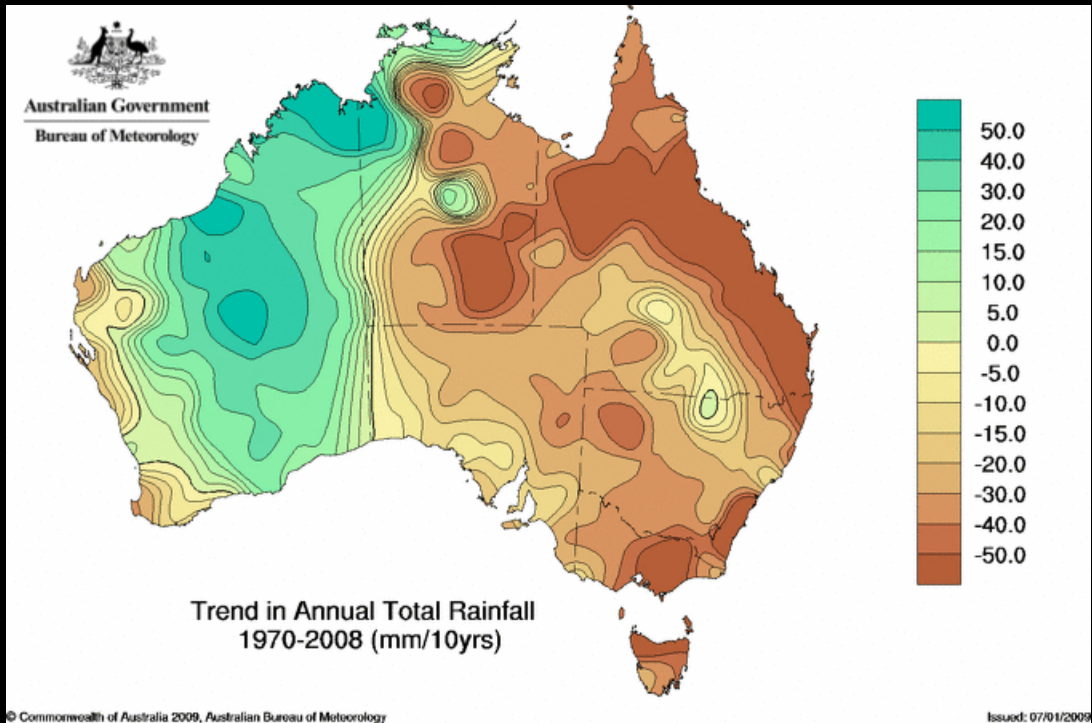
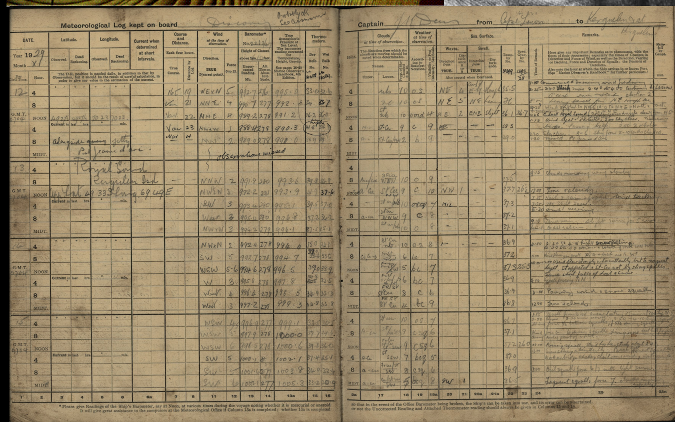
Reconstructing climates of the past 500 years using annually-resolved palaeoclimate records: methods, challenges and recent advances





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THE UNIVERSITY OF MELBOURNE

SEARCH South Eastern Australian Recent Climate History

AUS2K

1. Australasian palaeoclimate records – a global context

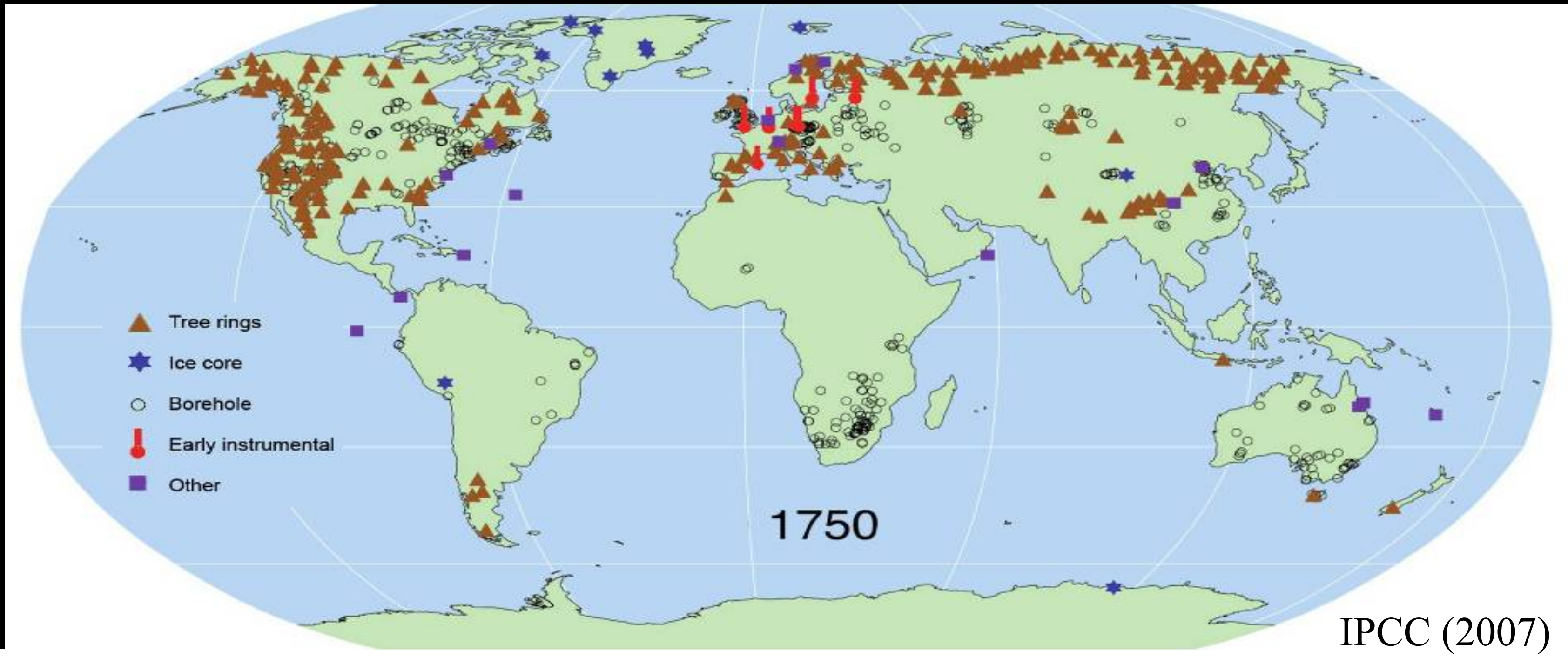
Palaeoclimatology of the last 2,000 years

- The last 2K contains a period of marked temperature fluctuations: Medieval Warm Period, Little Ice Age and ~1870s transition into the industrial era: period contains solar, volcanic and anthropogenic forcing that models can assess climate sensitivity

- Period where we have the highest confidence in our palaeoclimate record e.g. more records, calendar dates

- Complementary aspects of climate system (e.g; marine vs. terrestrial, tropics vs. mid-latitudes) are needed to understand global and regional climate variability: major gaps in the Southern Hemisphere, particularly in mid-latitude regions across Australasia

- Comparing multiple proxies reduces uncertainty by focusing on large-scale forcing represented by as co-variability in multi-variate studies



IPCC (2007)

Reviews of high-resolution palaeoclimatology

Very little input from SH science or input from our scientists: we need to consolidate our efforts (Aus2k?) and contribute to global progress/ IPCC synthesis

