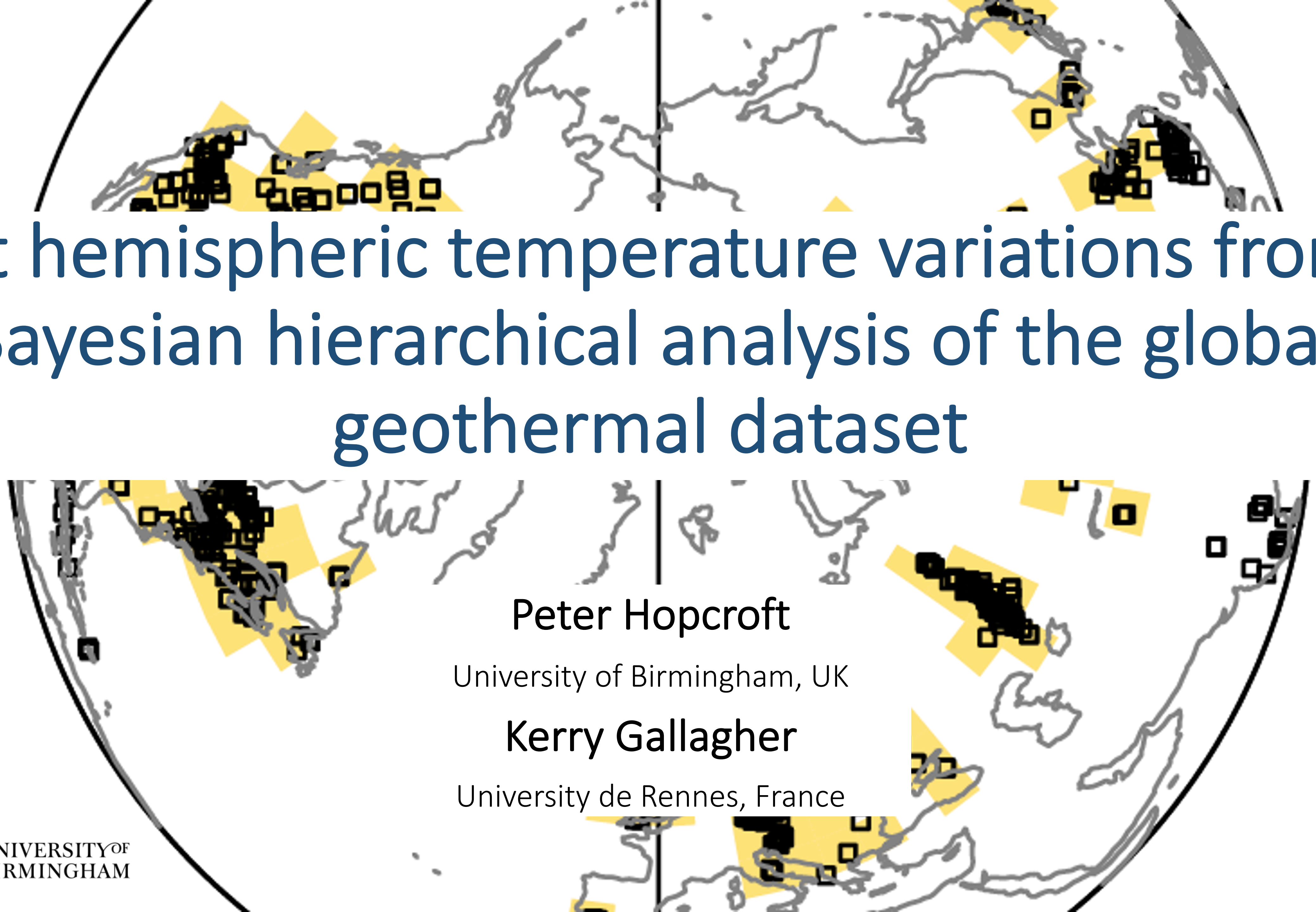

Past hemispheric temperature variations from a Bayesian hierarchical analysis of the global geothermal dataset

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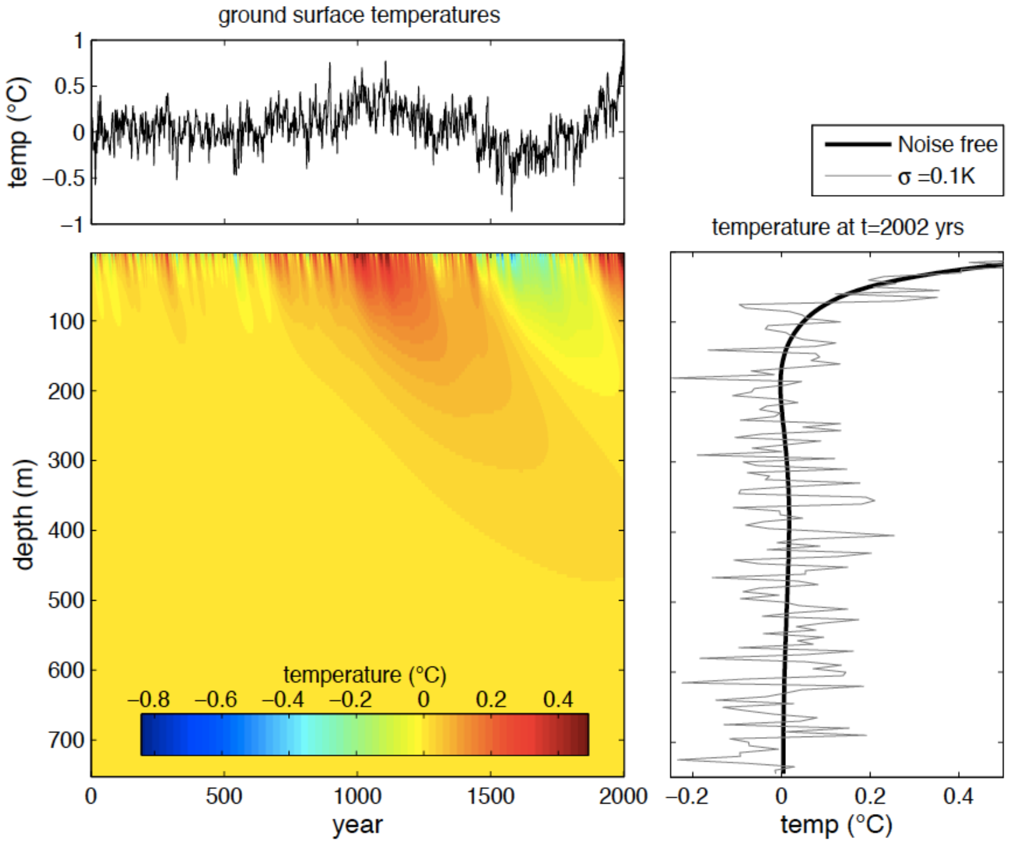
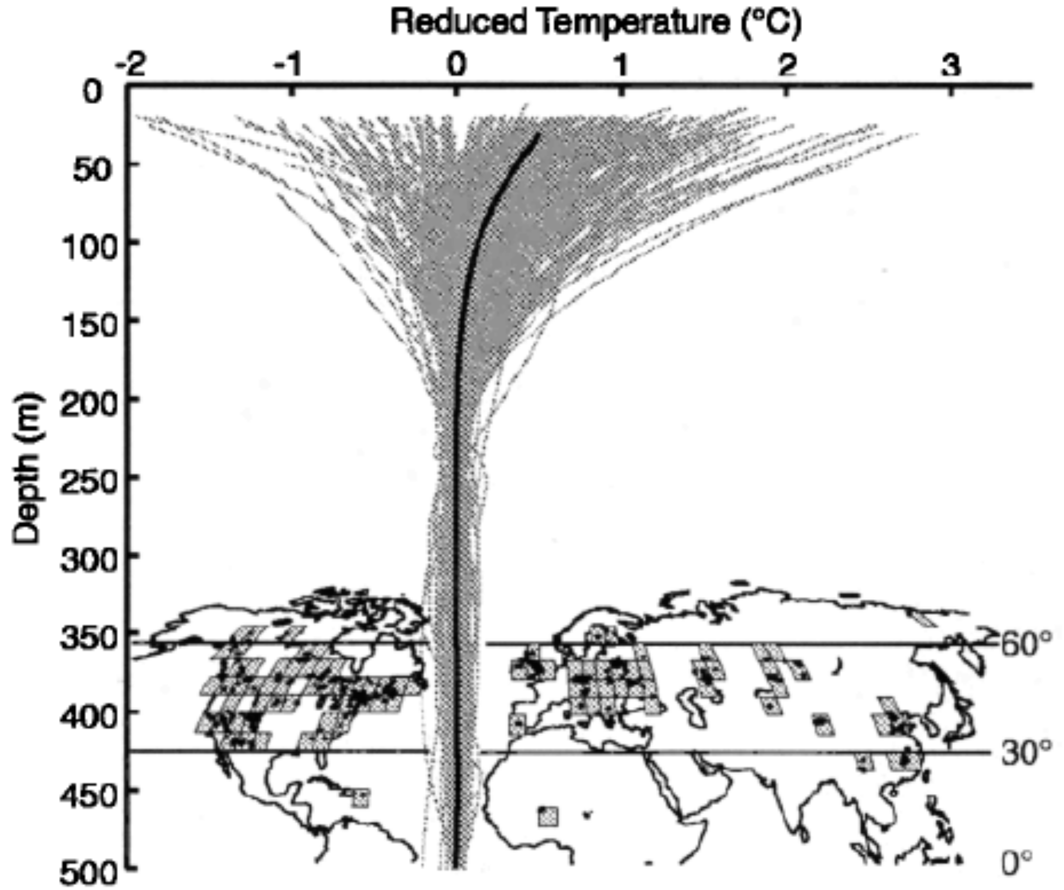
How do underground temperatures record past climate?

