEARS C.E.)
ADVANTAGES OF THE 2-KYR TARGET

TEMPORAL RESOLUTION  SPATIAL AVAILABILITY  MEAN STATE
The number of climate model simulations is growing.
COMPUTATIONAL CONSISTENCY (PMIP3 to CMIP5)

LAST-MILLENNIUM SIMULATIONS (PMIP3)
[850-1850]

HISTORICAL SIMULATIONS (CMIP5)
[1850-2005]

FUTURE PROJECTIONS (CMIP5)
[2005-2100]

~5-7

~30-40
CLIMATE AND THE FUTURE

• How will the climate respond to increasing concentrations of GHGs in the atmosphere?

• How well do our models capture forced and internal variability over decades and centuries?

• How will internal climate variability combine with forced GHG changes to define impacts and risks?
Smerdon PaleoDynamics Lab
Proxy Synthesis, Modeling, and Climate Dynamics - From Past to Future

Graduate Students: Hun Baek
                     Yuxin Zhou

Postdocs: Justin Mankin
          Nathan Steiger

Former Grad Student: Sloan Coats

Lamont Collaborators: Ben Cook
                      Ed Cook
                      Richard Seager
                      Park Williams
2 Examples:

1) Climate Reconstruction

2) Model-Data Comparison
BERENSTAIN BEARS
RECONSTRUCTING SPATIOTEMPORAL TARGETS

**NORTHERN HEMISPHERE MEAN TEMPERATURE**

- **Proxy Reconstructions**
- **Instrumental Estimates**

**Reconstruction of Gridded Soil Moisture Index**

- **Boreal Summer Mean for 1528 C.E.**

Palmer Drought Severity Index

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute
The availability of proxy data is heterogeneous in space and time.
RECONSTRUCTION DATA MATRIX

INCREASING TIME BEFORE PRESENT

PROXY NETWORK

NUMBER OF PROXIES

SPATIAL LOCATIONS

RECONSTRUCTION PERIOD

INSTRUMENTAL DATA

THIS IS AN ILL-POSED ESTIMATION PROBLEM
CANONICAL CORRELATION ANALYSIS

\[ T' = BP' + \varepsilon \]

\[ B = (T'P'^T)(P'P'^T)^{-1} \]

1. \[ P^r = U_p^r \Sigma_p^r V_p^T \]

2. \[ T^r = U_t^r \Sigma_t^r V_t^T \]

3. \[ B_{\text{cca}} = U_t^r \Sigma_t^r V_t^T V_p^r (\Sigma_p^r)^{-1} U_p^T \]

\[ = U_t^r \Sigma_t^r O_t^r \Sigma_{\text{cca}}^r O_p^T (\Sigma_p^r)^{-1} U_p^T \]
DIMENSIONAL SELECTIONS

Data Matrix

<table>
<thead>
<tr>
<th>Out-Of-Sample Validation Interval</th>
<th>Split Calibration Interval</th>
</tr>
</thead>
</table>

RMSE (K)

SNR = 1.0

(10, 23, 12)  (15, 23, 20)

Smerdon et al., Journal of Climate, 2010
BURGEONING METHOD APPLICATIONS

- Traditional Multivariate Regression
  - PC Regression
  - Canonical Correlation Analysis
  - Ridge Regression

- Bayesian Hierarchical Models

- Regularized Expectation Maximization
  - Ridge Regression
  - Truncated Total Least Squares
  - Graphical Models

- Data Assimilation
ENSEMBLE DATA ASSIMILATION

Climate states

Observations

Time

DA

DA

DA

Analysis (posterior)

Weights

Proxies

$x_a = x_b + K[y - H(x_b)]$

Background (prior)

Model estimate of proxies

Slide Courtesy of Nathan Steiger
PROXY SYSTEM MODELING

RECONSTRUCTION

CALIBRATION

ENVIRONMENT

SENSOR

ARCHIVE

OBSERVATION

SENSOR MODEL

ARCHIVE MODEL

OBSERVATION MODEL

TEMPERATURE
PRECIPITATION
SOIL MOISTURE
SUNLIGHT
SNOW

TREE

WOOD

RING WIDTH
MXD
EARLYWOOD
LATEWOOD
ISOTOPES

Evans, Tolwinski-Ward, Thompson, Anchukaitis, 2013

Slide Courtesy of Kevin Anchukaitis
PSEUDOPROXY EXPERIMENTS

Synthetic model experiments to quantify uncertainties in paleoclimatic reconstructions.
1. Sample model field to mimic available climate observations

2. Sample model field to mimic available proxy observations

3. Perturb sampled proxy observations to mimic noise in proxies

4. Use subsampled data to perform reconstruction

5. Compare reconstructed climate to known model values
CORRELATION SKILL IS METHOD AND MODEL DEPENDENT
YOUR OWN PERSONAL HACKATHON…
Climate models as a test bed for climate reconstruction methods: pseudoproxy experiments

