Reconstruction of climate fields for the Australasian region using data assimilation

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Context

Context: The climate of the last 2000 years

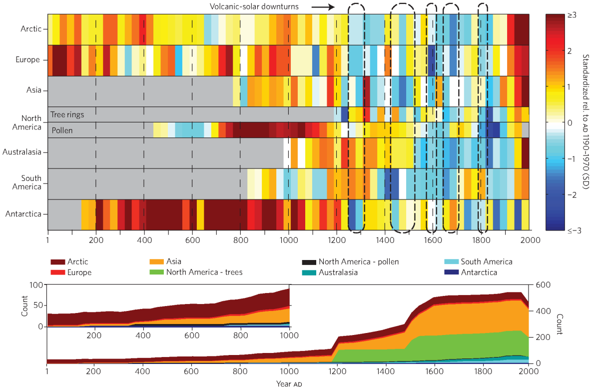
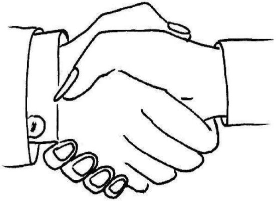


Figure 2 | Continental-scale temperature reconstructions. 30-year-mean temperatures for the seven PAGES 2k Network regions, standardized to have the same mean (0) and standard deviation (1) over the period of overlap among records (AD 1190–1970). North America includes a shorter tree-ring-based and a longer pollen-based reconstruction. Dashed outlines enclose intervals of pronounced volcanic and solar negative forcing since AD 850 (see Methods). The lower panel shows the running count of number of individual proxy records by region. Data are listed in Supplementary Database S2.

PAGES 2k Consortium (2013)

The "handshake" question

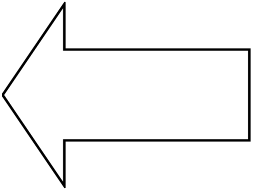


How do we integrate data from natural archives with climate models in a way that extracts the maximum possible information about the dynamics of the climate system?

The inverse approach

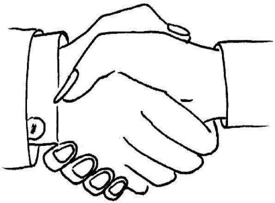
- Translate proxy variables into physical climate variables.
- Achieved by calibrating proxy variables against local or remote climatic variables, typically using observational data.
- Involves the necessary but usually implicit assumption of stationarity.
- Proxies can integrate multiple environmental variables, so information is lost when only reconstructing a single variable.

