Reconstructions of climate fields of the last millennium with Paleoclimate Data Assimilation

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Climatology seminar
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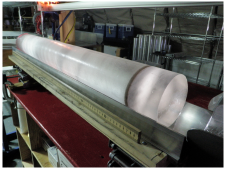
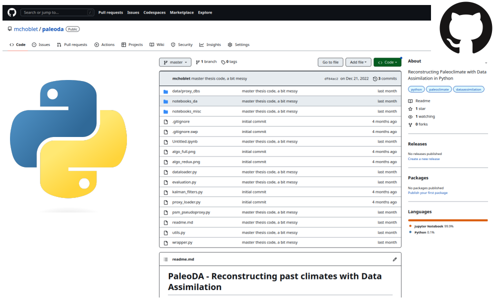
Goals of my thesis

Central task

Implement a framework for PaleoDA with speleothem and ice core data





Scientific questions

- What are the **characteristics** of reconstructed global and regional (hydro)climate for the last millennium?

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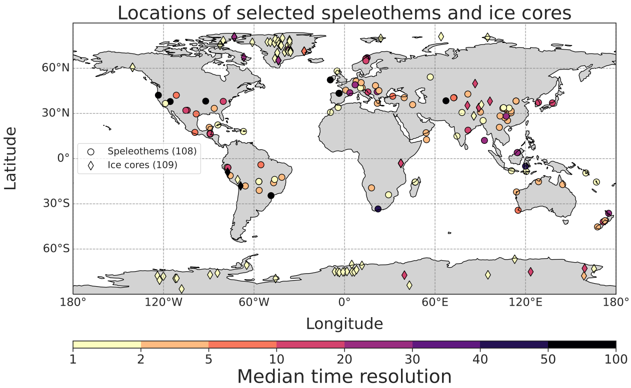
- How do the speleothem and ice core records **contribute** to the climate reconstructions?
- What is the **temporal variability** of the reconstructions?
- How do **model-biases** and **inter model-differences** affect the PaleoDA reconstructions?

The Data

Proxy records (δ^{18}O)

- Speleothems (SISAL v2)
- Ice cores (Iso2k)



The Data

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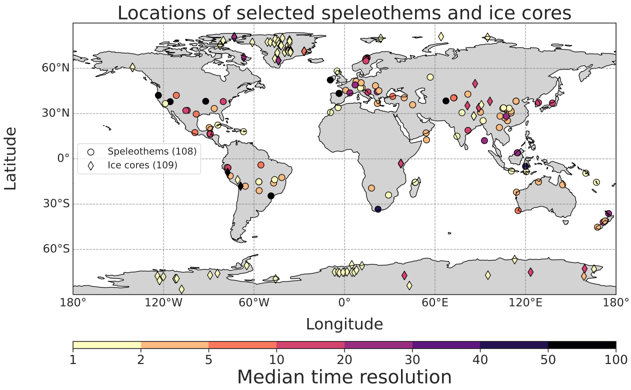
- Speleothems (SISAL v2)
- Ice cores (Iso2k)

Models (isotope-enabled)

- ECHAM5-wiso (96 x 48)
- iHadCM3 (96 x 73)
- GISS (140 x 90)
- iCESM (144 x 96)
- isoGSM (192 x 94)



The Method: The Kalman Filter

X^{prior}	Prior state (Climate model)
Y	Observations (Proxy records)
H	Observation operator (PSM)
HX^{prior}	Observation estimates
R	Measurement error

Update and Kalman Gain equation

$$X^{prior} + K(Y - HX^{prior}) = X^{post}$$

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  - ⇒ **Ensemble** Kalman Filter
  - ⇒ **Offline** DA uses a static covariance

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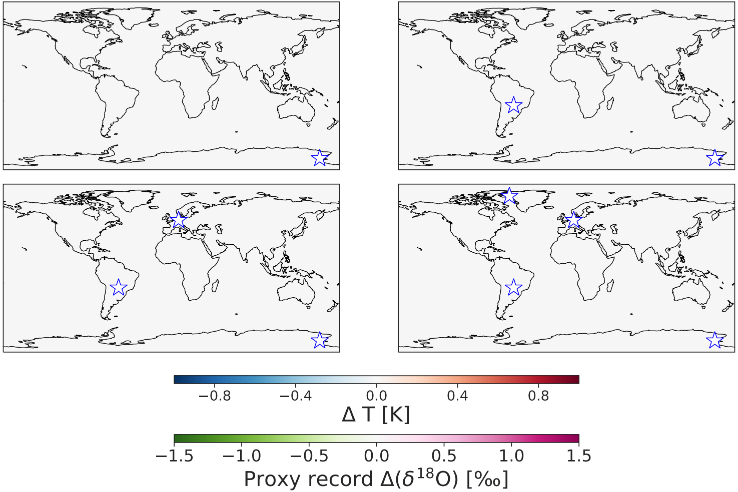
- Covariance computation:
  - ⇒ **Ensemble** Kalman Filter
  - ⇒ **Offline** DA uses a static covariance
- Ensemble Kalman Filter also computes posterior uncertainty (smaller)