Jason E. Smerdon*

Millennium-length, forced transient simulations with fully coupled general circulation models have become important new tools for addressing uncertainties in global and hemispheric temperature reconstructions targeting the Common Era (the last two millennia). These model simulations are used as test beds on which to evaluate the performance of paleoclimate reconstruction methods using controlled and systematic investigations known as pseudoproxy experiments (PPEs). Such experiments are motivated by the fact that any given real-world reconstruction is the product of multiple uncontrolled factors, making it difficult to isolate the impact of one factor in reconstruction assessments and comparisons. PPEs have established a common experimental framework that can be systematically altered and evaluated, and thus test reconstruction methods and their dependencies. Although the translation of PPE results into real-world implications must be done cautiously, their experimental design attributes allow researchers to test reconstruction techniques beyond what was previously possible with real-world data alone. This review summarizes the development of PPEs and their findings over the last decade. The state of the science and its implications for global and hemispheric temperature reconstructions is also reviewed, as well as near-term design improvements that will expand the utility of PPEs. © 2011 John Wiley & Sons, Ltd.

How to cite this article:
Reconstructing Earth’s surface temperature over the past 2000 years: the science behind the headlines

Jason E. Smerdon¹* and Henry N. Pollack²

Edited by Eduardo Zorita, Domain Editor, and Mike Huime, Editor-in-Chief

The last quarter century spans the publication of the first assessment report of the Intergovernmental Panel on Climate Change in 1990 and the latest report published in 2013-2014. The five assessment reports appearing over that interval reveal a marked increase in the number of paleoclimate studies addressing the climate of the last 2000 years (the Common Era). An important focus of this work has been on reconstruction of hemispheric and global temperatures. Several early studies in this area generated considerable scientific and public interest, and were followed by high-profile and sometimes vitriolic debates about the magnitude of temperature changes over all or part of the Common Era and their comparison to 20th- and 21st-century global temperature increases due to increasing levels of atmospheric greenhouse gases. Behind the more public debates, however, several consistent themes of scientific inquiry have developed to better characterize climate variability and change over the Common Era. These include attempts to collect more climate proxy archives and understand the signals they contain, improve the statistical methods used to estimate past temperature variability from proxies and their associated uncertainties, and to compare reconstructed temperature variability and change with climate model simulations. All of these efforts are driving a new age of research on the climate of the Common Era that is developing more cohesive and collaborative investigations into the dynamics of climate on time scales of decades to centuries, and an understanding of the implications for modeled climate projections of the future. © 2016 Wiley Periodicals, Inc.

How to cite this article: WIREs Clim Change 2016. doi: 10.1002/wcc.418
M drougths
what we talk about when we talk about drought
SOIL MOISTURE BALANCE

Supply: Precipitation

Demand: Temperature + Wind + Radiation + Humidity
PDSI

Soil Moisture Balance = Precipitation – PET\((\text{Temp, Wind, Radiation, Humidity})\)

- PDSI = Drier than normal conditions
+ PDSI = Wetter than normal conditions
WHAT IS A DROUGHT?

Cook et al., WIRES Climate Change, 2015
MDROUGHTS IN TIME

LONG-TERM CHANGES IN DROUGHT AREA IN THE WEST

THE CENTRAL DATES OF THE SIGNIFICANT (p<0.05) EPOCHS ARE INDICATED WITH ARROWS

AD 1130-70

MEGADROUGHT EVENTS IN THE AMERICAN SOUTHWEST

WETTER

DRIER

Medieval Climate Anomaly (MCA)
What Causes M Droughts?
An Ocean Dynamical Thermostat

Amy C. Clement, Richard Seager, Mark A. Cane, and Stephen E. Zebiak

Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York

(Manuscript received 27 November 1995, in final form 19 March 1996)
SOME CORAL EVIDENCE SUPPORTS THE LIKELIHOOD OF  `LA-NIÑA-LIKE` CONDITIONS DURING THE MCA

Cobb et al., Nature, 2003
A multiproxy reconstruction also estimates ‘La-Niña-like’ conditions during the MCA.
But field reconstructions of the cold tropical Pacific are not robust

Different Field Reconstruction Methods

Different Screens of the Proxy Network

Wang et al., Geophysical Research Letters, 2015
OTHER PALEO ESTIMATES OF ENSO (Niño3.4) VARIABILITY ARE ALSO VARIABLE

Coats et al., Geophysical Research Letters, 2016
Can we use the Northern Hemisphere Drought Atlases for this problem?