The forward approach

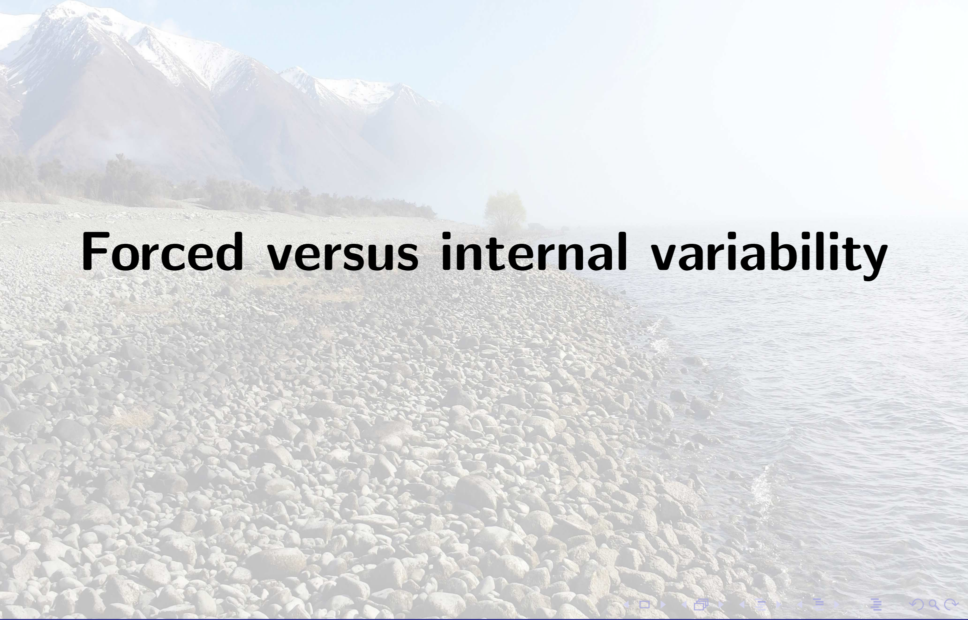


- Translate model variables into proxy variables.
- Achieved by using physical and biological principles to simulate the evolution of proxy variables within a modelling framework.
- Capable of avoiding the assumption of stationarity.
- Can account for the fact that proxies integrate multiple variables.
- Require a complete description of all the relevant processes.

Embracing integrated approaches



- If we really want to learn everything that we can from the climate of the last 2000 years, then we need to embrace integrated approaches.
- The models and the proxies should be employed in a unified fashion to reconstruct and understand past changes in the climate.
- Climate modelling needs to be seen as part of the process of palaeoclimate reconstruction itself.



Forced versus internal variability

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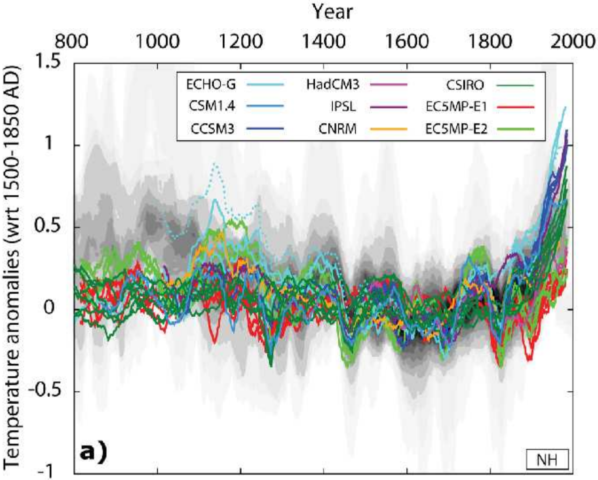
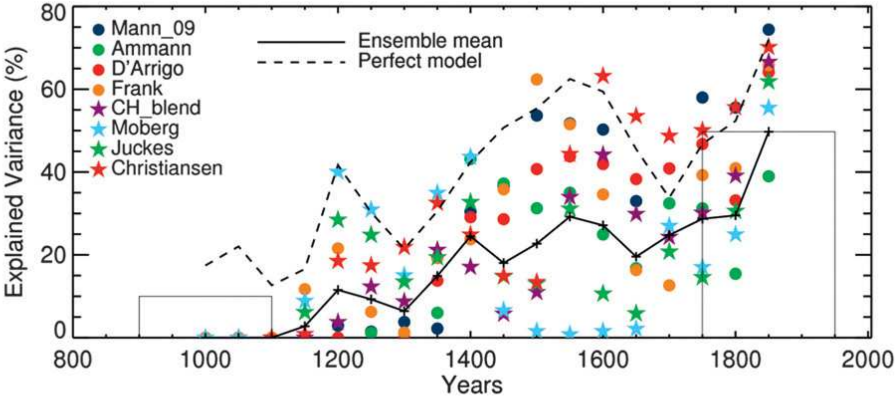


Fernández-Donado et al. (2013)

Forced versus internal variability

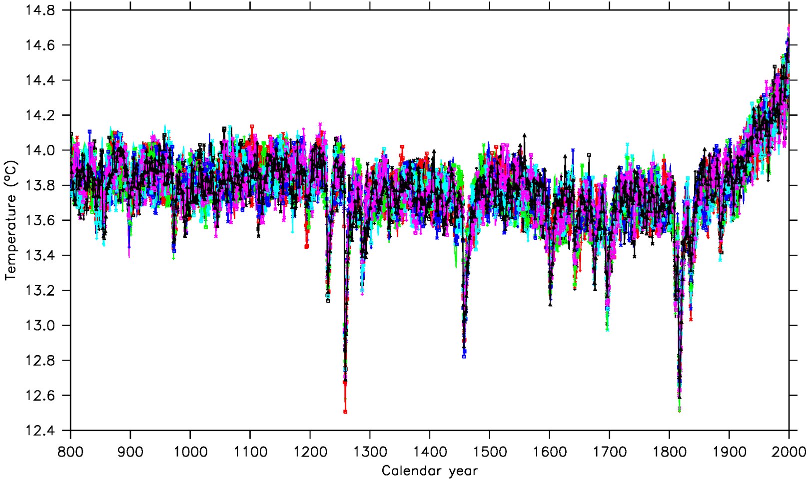


Schurer et al. (2013)