Assuming heat conduction dominates, long-term perturbations at the surface are evident in the temperature-depth (T-z) profile.



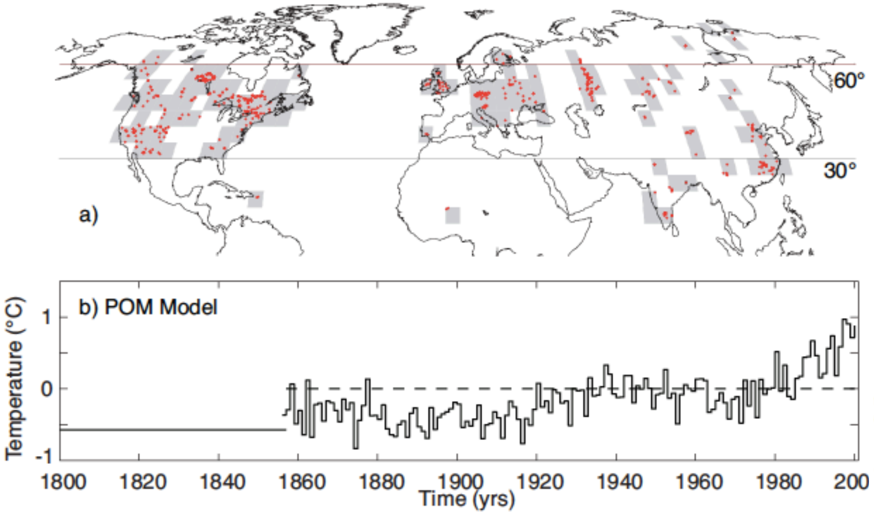
Hopcroft (2009), PhD Thesis

Measured T-z profiles (below) show a net warming signal but with considerable scatter.



Harris & Chapman, 2001
GRL

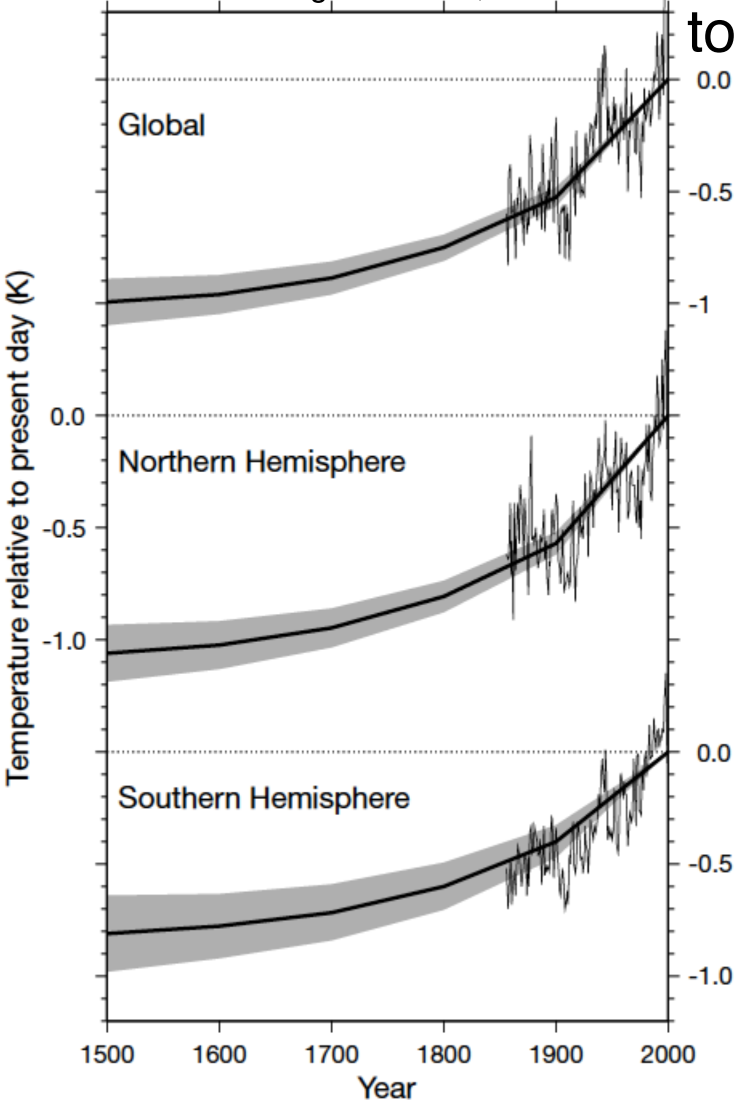
Existing global and hemispheric reconstructions from geothermal data