Cook et al., 2004, 2010, 2015
Modes of SST variability affect hydroclimate in North America.
INSTRUMENTAL IMPACT MAPS

Coats et al., Geophysical Research Letters, 2016
IMPACT MAPS ESTIMATE THE STATE OF FOUR OCEAN-ATMOSPHERE MODES OVER THE LAST MILLENNIUM

Coats et al., Geophysical Research Letters, 2016
Megadroughts are principally associated with decadal periods of negative ENSO states.
NO ADDITIONAL DYNAMICAL BEHAVIOR (E.G. FORCING) IS NECESSARY TO EXPLAIN THESE NEGATIVE ENSO PERIODS

Coats et al., Geophysical Research Letters, 2016
Do models simulate droughts and, if so, for the ‘right’ reasons?
Comparisons need to account for forced and internal variability.
MODELS SIMULATE UNFORCED MEGADROUGHTS FOR DIFFERENT DYNAMIC REASONS

North American Southwest Average PDSI

PDSI
FILTERED PDSI
MDROUGHTS

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE
The length and severity of simulated megadroughts are comparable to the proxy record...
But few models associate megadroughts with conditions in the tropical Pacific
North American megadroughts in the Common Era: reconstructions and simulations

Benjamin I. Cook, Edward R. Cook, Jason E. Smerdon, Richard Seager, A. Park Williams, Sloan Coats, David W. Stahle and José Villanueva Díaz

Edited by Eduardo Zorita, Domain Editor, and Mike Hulme, Editor-in-Chief

During the Medieval Climate Anomaly (MCA), Western North America experienced episodes of intense aridity that persisted for multiple decades or longer. These megadroughts are well documented in many proxy records, but the causal mechanisms are poorly understood. General circulation models (GCMs) simulate megadroughts, but do not reproduce the temporal clustering of events during the MCA, suggesting they are not caused by the time history of volcanic or solar forcing. Instead, GCMs generate megadroughts through (1) internal atmospheric variability, (2) sea-surface temperatures, and (3) land surface and dust aerosol feedbacks. While no hypothesis has been definitively rejected, and no GCM has accurately reproduced all features (e.g., timing, duration, and extent) of any specific megadrought, their persistence suggests a role for processes that impart memory to the climate system (land surface and ocean dynamics). Over the 21st century, GCMs project an increase in the risk of megadrought occurrence through greenhouse gas forced reductions in precipitation and increases in evaporative demand. This drying is robust across models and multiple drought indicators, but major uncertainties still need to be resolved. These include the potential moderation of vegetation evaporative losses at higher atmospheric [CO₂], variations in land surface model complexity, and decadal to multidecadal modes of natural climate variability that could delay or advance onset of aridification over the next several decades. Because future droughts will arise from both natural variability and greenhouse gas forced trends in hydroclimate, improving our understanding of the natural drivers of persistent multidecadal megadroughts should be a major research priority. © 2016 Wiley Periodicals, Inc.

How to cite this article:
WIREs Clim Change 2016. doi: 10.1002/wcc.394
MODELS PROJECT A DRIER FUTURE THAN THE MODROUGHT PERIOD FOR A BUSINESS-AS-USUAL SCENARIO

Cook et al., Science Advances, 2015
The severity of the projected drying (or wetting) varies across the CMIP5 ensemble.

- Significantly different from modeled 20th-century climate
- Significantly different from NADA-estimated megadrought period

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Cook et al., Science Advances, 2015
A FRAMEWORK FOR PALEO CONSTRAINTS ON FUTURE PROJECTIONS?

Multivariate Paleo-Model Assessments → Modern Validation

Paleo Data:
Multiple products and variables
Large uncertainties

Model Data:
Increasing Ensemble Size (LM and Historical)
Data sizes approaching petabytes

Weighted/Subselected Future Projections
The temporal stability of teleconnections is not well constrained

Coats et al., Geophysical Research Letters, 2013
Regularized Expectation Maximization

\[ \{ \mu_0, \Sigma_0 \} \]

Filter \( \sum \) (Regularization)

\[ (X'_a X'_a)^{-1} \rightarrow (X'_a X'_a + \lambda^2 I)^{-1} \]

Ridge Regression

Truncated Total Least Squares

Graphical Models

Compute \( \{ \mu, \Sigma \} \)

Compute regression coefficients

\[ B = (X'_m X'_a)(X'_a X'_a)^{-1} \]

\[ X_m = M_m + S_m B S_a^{-1} (X_a - M_a) \]

Gaussian sufficient statistics:

\[ \mu = \text{mean} \]

\[ \Sigma = \text{covariance matrix} \]

Estimate unknown values from available ones

\[ \text{Slide Courtesy of} \]

Julien Emile-Geay

Schneider, J. Clim. 2001

Dempster, Laird & Rubin, 1977
GROWING RESEARCH ON THE CLIMATE OF THE COMMON ERA

Topic = (last millennium OR common era) AND climate AND reconstruction

Published Items in Each Year

Records: 4,952

Citations in Each Year

Sum of Times Cited: 106,253
Changes in Precipitation Only

Soil Moisture: 2080-99
High Emissions Scenario

Cook et al., Climate Dynamics, 2014
CHANGES IN PRECIPITATION AND TEMPERATURE

Soil Moisture: 2080-99
High Emissions Scenario

Cook et al., Climate Dynamics, 2014
WHERE WE ARE GOING
MODELING MEGADROUGHTS (ECHO-G)

Forced Modeled Soil Moisture

Naturally Varying Modeled Soil Moisture

Drought Severity Estimated From Tree Rings

Solar and Volcanic Forcings in Forced Run

Spectral Fidelity

Smerdon et al. Climate Dynamics, 2015