The Holocene 19,1 (2009) pp. 3–49

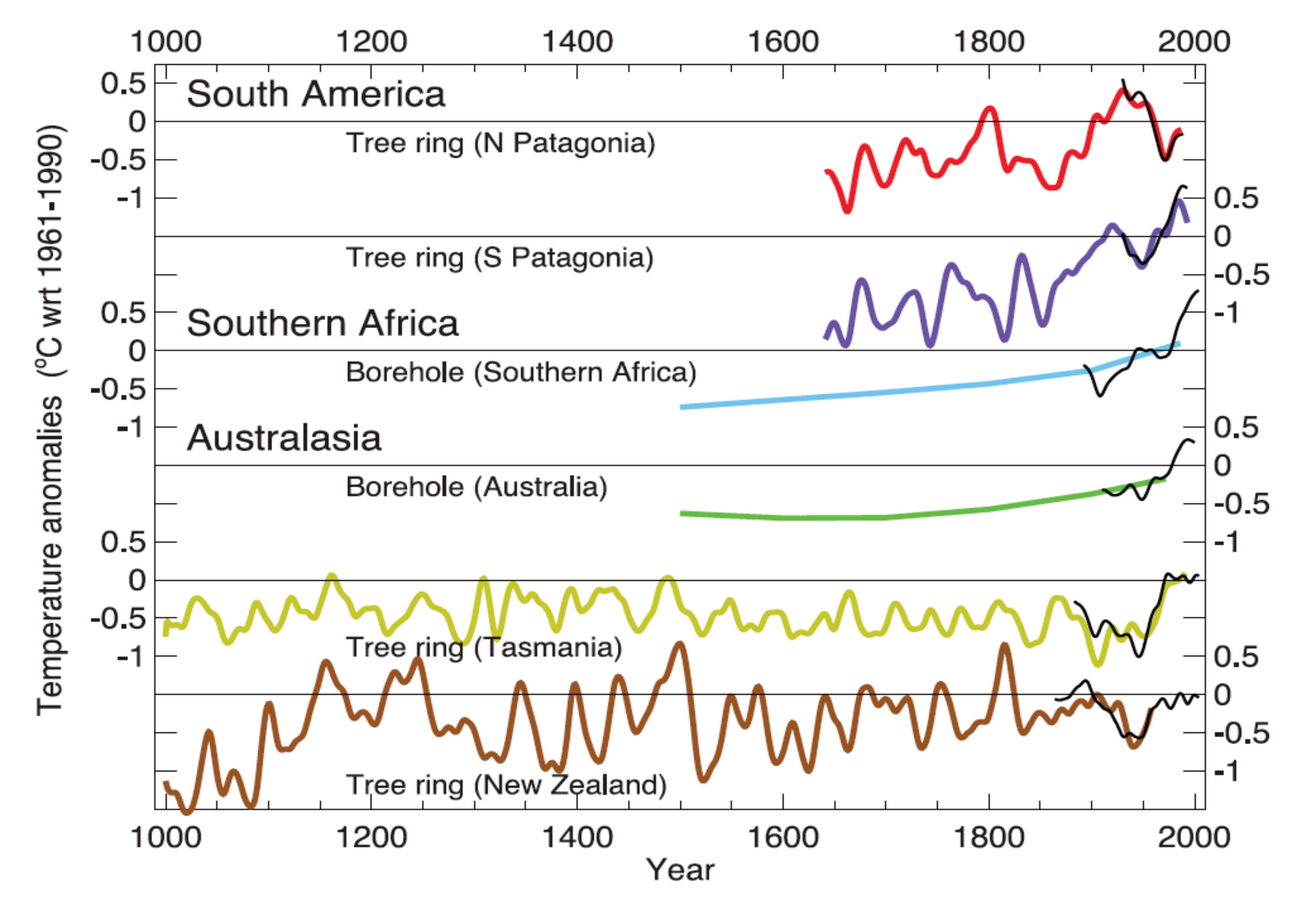
High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects

P.D. Jones,[1]* K.R. Briffa,[1] T.J. Osborn,[1] J.M. Lough,[2] T.D. van Ommen,[3] B.M. Vinther,[4] J. Luterbacher,[5] E.R. Wahl,[6] F.W. Zwiers,[7] M.E. Mann,[8] G.A. Schmidt,[9] C.M. Ammann,[10] B.M. Buckley,[11] K.M. Cobb,[12] J. Esper,[13] H. Goosse,[14] N. Graham,[15] E. Jansen,[16] T. Kiefer,[17] C. Kull,[18] M. Küttel,[5] E. Mosley-Thompson,[19] J.T. Overpeck,[20] N. Riedwyl,[5] M. Schulz,[21] A.W. Tudhope,[22] R. Villalba,[23] H. Wanner,[5] E. Wolff[24] and E. Xoplaki[5]

Source: Jones et al. (2009) The Holocene 19(1):3-49

Southern Hemisphere temperature reconstructions

IPCC AR4, only 6 records used to reconstruct annual mean SH temperature change over the past 1.5 ka (only 2 from Australia)



Source: Jansen et al. (2007) IPCC WG1 chapter 6

Regional 2K progress: LOTRED-SA

Clim Dyn
DOI 10.1007/s00382-010-0793-3

Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries

R. Neukom · J. Luterbacher · R. Villalba · M. Küttel · D. Frank · P. D. Jones · M. Grosjean · H. Wanner · J.-C. Aravena · D. E. Black · D. A. Christie · R. D'Arrigo · A. Lara · M. Morales · C. Soliz-Gamboa · A. Srur · R. Urrutia · L. von Gunten

Received: 12 November 2009 / Accepted: 8 March 2010

Abstract We statistically reconstruct austral summer (winter) surface air temperature fields back to AD 900 (1706) using 22 (20) annually resolved predictors from natural and human archives from southern South America (SSA). This represents the first regional-scale climate field reconstruction for parts of the Southern Hemisphere at this high temporal resolution. We apply three different reconstruction techniques: multivariate principal component regression, composite plus scaling, and regularized expectation maximization. There is generally good

Electronic supplementary material The online version of this article (doi:10.1007/s00382-010-0793-3) contains supplementary

What about Australasia?

- Despite major climate impacts in our region progress on multi archive data synthesis has been slow and haphazard
- Lack of data integration and consolidated research effort in our region…a capacity/training issue?
- NOAA has a strong palaeoclimate program, still disconnected from mainstream climate science in Australia…collaborative work?
- Limited/no funding for large-scale data synthesis efforts

Source: Fairfax Publishers

Australian Research Council (ARC) Linkage project (Sept 2009–Sept 2012): targeting a knowledge gap

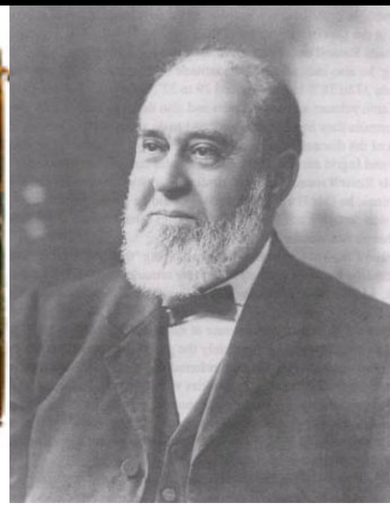
AIM: To develop multi-record, temperature, rainfall and pressure reconstructions for SE Australia for the past 200–500 years using:

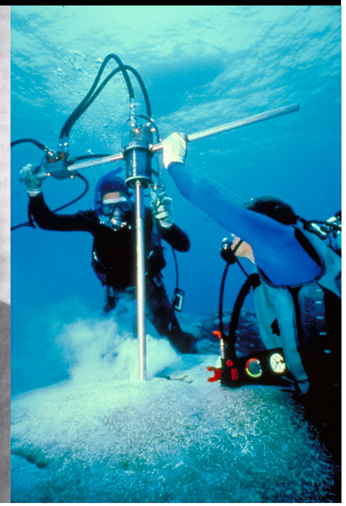
1. Palaeoclimate: tree-rings, corals, cave records, ice cores (~500 yrs)

2. Documentary: early settler accounts, newspapers, government records (1788–1900)

3. Early weather data: BoM holdings, weather/farm diaries, early observatories (pre 1900)

** First funded project of its kind in the Australasian region**





ARC Linkage project to reconstruct pre-C20th rainfall, temperature and pressure in SE Australia (Sept 2009–Sept 2012)

10 PARTNER ORGANISATIONS

1. Bureau of Meteorology
2. UK Met Office Hadley Centre
3. Murray–Darling Basin Authority
4. VIC Depart Sustainability & Environment
5. Melbourne Water
6. National & State Libraries Australasia
7. National Library of Australia
8. State Library of NSW
9. State Library of VIC
10. Powerhouse Museum