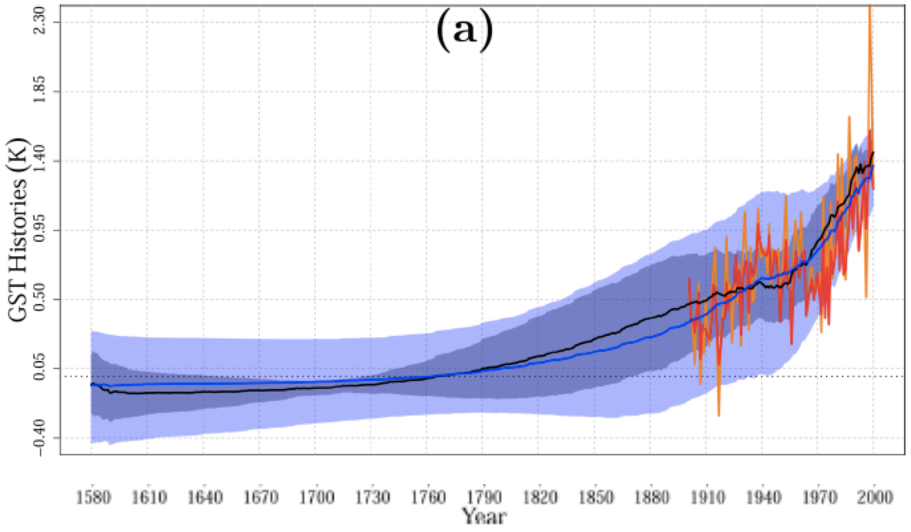
Harris 2007, *Clim Past,*
Harris & Chapman, 2001, *GRL*