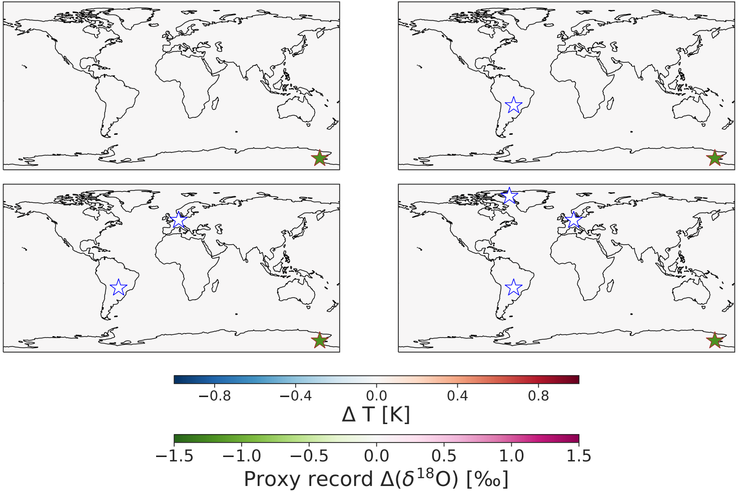
The Method (example)

Assimilating 4 δ^{18}O measurements into a temperature field



The Method (example)

Assimilating 4 $\delta^{18}O$ measurements into a temperature field



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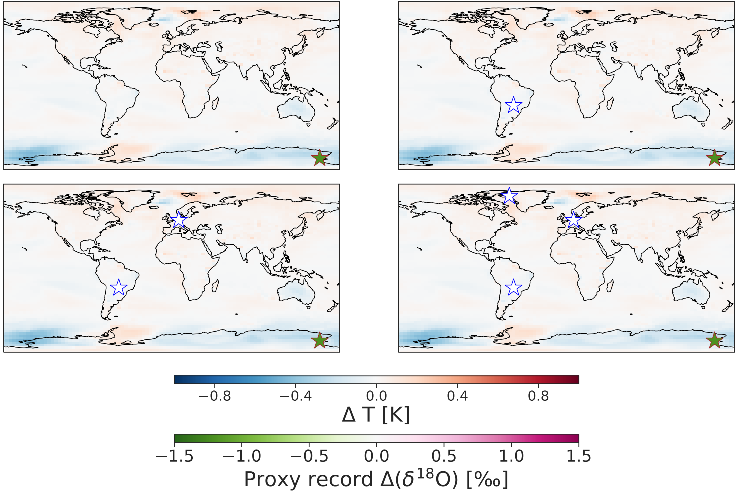

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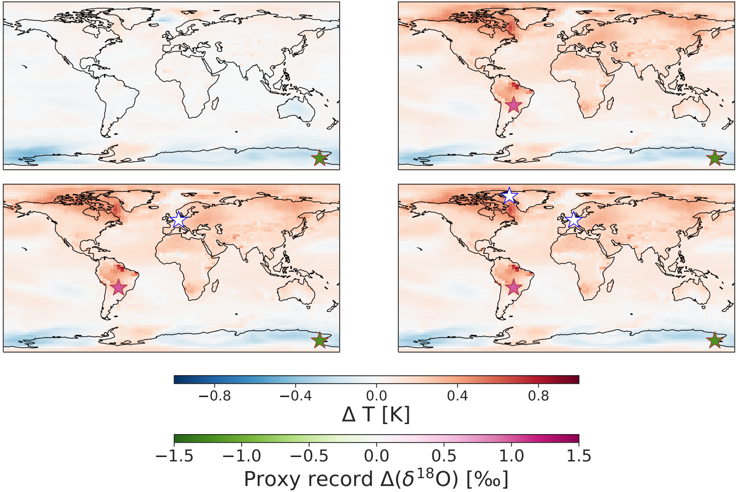