Australian Government
Bureau of Meteorology

Australian Government
MURRAY–DARLING BASIN AUTHORITY

Department of Sustainability and Environment

Victoria The Place To Be | Melbourne Water

Met Office

NATIONAL LIBRARY OF AUSTRALIA

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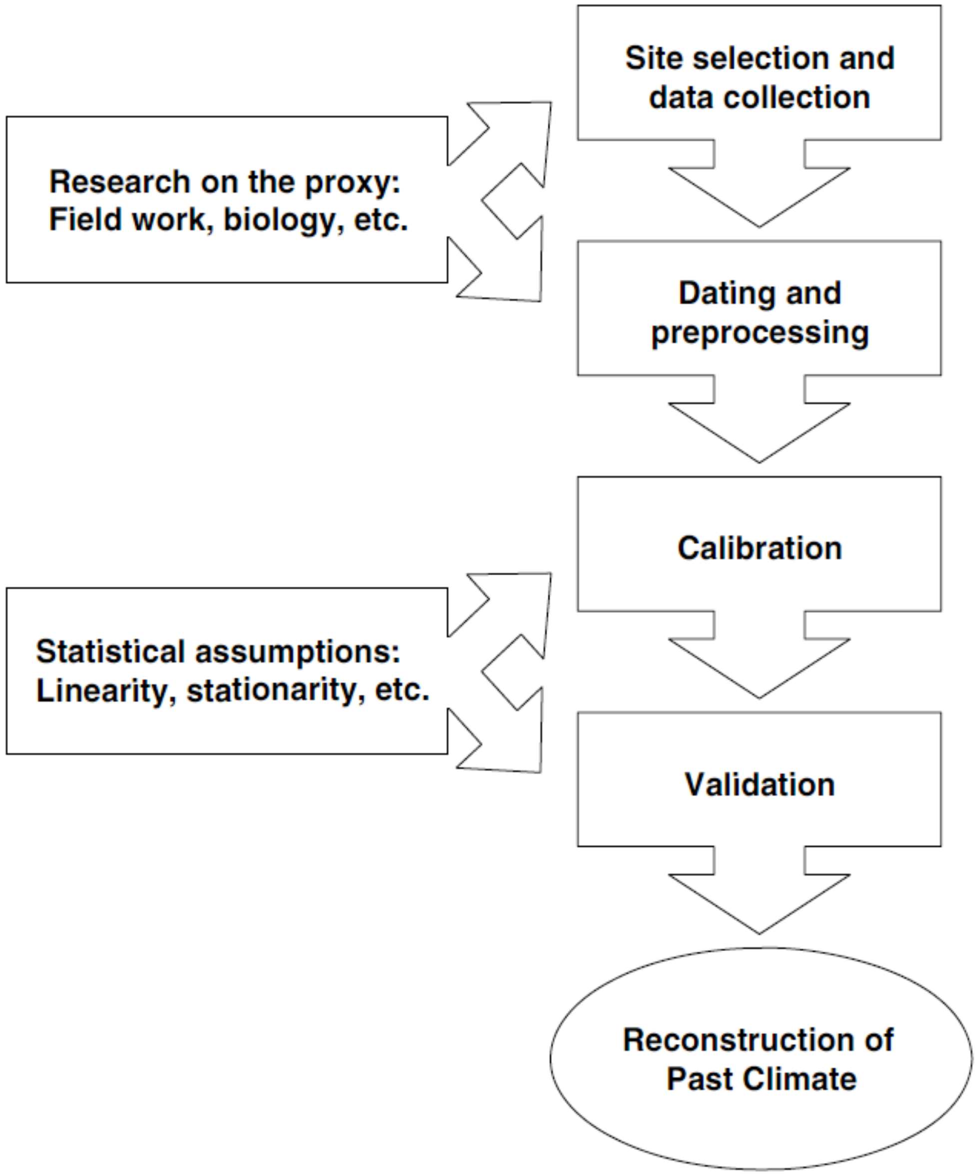
National and State Libraries Australasia

phm powerhouse museum science+design

State Library of Victoria

2. Reconstruction methods

Common reconstruction methods



- Exploit known relationships of chemical, biological and/or ecological processes to convert natural proxy data into climate variables (calibration)

- Calibration is a statistical process that typically involves linear regression of proxy data against overlapping instrumental climate record: linearity and stationarity are assumed

- Linear regression coefficients derived from the calibration are then used as a model to reconstruct time series of climate variables from the proxy data

- Part of the instrumental data are with held from calibration to run verification tests (a suite of metrics is used to assess model skill)

Source: Surface Temperature Reconstructions for the Last 2,000 years, US National Academy of Sciences, 2006

Estimating reconstruction skill

- There are a number of metrics that can be used to estimate the skill of a palaeoclimate reconstruction through comparison with observations during some independent period of overlap

- All metrics are equally valid, but should not be taken in isolation to test model skill. Conversely, if one metric does not show skill, this does not mean the reconstruction should be considered as having no skill – BUT the reason why this metric fails should be determined

- There will always be errors associated with a linear fit to the data – e.g. biological influences, human influences, other climate influences not associated with your particular variable OR a linear fit may not be a good assumption

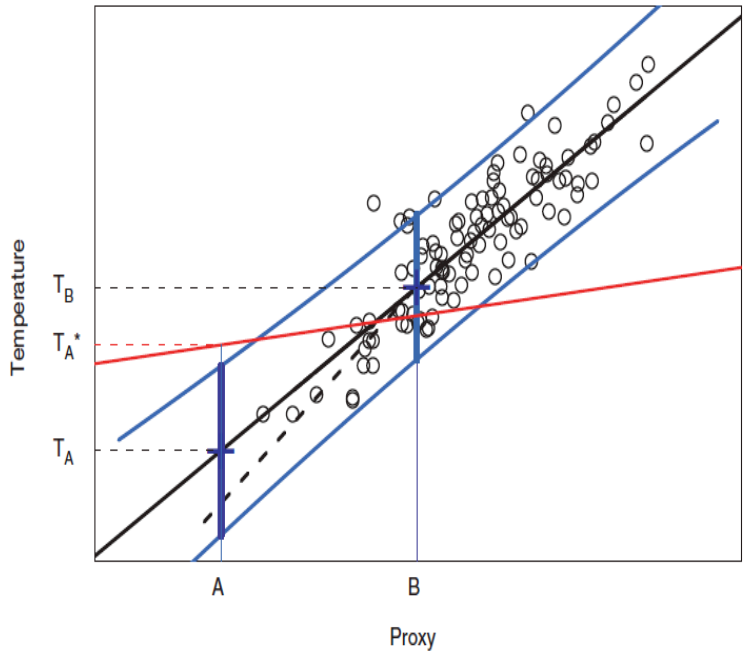


FIGURE 9-1 An illustration of using linear regression to predict temperature from proxy values. Plotted are 100 pairs of points corresponding to a hypothetical dataset of proxy observations and temperature measurements. The solid black line is the least-squares fitted line and the blue lines indicate 95 percent prediction intervals for temperature using this linear relationship. The dashed line and the red line indicate possible departures from a linear relationship between the proxy data and the temperature data. The figure also illustrates predictions made at proxy values A and B and the corresponding prediction intervals (wide blue lines) for the temperature.

Measures of Reconstruction Accuracy

Let y_t denote a temperature at time t and $\hat{y}_t$ the prediction based on a proxy reconstruction.

Mean squared error (MSE)

$$\mathrm{MSE}(\hat{y}) = \frac{1}{N}\sum (y_t - \hat{y}_t)^2,$$

where the sum on the right-hand side of the equation is over times of interest (either the calibration or validation period) and N is the number of time points.