0.6 °C warming up to 1960-1990 mean

Huang et al 2000, *Nature*



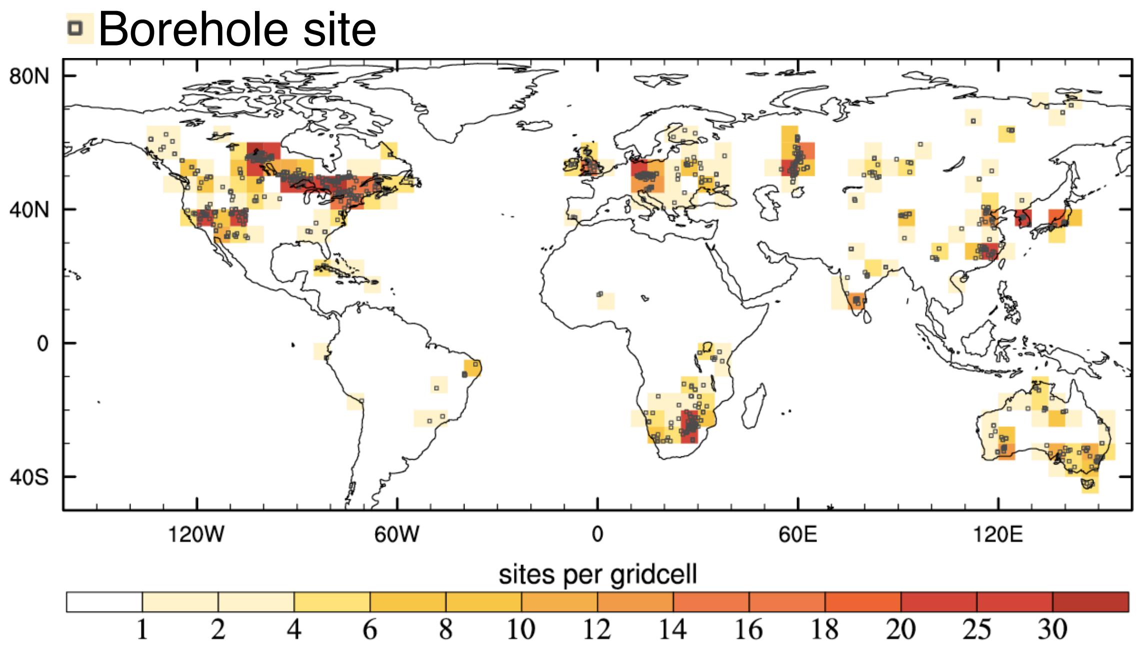
0.8-1.0 °C warming up to CE 2000

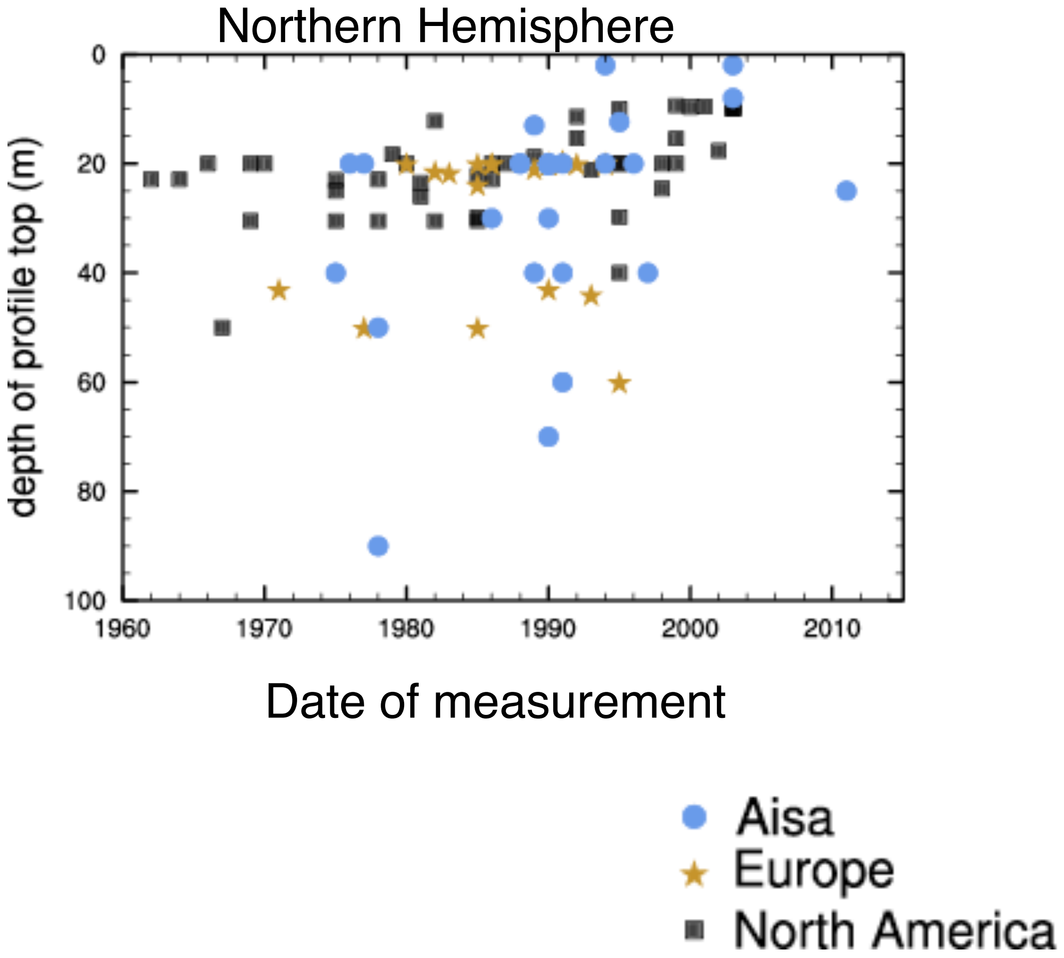


Cuesta—Velaro et al 2021, *Clim Past*

1.4 °C warming up to CE 2000

An overview of the global geothermal data used in these reconstructions





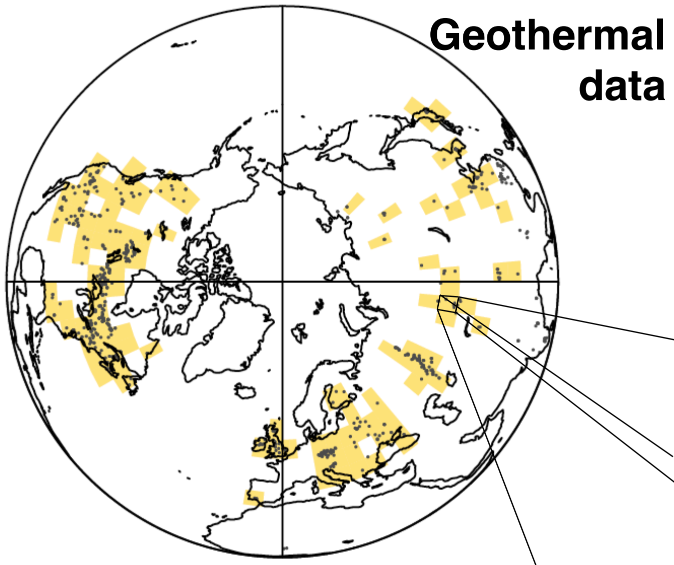
Geothermal data for climate are:

1. Spatially clustered
2. Noisy
3. Measured over nearly 60 years
4. Do not generally sample uppermost 10-50 m

Hopcroft & Gallagher, in prep

A new **Bayesian hierarchical** approach

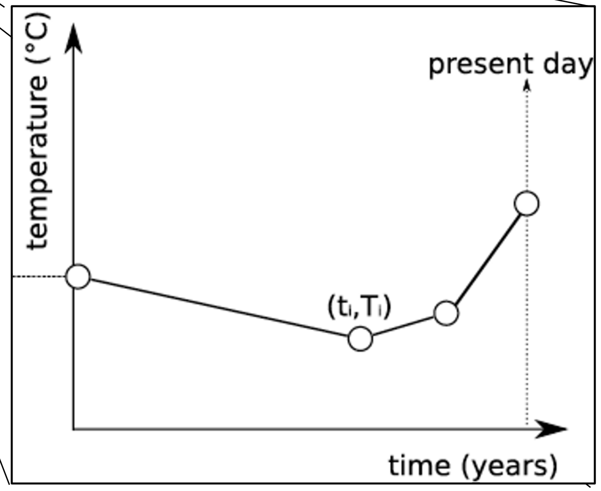
Geothermal data



Hierarchical: we infer key parameters from the data, including observational noise and uncertainty on the prior.

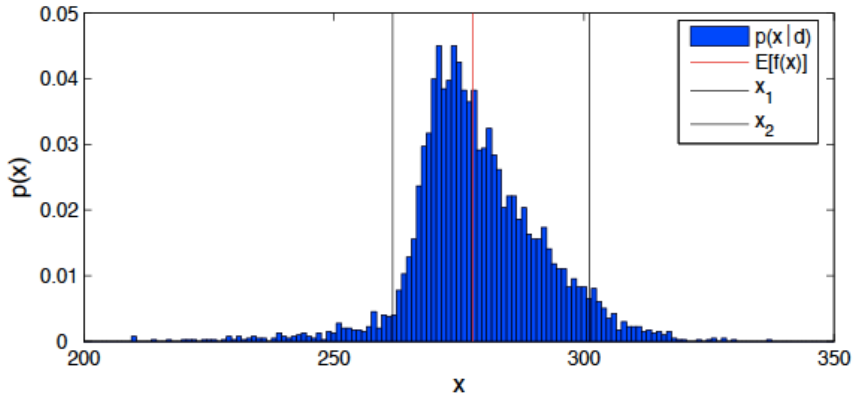
Trans-dimensional sampling: fit the number of temperature-time points to the data in each gridcell according to support from the data (Occam's razor)

We group data on a 5°x5° lat/lon grid.



Trans-dimensional hierarchical MCMC sampling

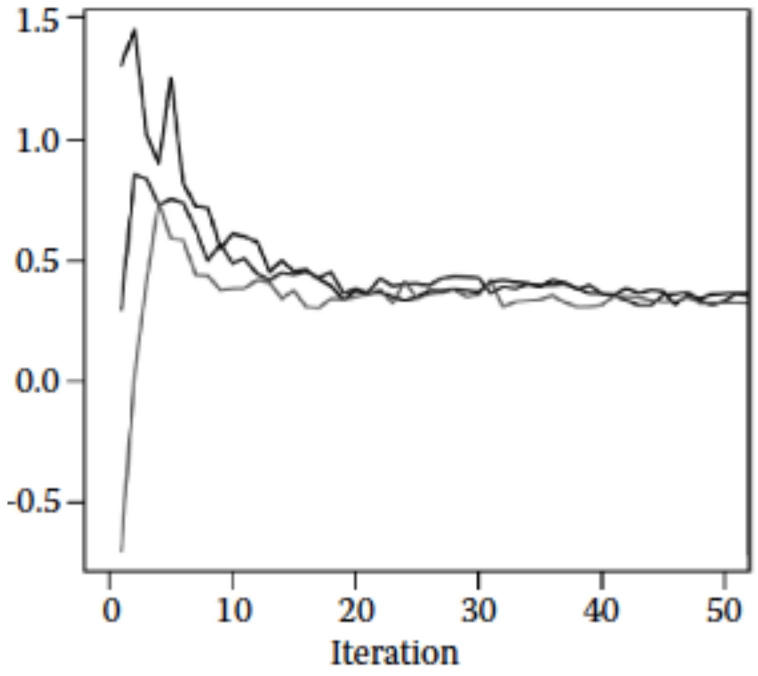
Posterior probability distribution on **past temperature**



Hopcroft et al. (2007) *Geophys J Int*
Hopcroft & Gallagher, in prep

Sampling: detecting convergence

MCMC sampling methods need to be checked for **convergence**, e.g. the algorithm should produce similar solutions independent of initial sampling conditions.