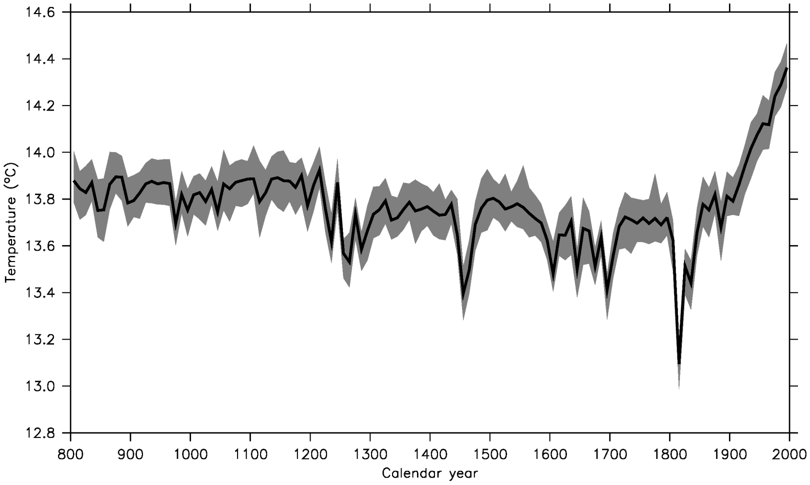
Climate model simulations

- The CSIRO Mk3L climate system model (Phipps et al., 2011, 2012)
  - Atmospheric general circulation model ($5.6^\circ \times 3.2^\circ$, 18 levels)
  - Ocean general circulation model ($2.8^\circ \times 1.6^\circ$, 21 levels)
  - Dynamic-thermodynamic sea ice model
  - Land surface scheme
- External boundary conditions:
  - Orbital changes (Berger, 1978)
  - Anthropogenic greenhouse gases (MacFarling Meure et al., 2006)
  - Solar irradiance (Steinhilber et al., 2009)
  - Explosive volcanism (Crowley and Unterman, 2013)
- Ensemble OGS25: 25 simulations 1–2000 CE (O, G, S)
  - Each member initialised from different year of control simulation
- Ensemble OGSV25: 25 simulations 801–2000 CE (O, G, S, V)
  - Each member branched off equivalent member of ensemble OGS25

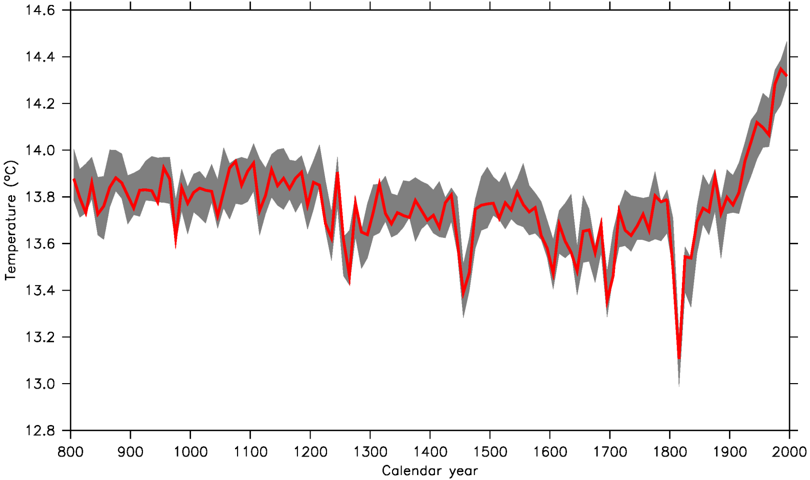
Simulated global-, annual-mean surface air temperature