Reduction of error statistic (RE)

$$\mathrm{RE} = 1 - \frac{\mathrm{MSE}(\hat{y})}{\mathrm{MSE}(\bar{y}_c)},$$

RE - compares the reconstruction to the instrumental mean during calibration period

where $\mathrm{MSE}(\bar{y}_c)$ is the mean squared error of using the sample average temperature *over the calibration period* (a constant, $\bar{y}_c$) to predict temperatures during the period of interest:

$$\mathrm{MSE}(\bar{y}_c) = \frac{1}{N}\sum (y_t - \bar{y}_c)^2$$

Coefficient of efficiency (CE)

$$\mathrm{CE} = 1 - \frac{\mathrm{MSE}(\hat{y})}{\mathrm{MSE}(\bar{y}_i)},$$

CE - compares the reconstruction to the instrumental mean during verification period

where $\mathrm{MSE}(\bar{y}_i)$ is the mean squared error of using the sample average *over the period of interest* ($\bar{y}_i$) as a predictor of temperatures during the period of interest:

$$\mathrm{MSE}(\bar{y}_i) = \frac{1}{N}\sum (y_t - \bar{y}_i)^2$$

Squared correlation (r^2)

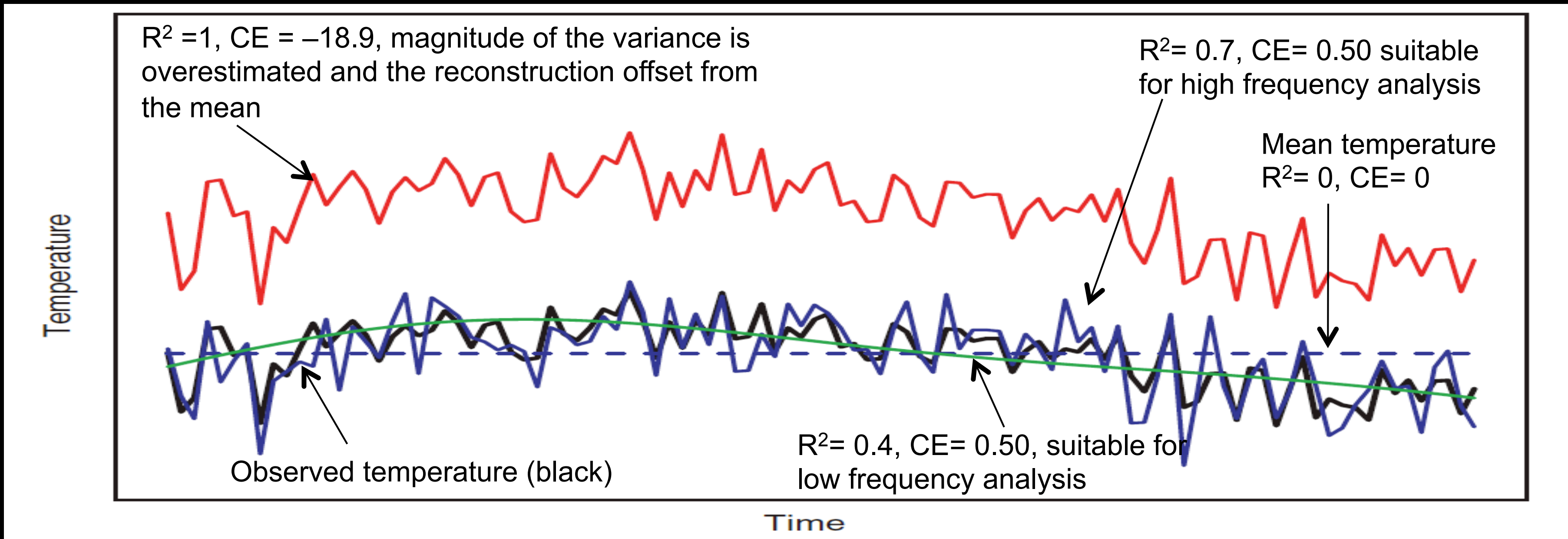
$$r^2 = \frac{\left[\sum (y_t - \bar{y}_i)(\hat{y}_t - \bar{\hat{y}})\right]^2}{\sum (y_t - \bar{y}_i)^2 (\hat{y}_t - \bar{\hat{y}})^2}$$

R^2 - variance in the instrumental record that can be explained by the reconstruction

If $\hat{y}_t$ are the predictions from a linear regression of y_t on the proxies, and the period of interest is the calibration period, then RE, CE, and r^2 are all equal. Otherwise, CE is less than both RE and r^2.

Source: Surface Temperature Reconstructions for the Last 2,000 years, US National Academy of Sciences, 2006

Estimating reconstruction skill - beyond correlations



- Black line is a hypothetic temperature series (predictand we are fitting palaeo predictors to)

- Red reconstruction has an r^2 of 1 but a CE of –18.9 (CE measures how well the reconstruction tracks high frequency variations in the validation period)

- The red time series is an example of a perfectly correlated reconstruction with no predictive skill according to the metrics

-The blue and green reconstructions both have a CE of 0.50. For either of these reconstructions to be better than just the mean, they must exhibit some degree of correlation with the temperatures. Green line tracks low frequency variations, the blue tracks high frequency

* A suite of calibration/verification measures are needed to adequately and robustly estimate uncertainty……this work is politically sensitive and will be heavily scrutinised !!

3. Southern Hemisphere annual multi-proxy reconstructions

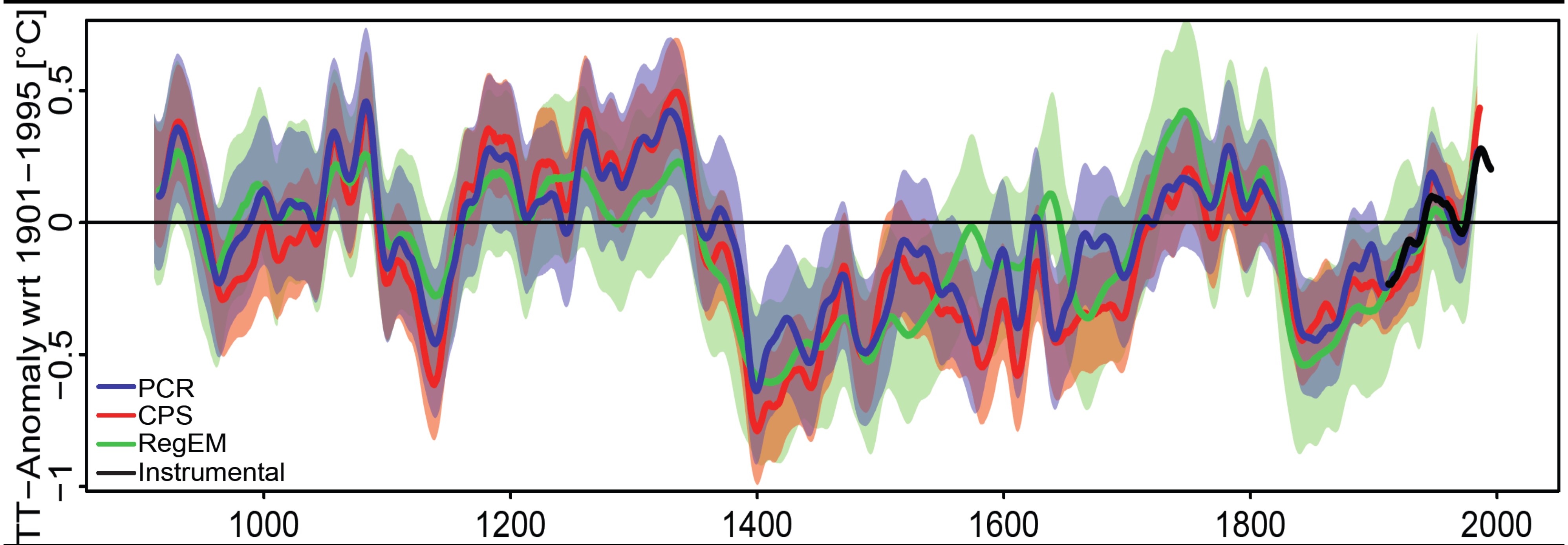
Progress in South American multi proxy climate reconstructions

- First multi proxy temperature (and precipitation) reconstructions from southern South America using 22 proxies: most confidence in post 1706 period

- Three statistical techniques used to check sensitivity of the results (PCR highest skill)