Gelmn & Shirley, 2011 MCMC Handbook

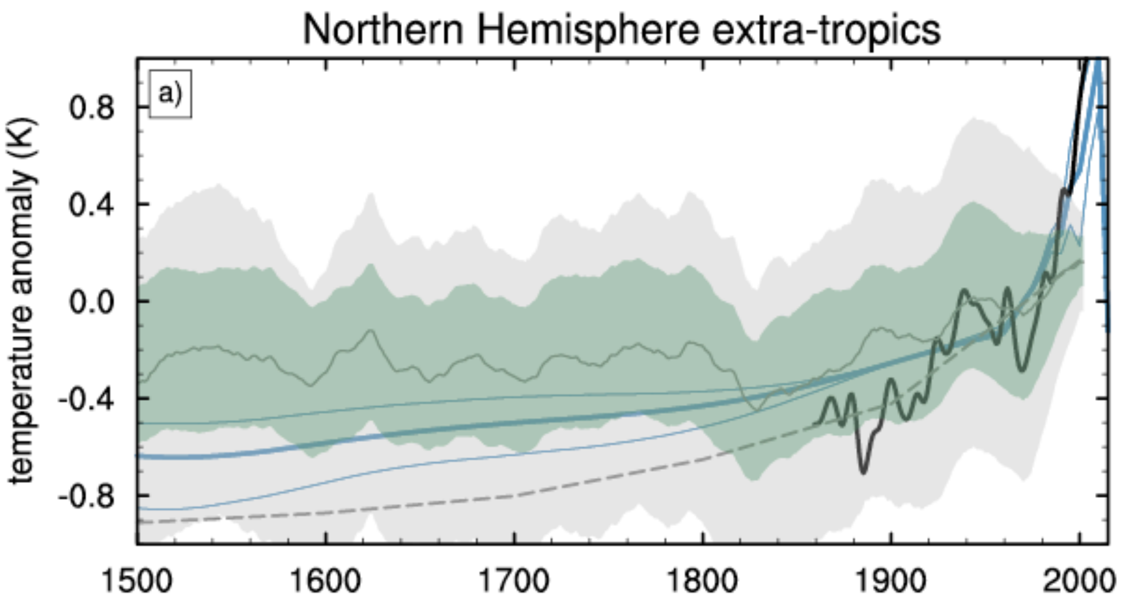
We ran **10 MCMC chains in parallel** starting from different randomly assigned placed in model parameter space.

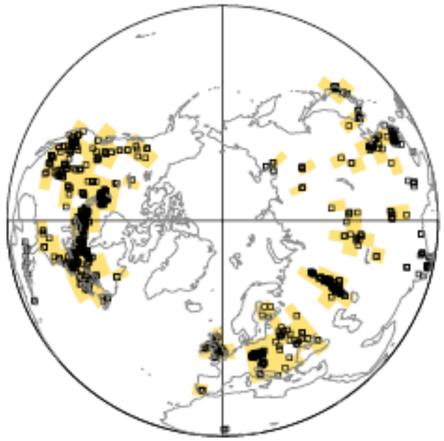
Variances within and across the 10 chains are compared to verify convergence, i.e. posterior probability density functions are not significantly different.

Convergence was confirmed in both Northern and Southern Hemispheric averages. In individual gridcells (5°x5°) only 3 gridcells out of 173 were not converged. These have not been excluded from results yet as this has no discernible impact.

Hemispheric trends compared with previous work (wrt CE 1960-1990)

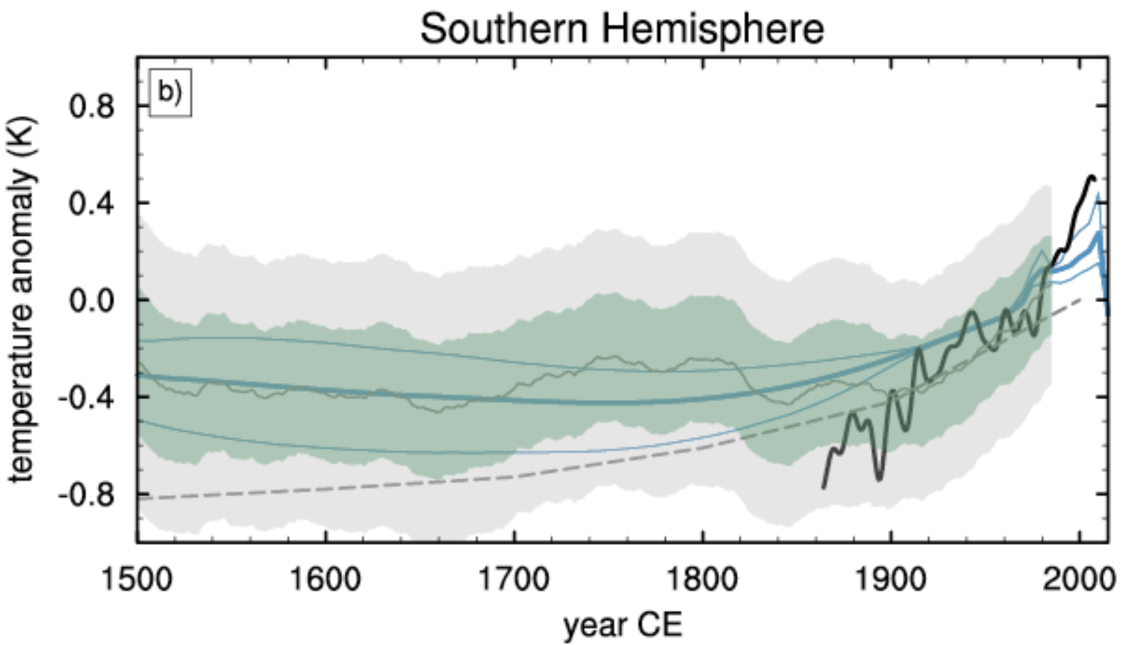
Posterior (mean, 95% limit)
Observed climate (CRU)
Multi-proxy (PAGES 2k)
Multi-proxy ±1σ
Multi-proxy ± 2σ
Existing geothermal (Huang *et al.* 2000)

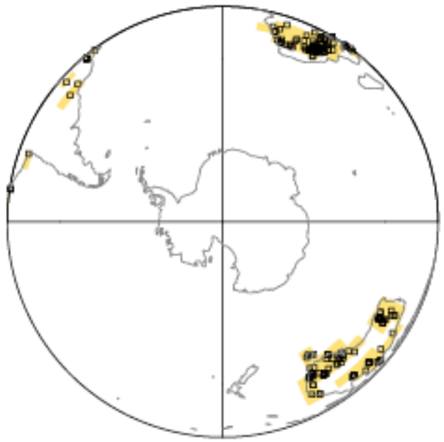




Our posterior (——) shows less warming than past work of Huang et al 2000 (-----).