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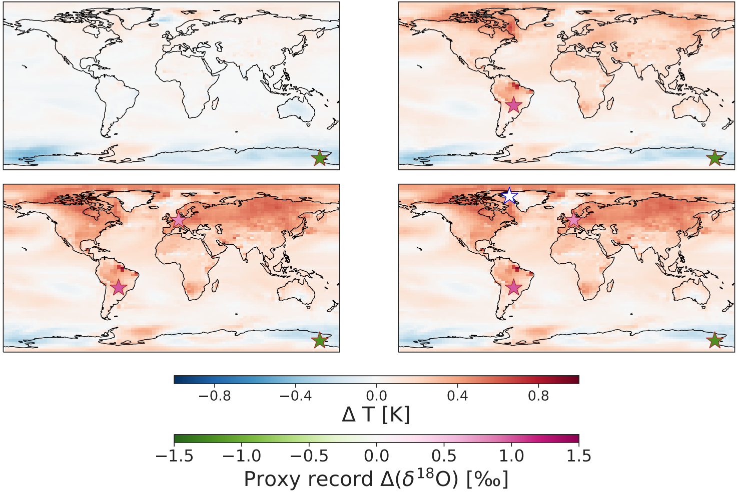

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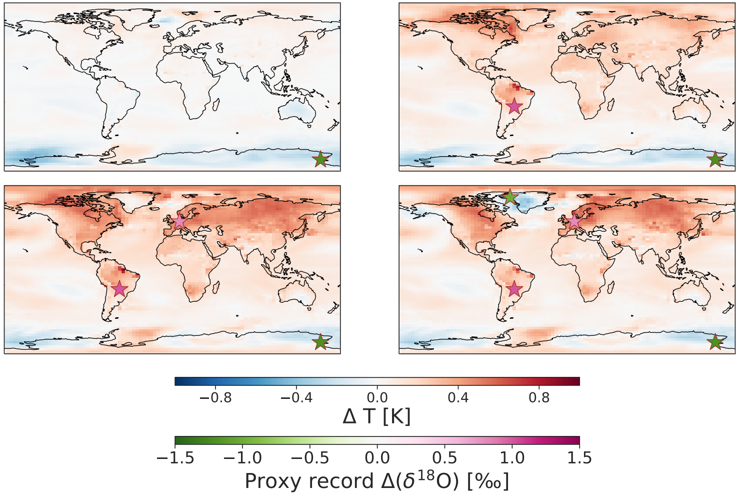

Reconstruction method in short:

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Two restrictions for the previous example

1. In practice: Simultaneous assimilation (computation speed is relevant)
2. Posterior uncertainties not shown in this example

Challenges

- Large model-proxy δ^{18}O offsets at individual locations

- Irregular time resolution of proxy records

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  - Resampled proxy record time series to median resolution
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  - Question open because proxy-system-model not calibrated

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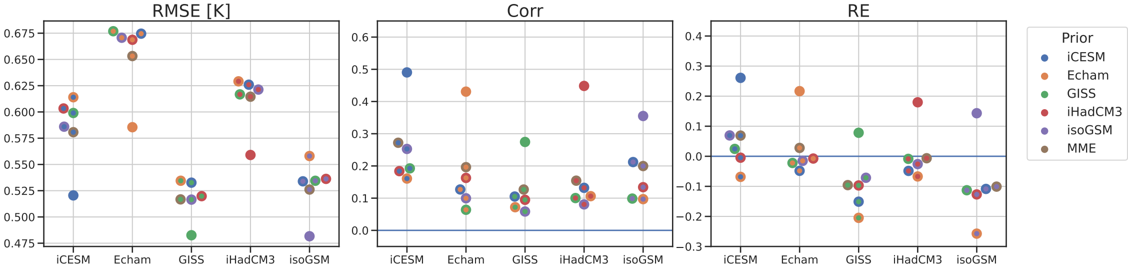