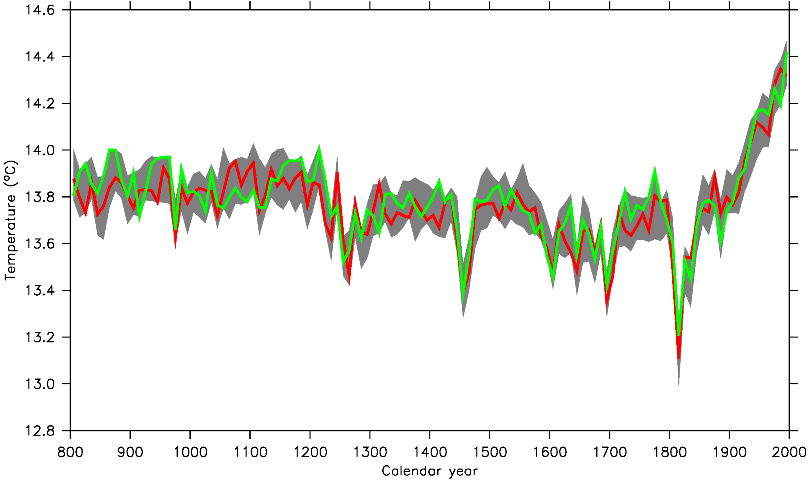
Simulated global-, decadal-mean surface air temperature



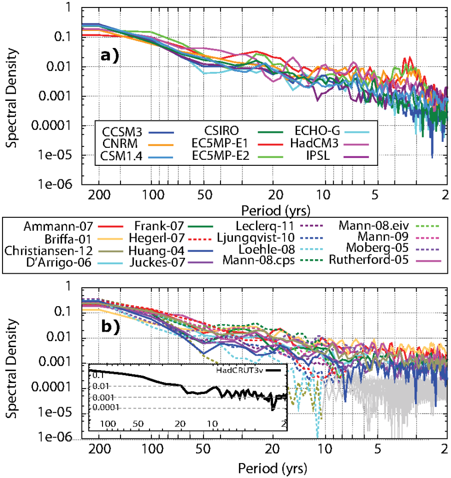
Each ensemble member is just one roll of the dice ...



... but so is the real world



One solution: think in the frequency domain



Fernández-Donado et al. (2013)

Climate field reconstruction using data assimilation

Data assimilation: an opportunity

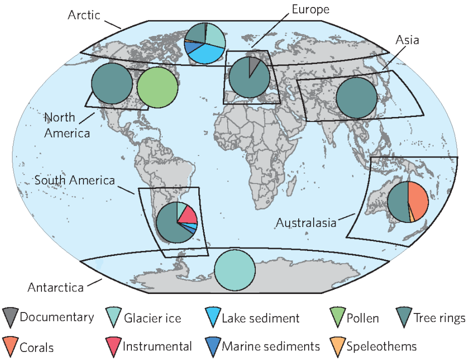
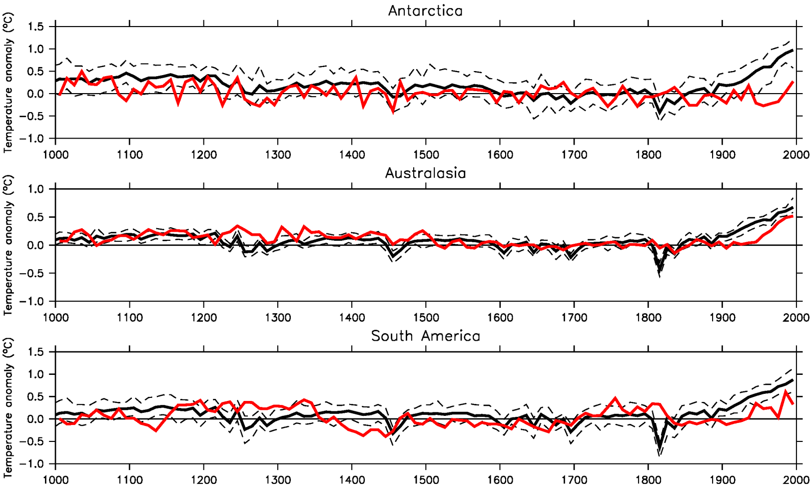


Figure 1 | The PAGES 2k Network. Boxes show the continental-scale regions used in this study. The pie charts represent the fraction of proxy data types used for each regional reconstruction. Supplementary Database S1 includes information about each study site and the proxy data for all time series used in the regional reconstructions.