In the **Southern Hemisphere** the **agreement** with the PAGES2k multi-proxy (——)is good.

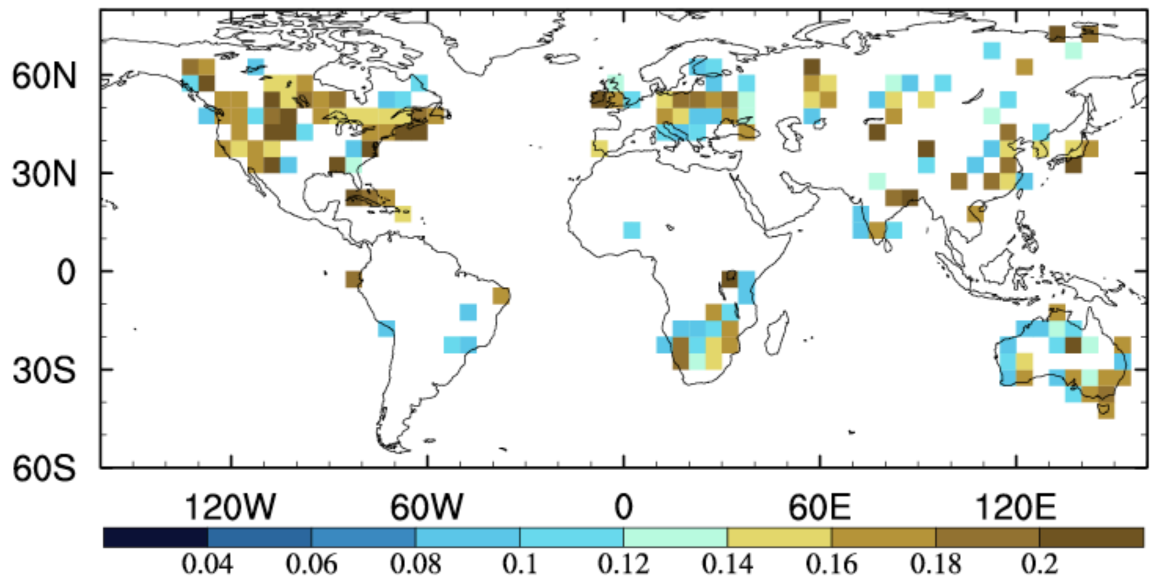




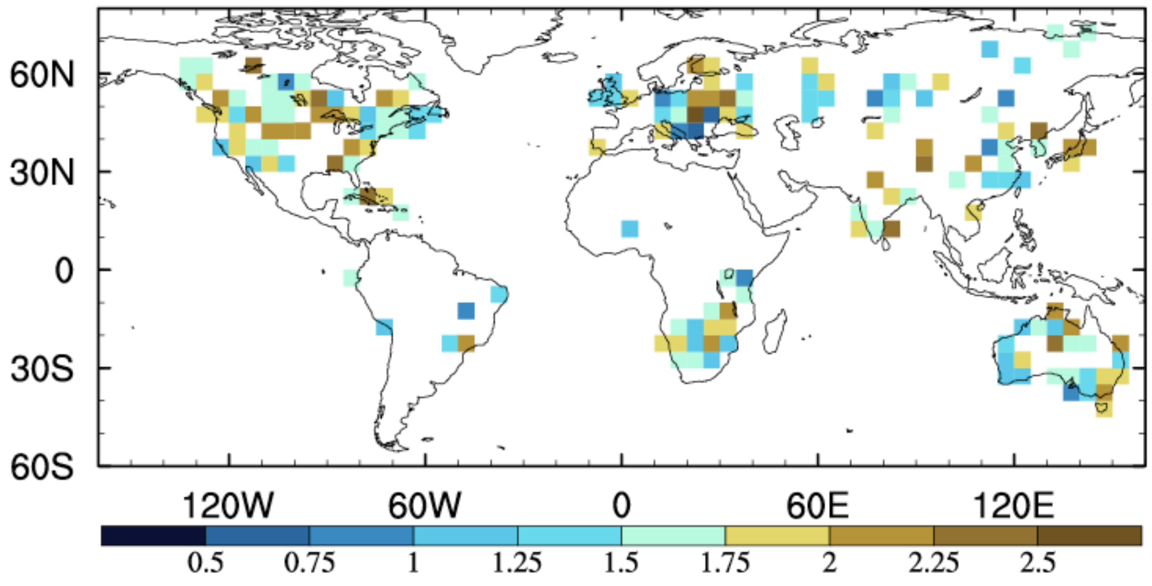
Hopcroft & Gallagher, in prep

Inferred model parameters (posterior means)