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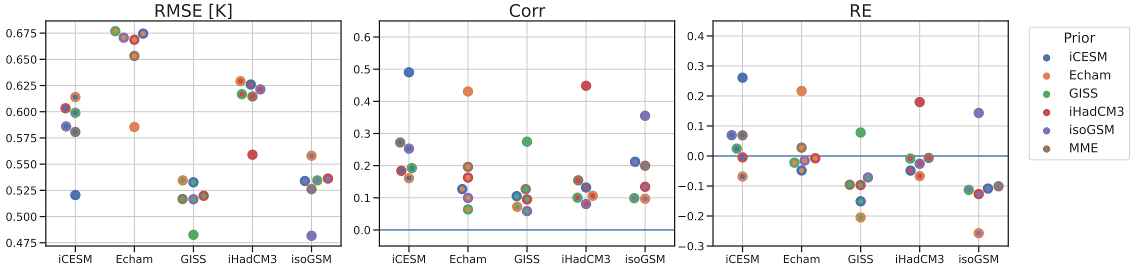
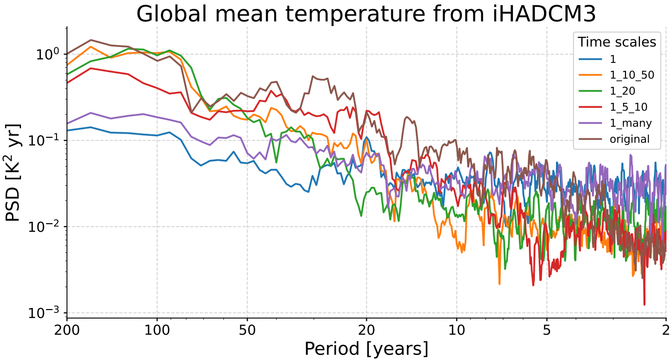


- Results are better for GMT
- Multi model ensemble (MME) yields slightly better results

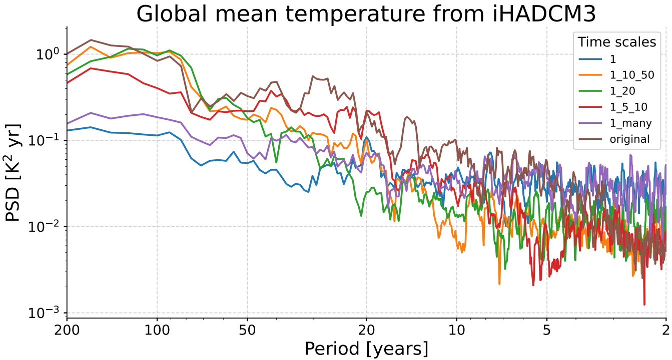
⇒ Biases in covariance even for anomaly reconstruction

PPE with δ^{18}O from 100 locations (SNR 0.5).



Reconstruction of variability by multi-time scale algorithm

PPE with $\delta^{18}O$ from 100 locations (SNR 0.5).

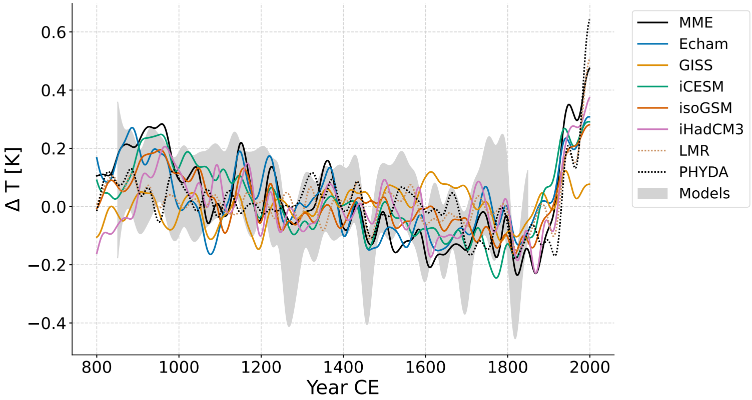


⇒ Hints at underestimation of multi-decadal variability

- Also real data experiments indicate better variability reconstruction

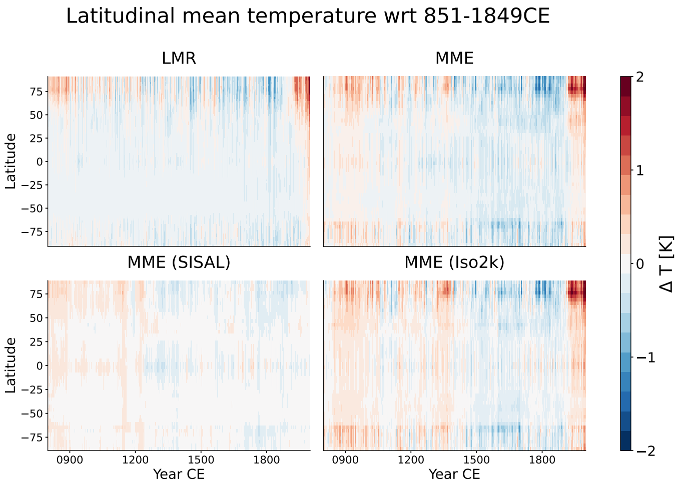
⇒ Requires more testing of experimental/pseudoproxy configurations