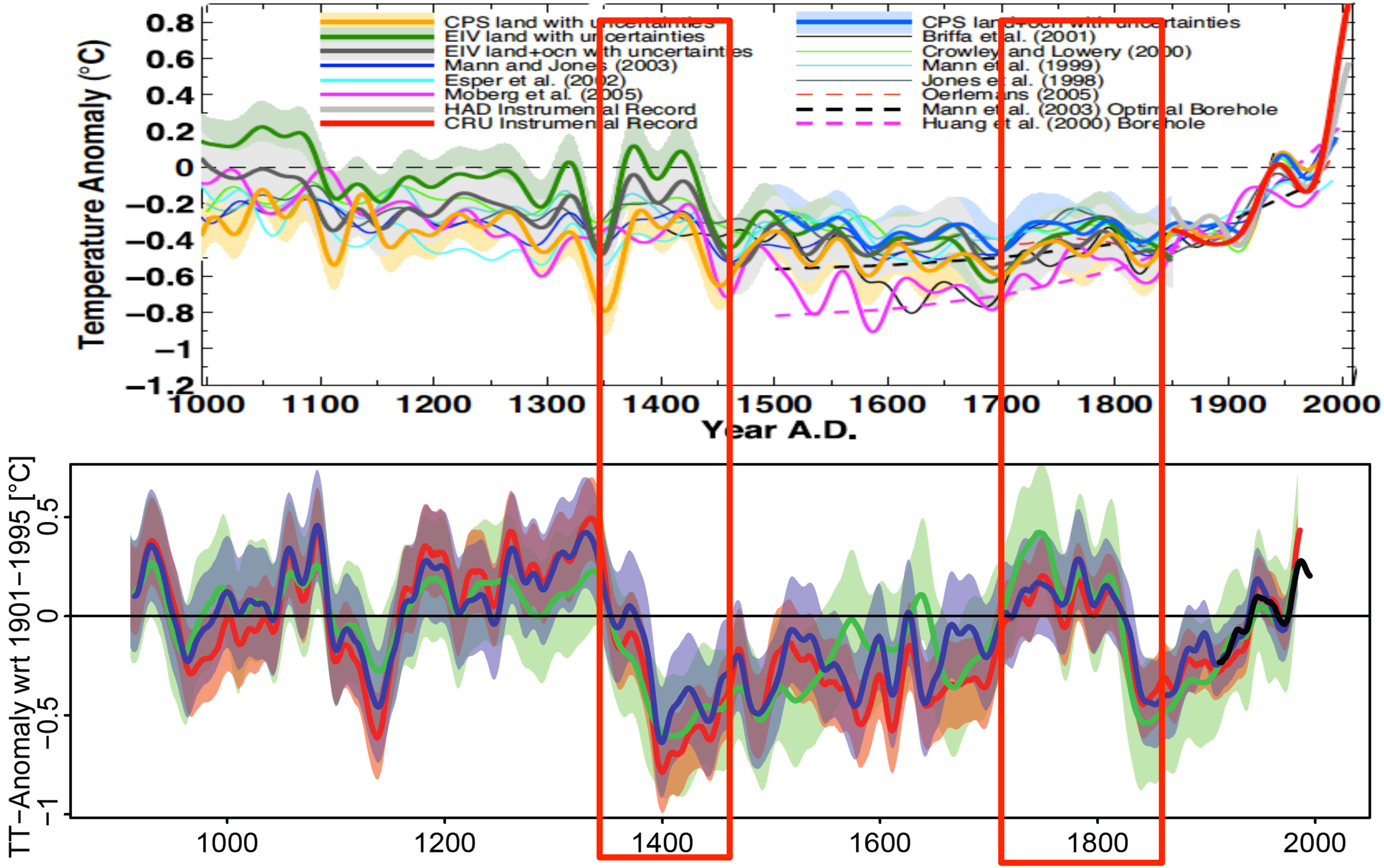
- 900-1350 around/above C20th average: cool periods ~1400–1700, 1850, warm 1710-1820

- Precipitation reconstructions also developed (Neukom et al, GRL in review)



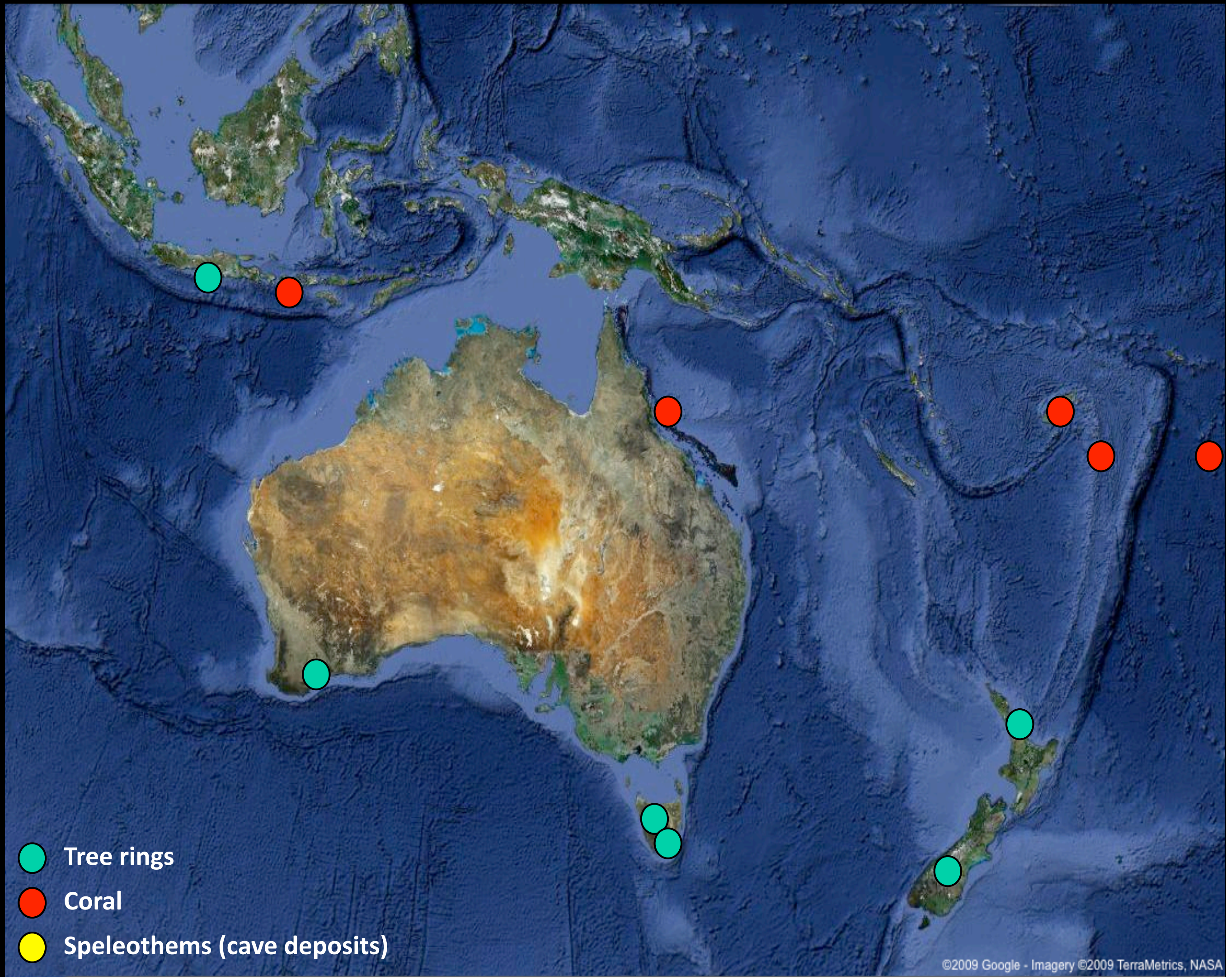
Neukom et al. (2010) Climate Dynamics

Northern Hemisphere temperature means vs. southern Southern America: regional differences, limited replication, calibration techniques?



An annually resolved rainfall reconstruction for SEA, 1782–1988

- Used 12 well dated, annually resolved records (4 coral records, 1 ice core and 7 tree ring chronologies) with published climate sensitivity from the Australasian region (largely ENSO)
- Run a pilot analysis to develop a rainfall reconstruction for SE Australia