Data noise parameter ($\boldsymbol{\sigma}_d$)
Posterior mean



Prior width on the temperature history ($\boldsymbol{\sigma}_P$)
Posterior mean

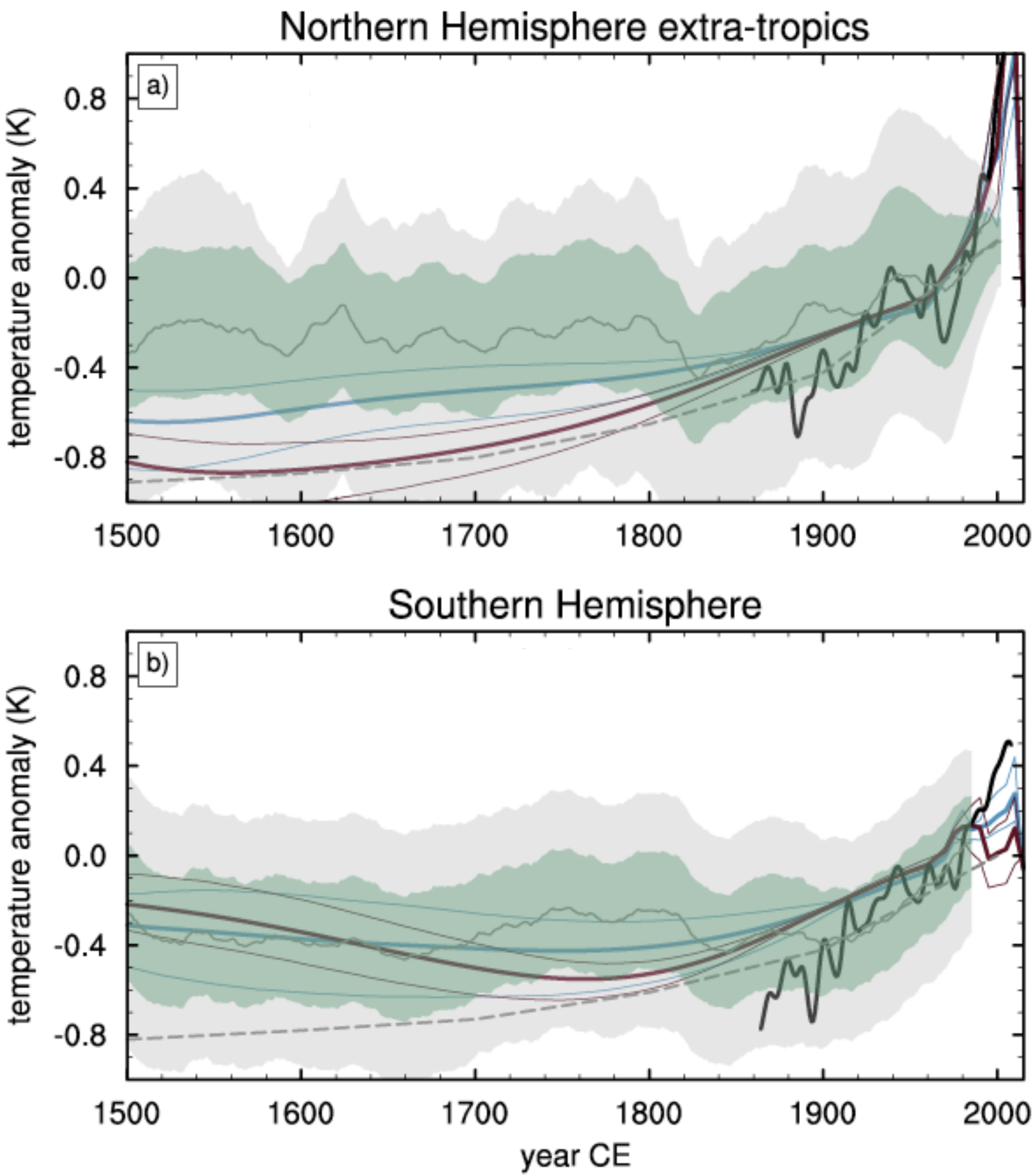


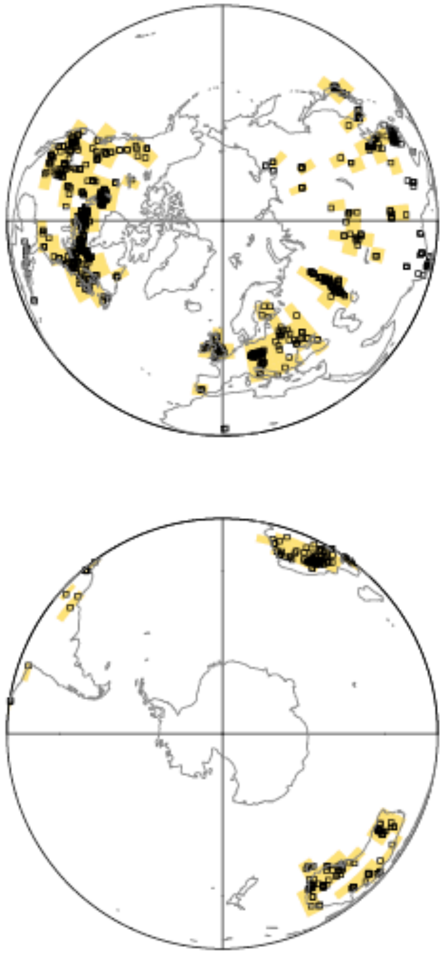
The hierarchical model infers fairly high values for the noise on the subsurface temperature measurements (left) and allows the uncertainty on our prior information to vary spatially (right).

Hopcroft & Gallagher, in prep

… impact of **observational uncertainties** in the geothermal data

Posterior (**mean**, 95% limit)
Posterior mean: **borehole data noise σ_L= 0.05 K**
Observed climate (CRU)
Multi-proxy (PAGES 2k)
Multi-proxy ±1σ
Multi-proxy ± 2σ
Existing geothermal (Huang *et al.* 2000)



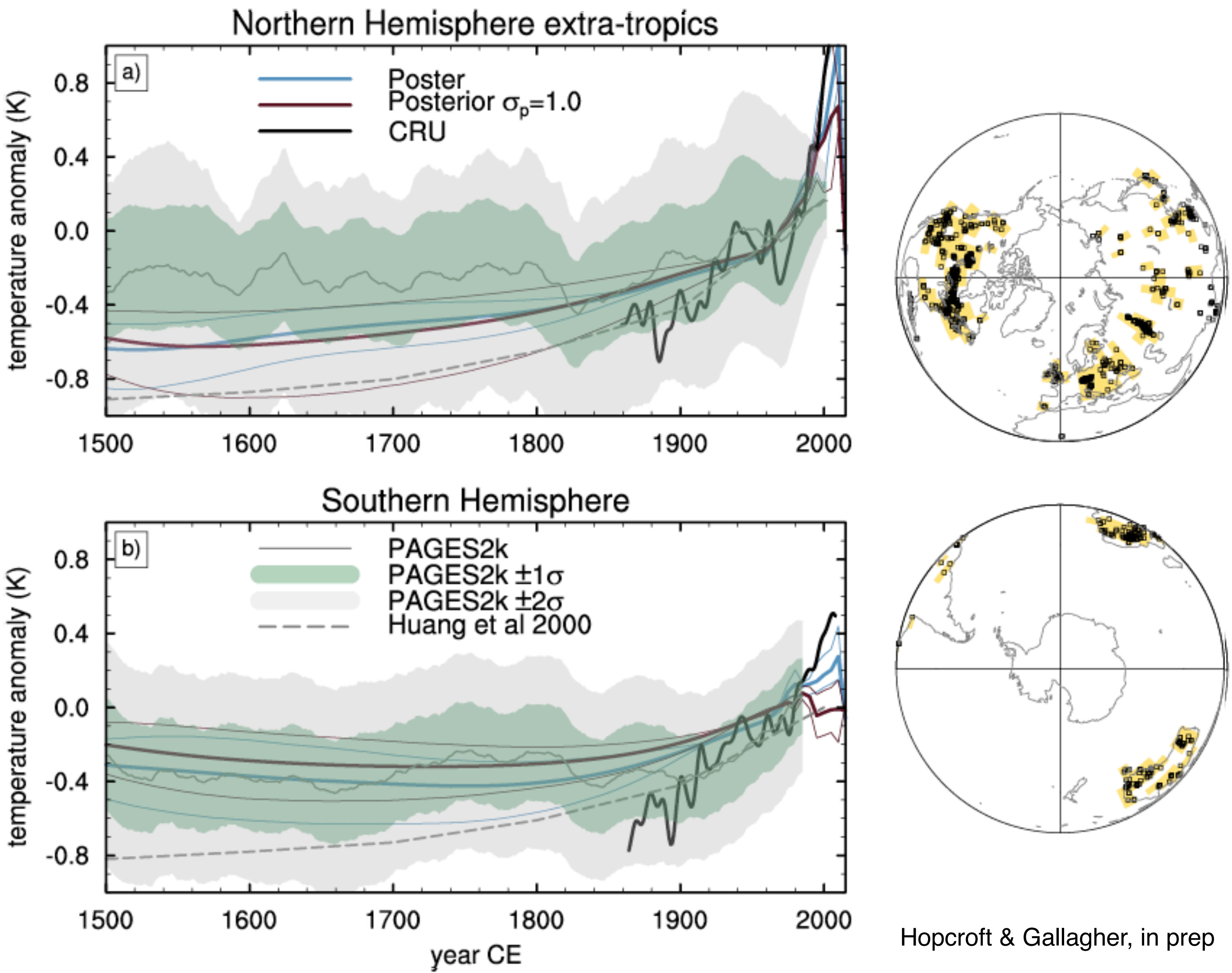


Setting *a-priori* the noise estimate for the geothermal data is important and increases the amplitude of the resultant climate signal (——).