Application to proxy record data: Global mean temperature (wrt 851-1849CE)



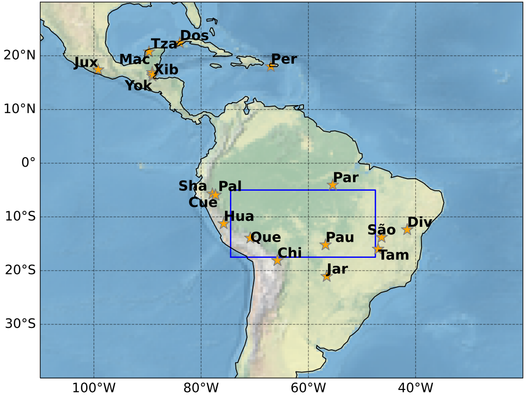
- Uncertainties in the range of 0.15K
- Prior dependency of amplitudes
- Fluctuations are comparable to LMR and PHYDA reconstruction

Hovmöller plots



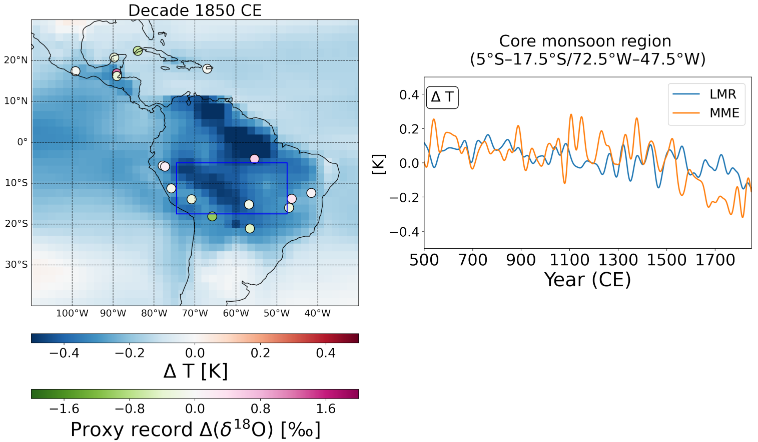
- Correlation analysis also underlines larger influence of the ice cores
- Smallest temperature changes in the mid latitudes

Proxy record locations Tropical South America



- Existing reconstructions use few proxy records from that region
- Blue box: Core South American summer monsoon region (Vuille 2012)

Reconstruction of South American Hydroclimate



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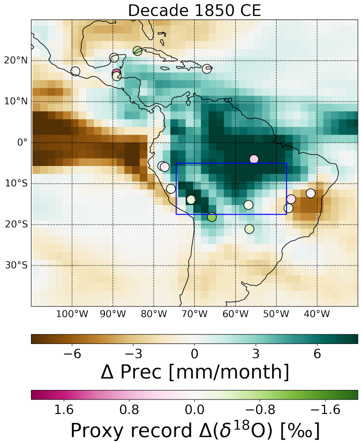

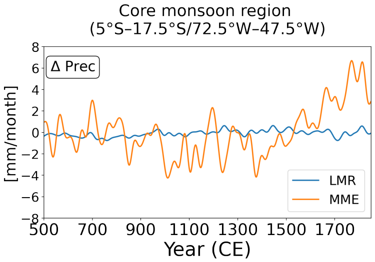

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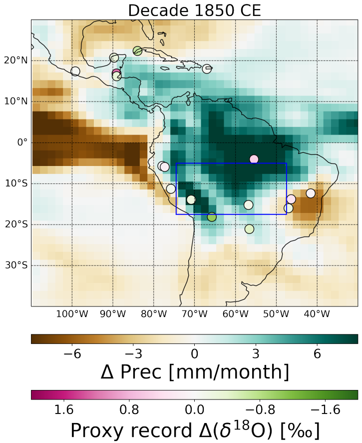

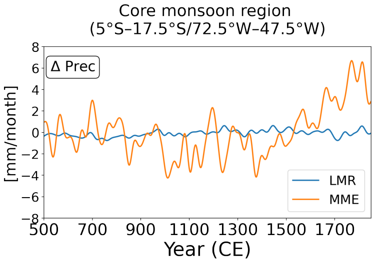

- "Little Ice Age" clearly visible in both temperature and precipitation
- Potential for more detailed reconstructions!