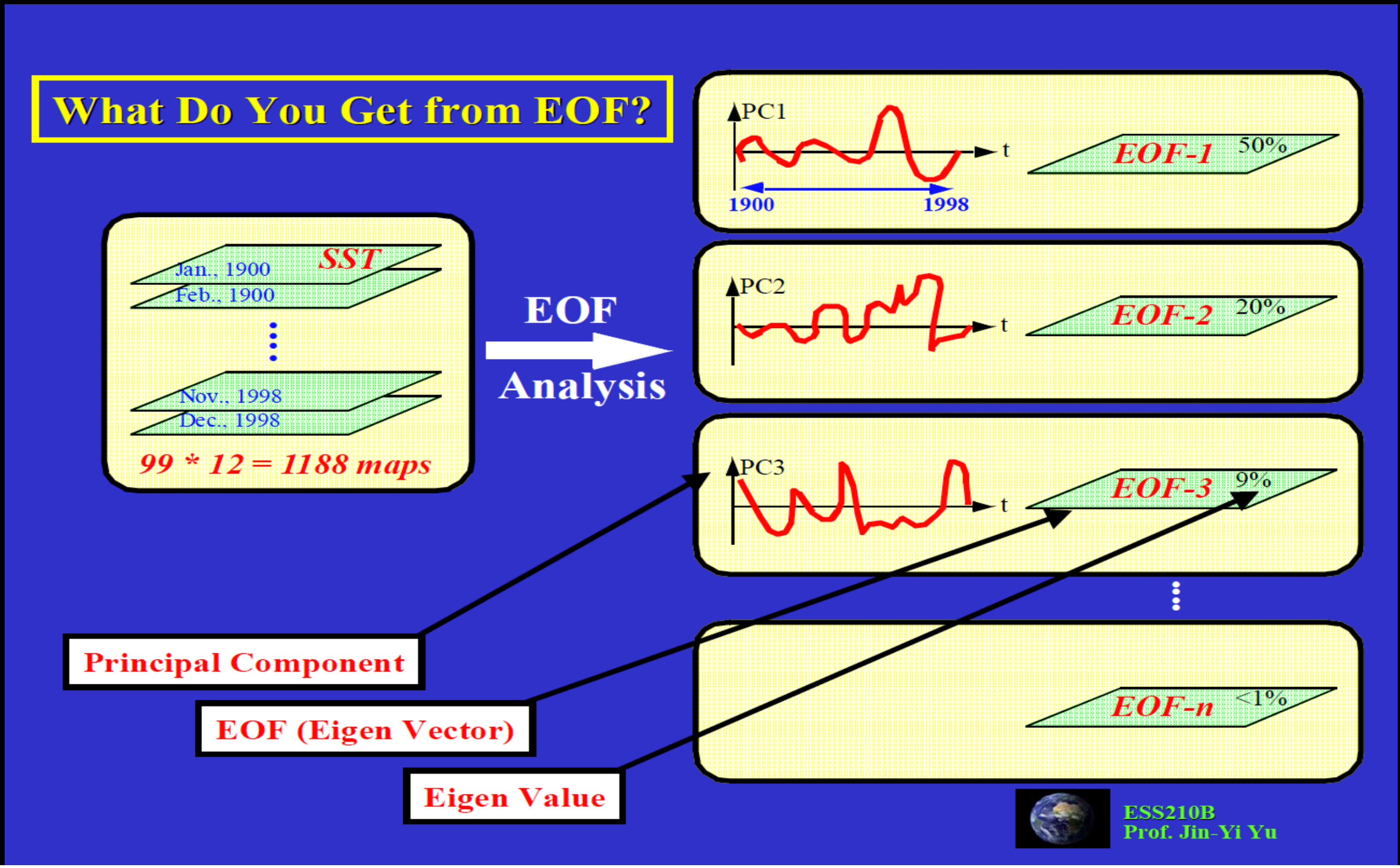
Methodology: Principal Component Regression

- Decomposes multi variate data sets into common modes of variability: producing a distinct spatial pattern correlation (eigen vector) and associated time series (principal component)

- Correlation of each grid point to the corresponding PC time series reveals coherent spatial structures.. pulls out commonalities…non-coherent modes fall out as higher order PCs (noise)

- Eigenvalues of the covariance matrix tells you the fraction of variance explained by each individual EOF: the first EOF often explains most of the variance

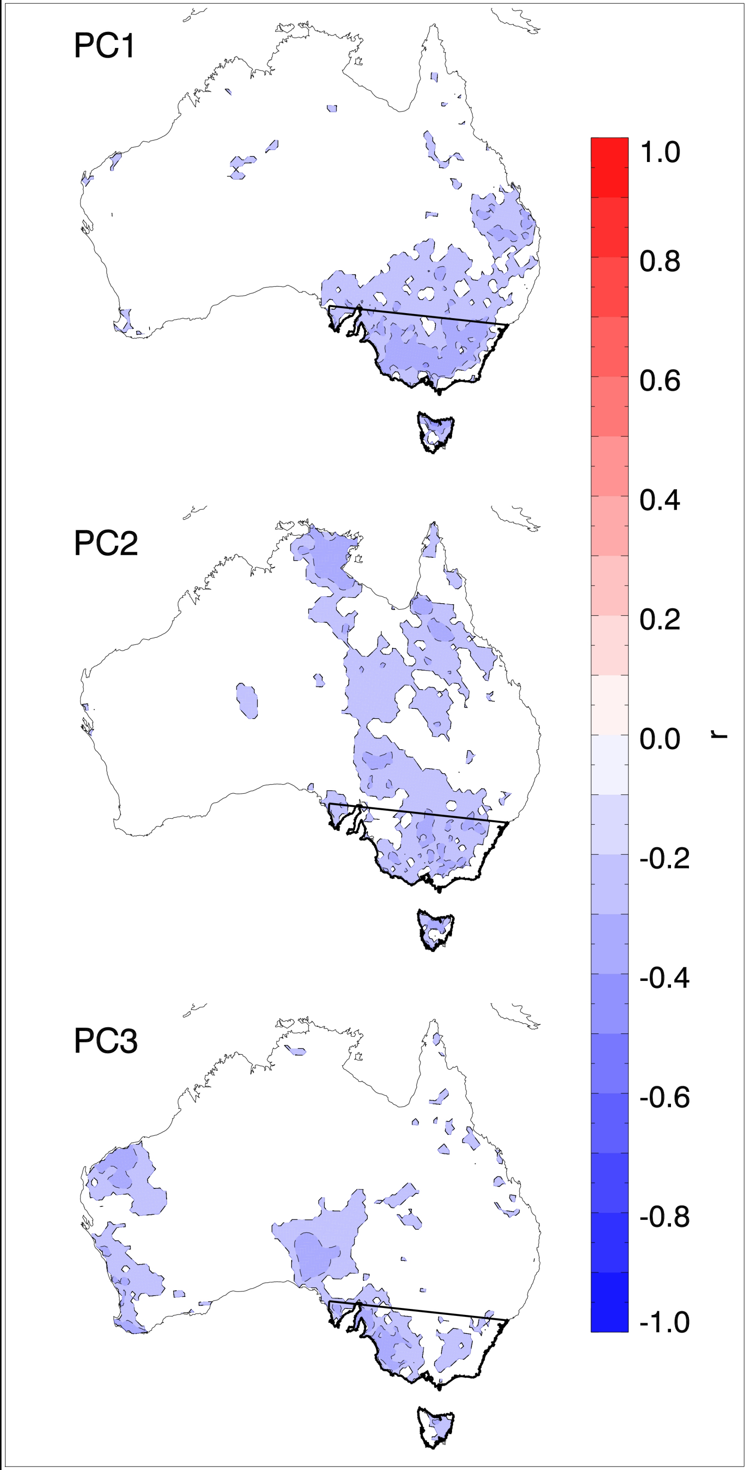
- Leading PCs of the palaeo network (predictors) to reconstruct instrumental rainfall, temp (predictands)



Correlations between leading palaeo PCs and Australian rainfall observations

Statistically significant correlations between PCs1–3 and annual (May–April) Australia rainfall (AWAP)

- PC only selected for the reconstruction if least 20% of the SEA region display a statistically significant correlations with the palaeo PC
- Distinct relationship with May–April SEA area averaged rainfall (PC1= –0.40, PC2= –0.34, PC3= –0.30), evenly spread in 3 leading modes
- PCs 1–3 combined using multiple regression show significant correlations with rainfall (r=0.57), SOI (r=0.63) and the IPO (–0.50) on inter-annual timescales
- Palaeo network of remote predictors clearly capturing SEA rainfall variations on annual and decadal timescales