Hopcroft & Gallagher, in prep

... impact of **prior** assumptions

Posterior (**mean**, 95% limit)
Posterior: **reconstruction prior width σ_P= 0.5 K**
Observed climate (CRU)
Multi-proxy (PAGES 2k)
Multi-proxy $\pm 1\sigma$
Multi-proxy $\pm 2\sigma$
Existing geothermal (Huang *et al.* 2000)



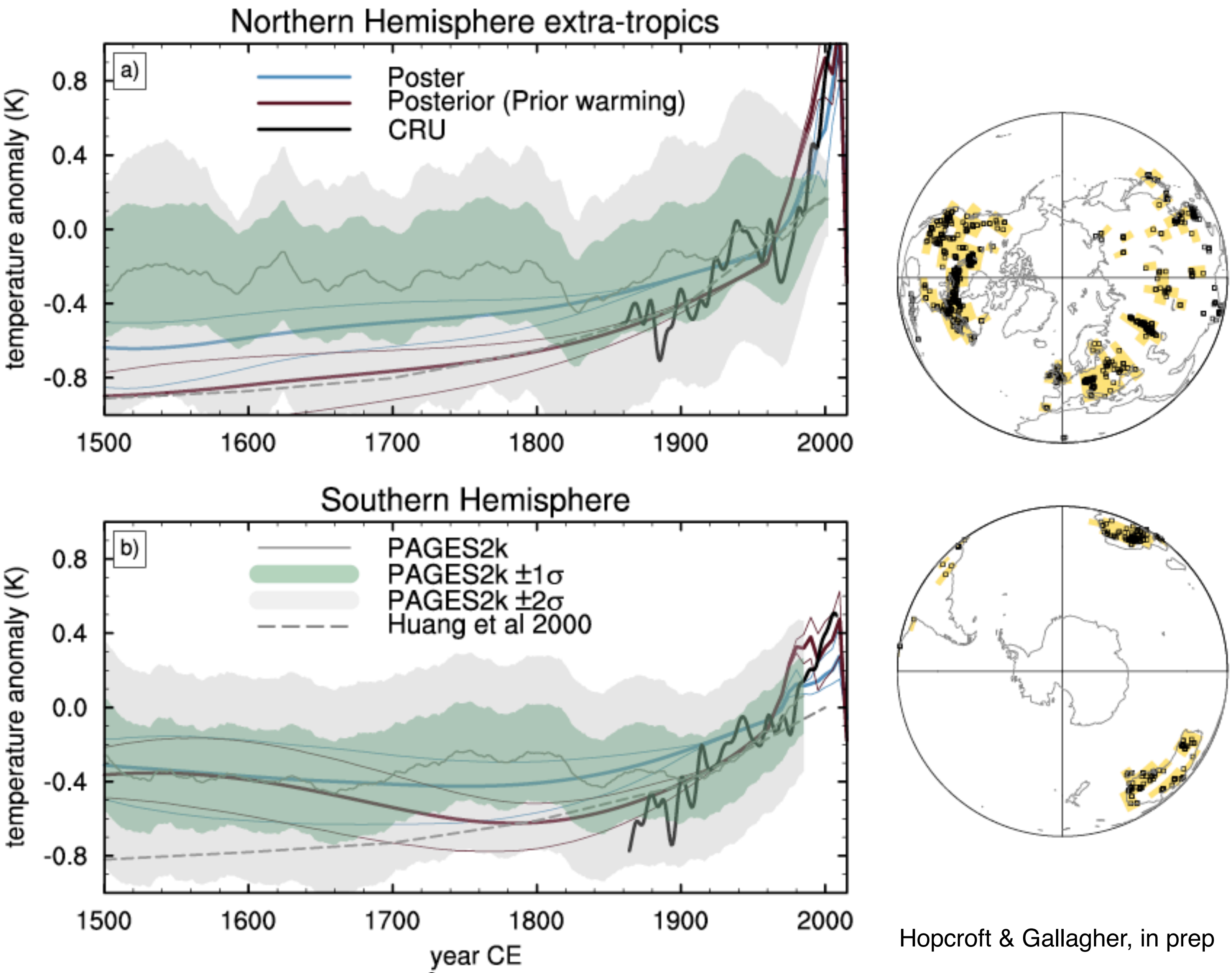
Setting *a-priori* the width of the prior on the temperature history doesn't make much difference (——).

Hopcroft & Gallagher, in prep

… impact of a-priori assuming 1K warming from **CE 1850-present day**

Posterior (**mean**, 95% limit)
Posterior mean: ***a-priori* assumed warming of 1K**
Observed climate (CRU)
Multi-proxy (PAGES 2k)
Multi-proxy ±1σ
Multi-proxy ± 2σ
Existing geothermal (Huang *et al.* 2000)

Including the observed ~1K warming since year CE 1850 in the prior increases the amplitude of the reconstruction (——) but has much less impact in the Southern Hemisphere.



Hopcroft & Gallagher, in prep

Conclusions

- Geothermal data are a potentially valuable source of past climate information (e.g. see Cuesta –Valero et al. 2021).
- The geothermal database is noisy and heterogenous.
- Bayesian hierarchical methods are one way to tackle this (e.g. Denison et al. 2002).
- Results broadly in agreement with other geothermal studies (e.g. Huang et al. 2000; Cuesta-Velero et al. 2021).
- **Noisier components** of the global database act to **amplify the reconstructed signal** - we reconstruct less warming (before about CE 1800.
- **Southern Hemisphere trends agree very well** with the multi-proxy (non-geothermal) results (PAGES 2k, 2013).

References:

Denison et al. (2002). Wiley & Sons, London.

Cuesta-Valero et al. (2021) *Clim Past*, doi: 10.5194/cp-17-451-2021.

Harris (2007) *Clim Past*, doi: 10.5194/cp-3-611-2007

Huang et al. (2000) *Nature*, doi: 10.1038/35001556

PAGES 2k Consortium (2013) *Nature Geoscience,* doi: 10.1038/NGEO1797

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