PAGES 2k Consortium (2013)

Simulated and reconstructed decadal-mean temperature



Correlations between model and reconstructions

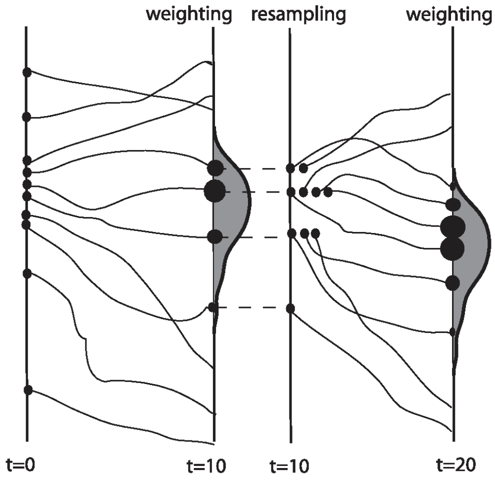
Region	Ensemble mean	Individual members	
		Minimum	Maximum
Antarctica	+0.20	+0.06	+0.27
Australasia	+0.52	+0.44	+0.55
South America	+0.15	+0.07	+0.25

An infinite number of monkeys ...

... or data assimilation?

- In data assimilation, we constrain a climate model to follow the evolution of proxies or reconstructions.
- We cannot perform data assimilation in the same manner as dynamical meteorology, because of the limited spatial extent and temporal resolution of the proxy data (Widmann et al., 2010).
- Palaeoclimate data assimilation can be performed offline:
  - Run a large ensemble and simply choose the simulation that performs best ("infinite monkeys").
  - Run a large ensemble and generate a weighted ensemble mean, based on some assessment of skill.
- Optimally, however, we perform interactive data assimilation, using a technique such as particle filtering (van Leeuwen, 2009).

Particle filter with resampling



van Leeuwen (2009)

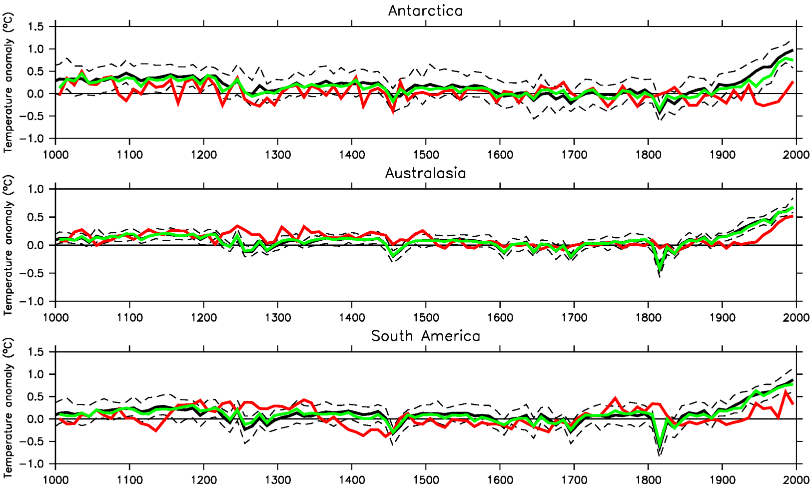
Proof of concept: offline data assimilation

- Let's try assimilating the three Southern Hemisphere PAGES 2k reconstructions into the OGSV25 ensemble.
- For each decade during the period 1001–2000 CE, calculate a cost function following e.g. Crespin et al. (2009):

$$C(t) = \sqrt{\sum_{\text{recon}} (T_{\text{recon}}(t) - T_{\text{model}}(t))^2}$$

- Use these values to calculate a *weighted* ensemble mean.
- Here, each ensemble member is weighted by e^{-10C}.