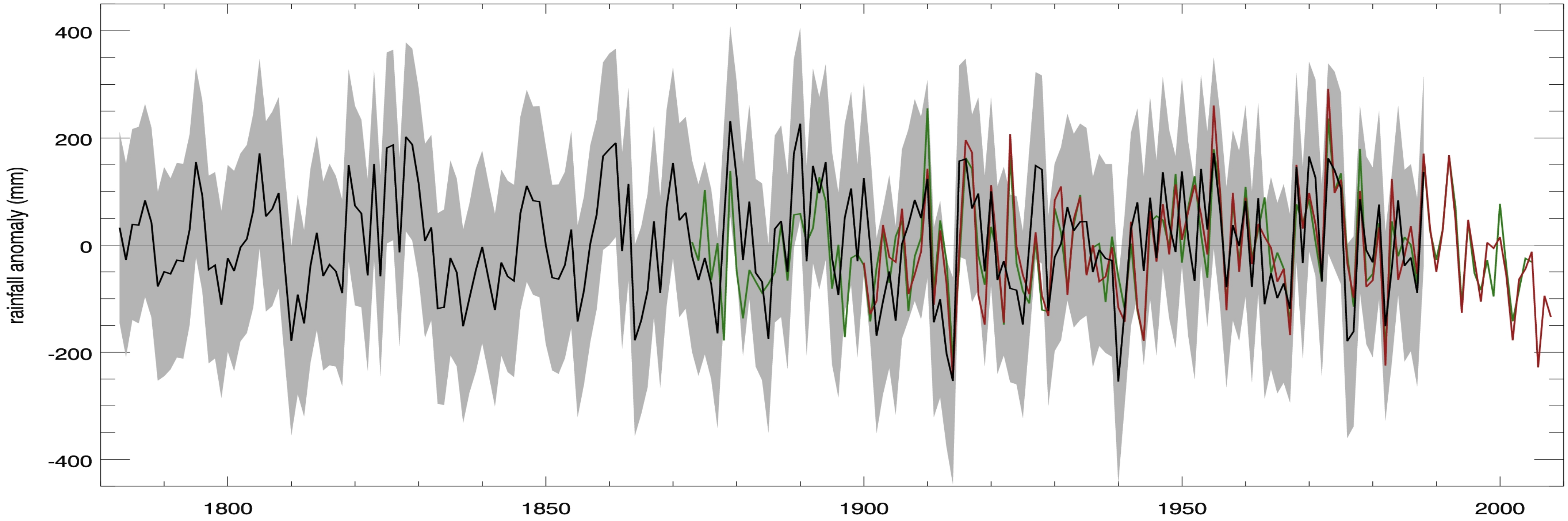


The potential dangers of single-period calibration – an example

- Period of overlap between the instrumental and palaeo PCs (1900–1988) was used to determine the transfer function to develop the reconstruction
- Tested full, early and late period calibration …and resampling technique (bootstrap method)
- The validation of the reconstruction is HIGHLY sensitive to the calibration periods selected - reflects that the parameters estimated for the linear model used to create the reconstruction are sensitive to the period chosen for calibration – this is a problem.
- Using the late period calibration fails verification in early period, early period calibration robustly verifies but only capture 11% of variance in calibration period
- Full period calibration gives no uncertainty estimates so hard to assess reliability/uncertainty
- Monte Carlo random sampling technique provides a suite of uncertainty estimates rather than measures derived from one verification period only (which may inflate true model skill)

Statistic	Full period calibration (1900–1988)	Early period calibration (1900–1944)	Late period calibration (1945–1988)	Monte Carlo calibration median (1900–1988)
r	0.57	0.41	0.71	0.57
ar^2	0.30	0.11	0.46	0.33
r	–	0.70	0.41	0.55
RE	–	0.39	0.16	0.13
CE	–	0.27	–0.02	0.10
ST	–	(35/45) 78%	(24/20) 56%	(27/12) 69%
RMSE	–	0.85	0.98	0.94

Annual SEA rainfall reconstruction 1783–1988

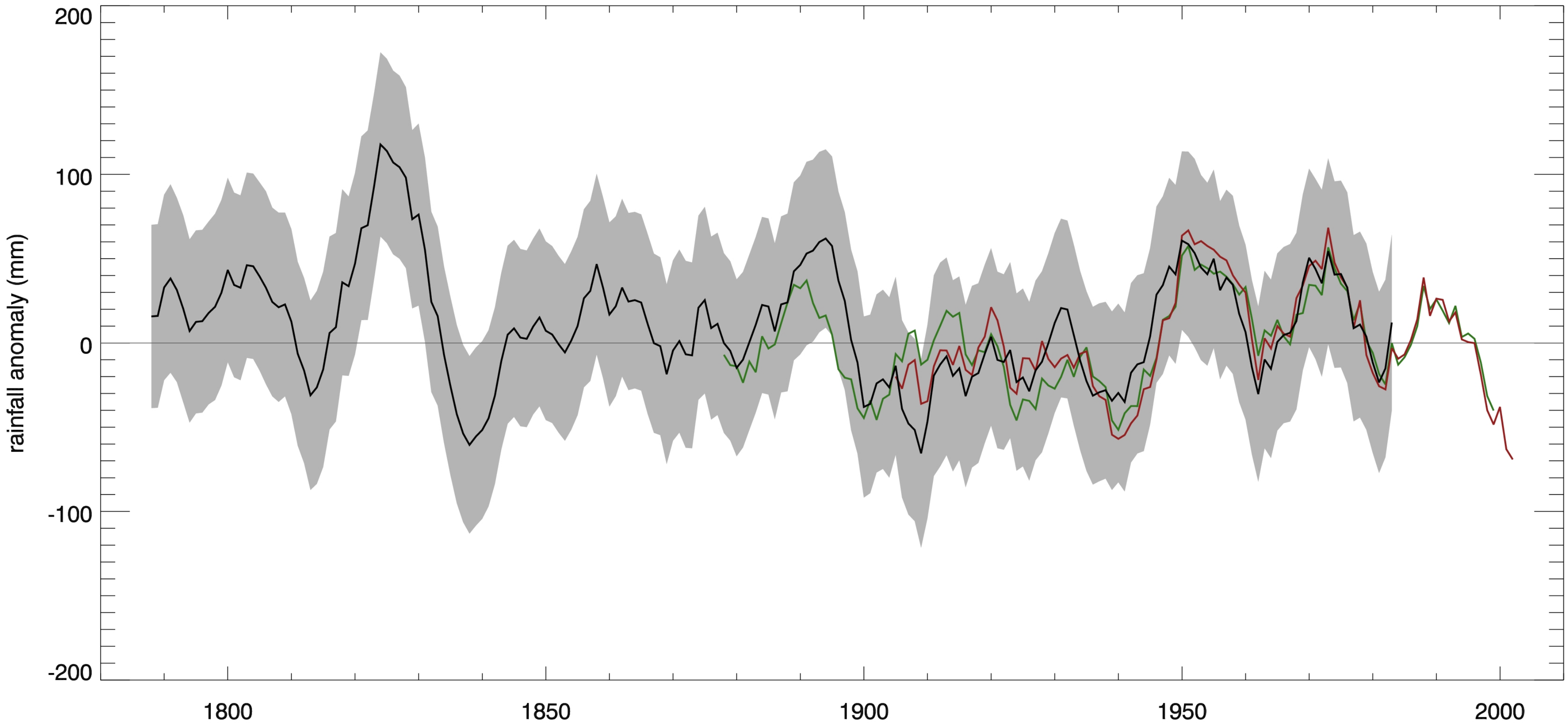


Gergis, J., Gallant, A., Braganza, K., Karoly, D., Allen, K., Cullen, L., D'Arrigo, R., Goodwin, I., Grierson, P. and McGregor, S. (2010)

Climate Dynamics (submitted)

- A bootstrapping approach to randomly select 5 independent decades of data from the 90 year period of overlap with observations for calibration and used remaining 40 years for verification.
- 10,000 reconstructions provide a “best estimate” reconstruction based on the median of the ensemble (black time series) with uncertainties due to calibration and random noise indicated as 2 SDs of the error distribution
- The the reconstruction r = 0.57 ± 0.08 (i.e. 33% ± 9% of the variance in instrumental rainfall)
- The red time series is AWAP observations and the green time series is 9 early rainfall records