Simulated and reconstructed decadal-mean temperature

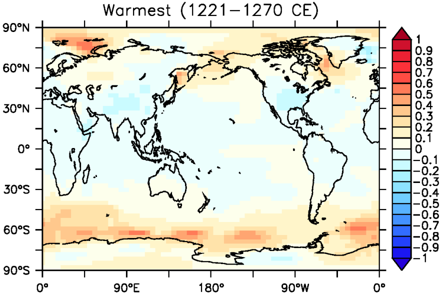


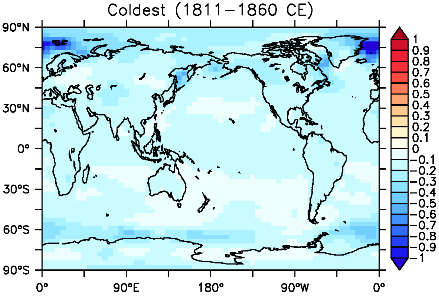
Correlations between model and reconstructions

Region	Ensemble mean	Individual members: Minimum	Individual members: Maximum	Assimilation
Antarctica	+0.20	+0.06	+0.27	+0.48
Australasia	+0.52	+0.44	+0.55	+0.56
South America	+0.15	+0.07	+0.25	+0.38

Reconstructed temperature anomalies (°C)

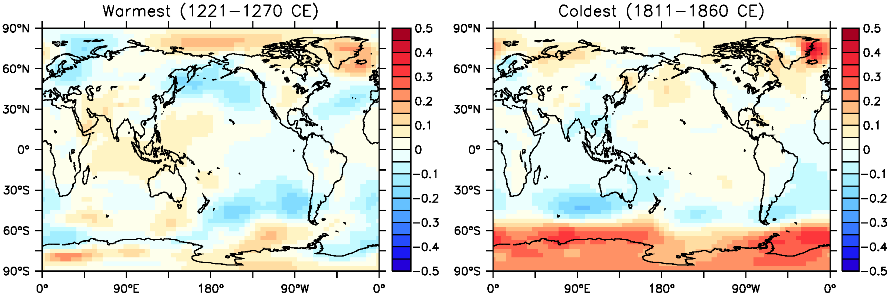
- Use the outcome of the data assimilation to reconstruct spatial fields for the warmest and coldest 50-year periods in Australasia during the pre-industrial period (pre-20th century).
- Anomalies are shown relative to 1501–1850 CE.





Reconstructed mean sea level pressure anomalies (hPa)

- Use the outcome of the data assimilation to reconstruct spatial fields for the warmest and coldest 50-year periods in Australasia during the pre-industrial period (pre-20th century).
- Anomalies are shown relative to 1501–1850 CE.



Data assimilation: pros

- Internal climate variability becomes the *solution*, not the *problem*.
- Avoids any assumption of stationarity.
- The cost function can be multi-variate and can seamlessly handle records with different temporal resolution: we can simultaneously assimilate low-resolution and high-resolution proxies for different climatic variables (temperature, precipitation, sea ice...).
- No lower limit on the number of records required (N.B. skill).
- Requires no modifications to existing models.
- For offline data assimilation, you don't even need to run a model.

Data assimilation: cons

- Still requires proxy variables to be converted to physical climate variables, so still requires local calibration (although this could be resolved by combining data assimilation with forward modelling).
- Relies on internal climate variability to sample climate states: we cannot generate the "true" state if this lies outside the range of simulated natural climate variability.
- Computationally expensive (e.g. 96 ensemble members).

Conclusions

- Climate modelling can play a much more fundamental role than just post-hoc comparison with reconstructions.
- Two particularly promising areas are:
  - testing and evaluating techniques for climate field reconstruction
  - directly assimilating proxies into a climate modelling framework
- Data assimilation has the potential to generate spatial reconstructions, but careful consideration needs to be given to the nature of the assimilation (frequency, spatial degrees of freedom).
- Has the potential to act as an independent check on other methods.
- Possible activity for the PAGES Aus2k Working Group:
  - Generate a large ensemble of model simulations (DONE).
  - Use this ensemble to test different ways of assimilating SH proxies.
  - Perform a fully interactive assimilation using particle filtering.

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