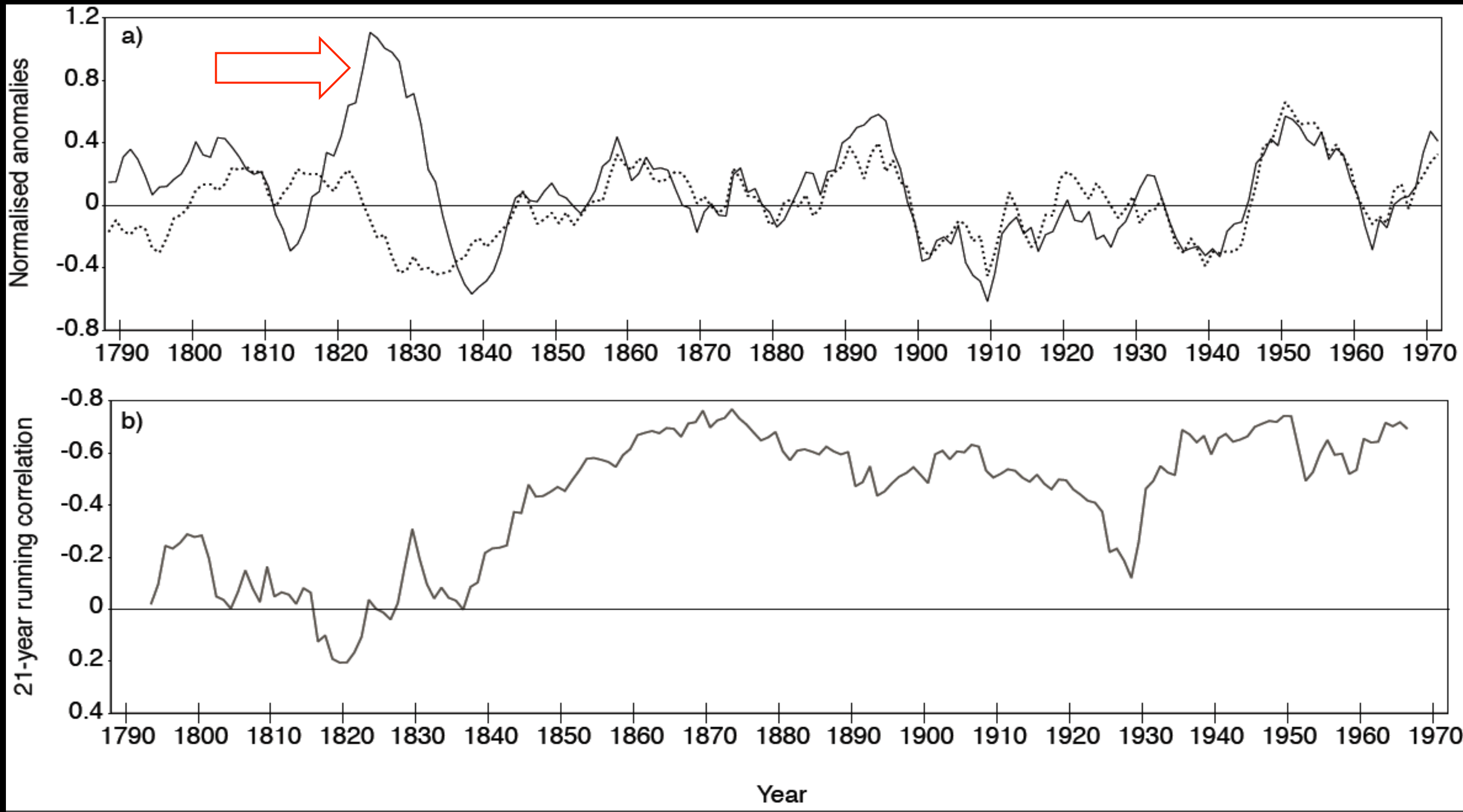
Decadal variability in SE Australian rainfall



Source: Gergis, Gallant, Braganza, Karoly, Allen, Cullen, D'Arrigo, Goodwin, Grierson and McGregor, Climate Dynamics (submitted)

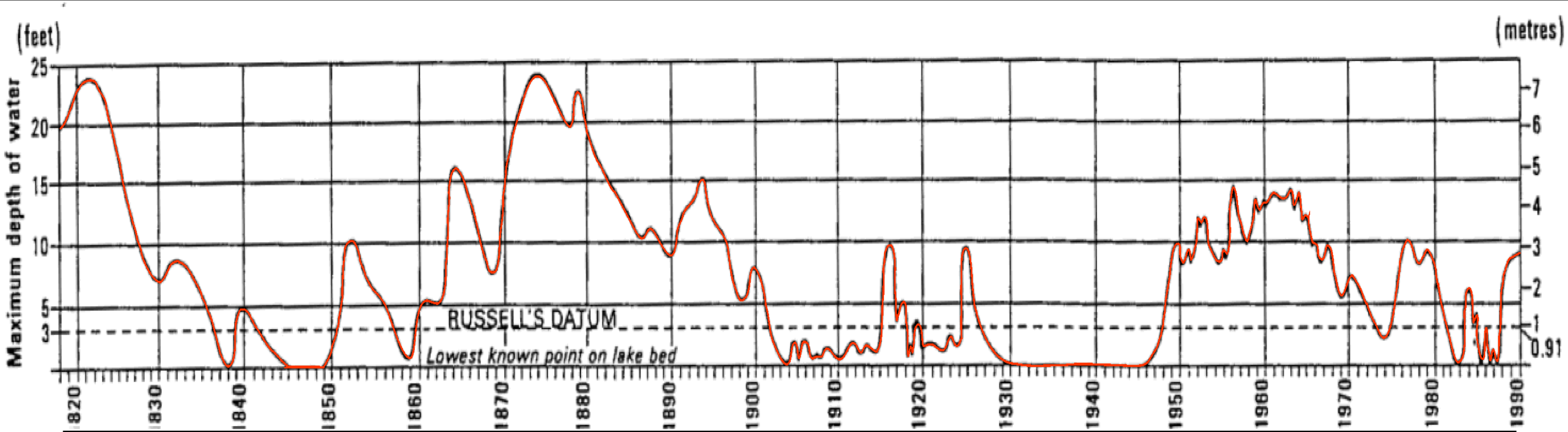
- The "best estimate" represents 73% decadal variability (r = 0.85) in SEA rainfall captured by the palaeo network
- Distinct decadal scale wet and dry phases associated with the IPO (r= –0.77, 1905–1983)
- Peak wet periods mostly associated IPO negative phase (warm SSTs in in W.Pac, La Nina-like)
- Prolonged drying mostly associated with IPO positive phases (cool SSTs in W.Pac, El Nino-like)

Decoupling of the the regional SEA rainfall–ENSO/IPO relationship



- Very close relationship between 11yr running means of McGregor's (2010) Unified ENSO Proxy (UEP minus Braganza, dotted line) and SEA rainfall (solid line)
- Decoupling of the the regional SEA rainfall–ENSO/IPO relationship
- Full period correlation (1788–1971) r= 0.47, partial period 1840–1971, r= 0.84)
- Marked decoupling of regional SEA rainfall and global ENSO/IPO: tested individual proxies sensitivity, combinations and independent ENSO reconstructions,
- We think the breakdown is associated with pronounced wet period 1818–1833 (peaking at ~100mm above C20th average) is a real climate signal not a data issue…

Independent verification – Lake George lake levels



SEA wet periods	IPO negative phases	SEA dry periods	IPO positivephases
1788–1793	1800–1823	1812–1815	1788–1799
1797–1809	1855–1870	1835–1842	1824–1854
1818–1833	1874–1898	1900–1904	1899–1918
1856–1865	1919–1925	1906–1911	1926–1945
1887–1897	1946–1960	1914–1918	1961–1964
1946–1959	1965–1971	1924–1927	
1969–1976		1935–1942	

- Marked pluvial in the SEA rainfall reconstruction (1818–1833) corroborates with independent documentary records and historical Lake George levels (1818–1990)…the wet interval is real !
- High rainfall in SEA rainfall associated with negative IPO phases (more La Nina-like)
- Pre 1840: early 1800s cooling (1^{o}C colder than present), and period of high tropical volcanism e.g. 1815 Tambora eruption ‘year without a summer’

Key results

- We can do this! There are enough records to skillfully reconstruct Australasian climate on inter-annual to decadal timescales…will now extend this method back 500yrs

- A skillful reconstruction of annual (May–April) SEA rainfall is possible using just 12 annually dated palaeo records.

- The SEA rainfall reconstruction shows:
  - The C18–19th markedly wetter: contains 75% of reconstructed wet periods

  - The C20th contains 70% of all the multi-year dry periods reconstructed since 1783: 8 year drought from 1835–1842 is the longest in the reconstruction and 1935–1942

  - A lack of multi year rewetting characterises the mid-1970 period: anthropogenic warming overlain on natural variability? Signs of negative IPO phase (more rain?)

  - ENSO and IPO relationship is robust post 1840 and exhibits some very interesting instability in the late C18th/ealry C19th..consistent with other studies from the SW Pacific

  - There is a need to determine the forcing of the decoupling of SEA rainfall and ENSO: global cooling, volcanic activity, changes in Pacific circulation

What's next?

- Our reconstruction scripts are now well developed and ready to go, flexible to accommodate different climate variables (rainfall, temperature, pressure) and geographic co-ordinates
- Welcome additional proxies to be tested and added to SEA and/or Australasian climate reconstructions
- Plan to examine the covariability of temperature and rainfall for proxy calibration: coherent regions of variability in the instrumental records vs. palaeo records
- Recommend the discussion of reconstruction uncertainty and the use of 'ensemble' approaches to calibration and address the under-utilisation of alternative statistical methods
- What can modelers tell us about climate forcing especially during transitions e.g. LIA>industrial era?
- Contact me if you'd like to collaborate…