- First multi-time scale PaleoDA with isotope-enabled models, ice cores and speleothems
- Anomaly reconstructions yield realistic results

Conclusion and outlook

- First multi-time scale PaleoDA with isotope-enabled models, ice cores and speleothems
- Anomaly reconstructions yield realistic results
- Methodological details of PaleoDA need to be assessed better:
    1. Realistic uncertainties
    2. Time scales of proxy records
    3. Quantifying the covariance structure and the influence of PSMs and observations
    4. Debiasing the model prior

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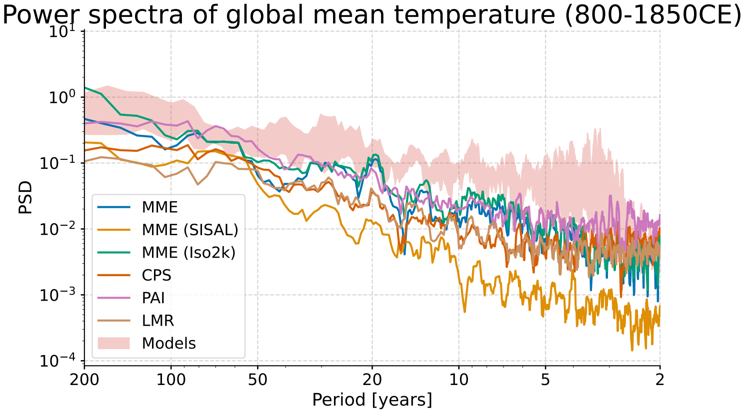
- Next months: Focus on South American Hydroclimate

Thank you!

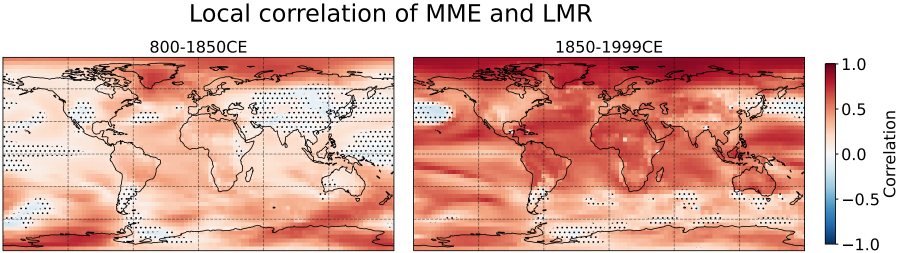
Backup slides

Spectra of GMT reconstructions



CPS and PAI are reconstructions from Pages2k 2019

LMR and MME local comparison.



No detrending.

Largest similarity over West Antarctica and Greenland.

Comparing Models to proxies: Proxy System Models (PSMs)

- Developed for data-model comparison
- What proxy value does a simulated state represent?

→ **forward approach** (Evans 2013, Dee 2015)

- physics-based/statistical PSMs

$$X^{post} = X^{prior} + K(Y - HX^{prior})$$

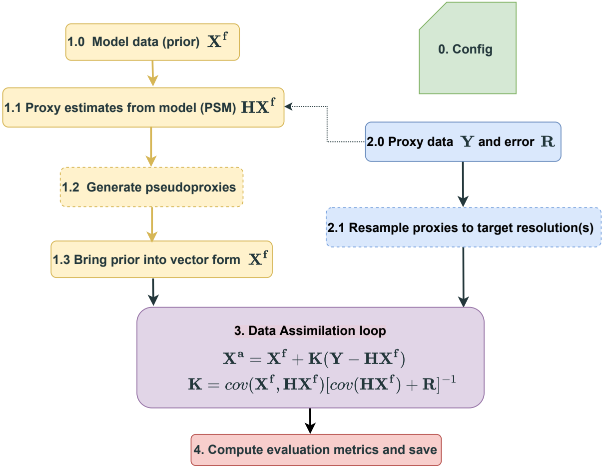
Icecore $\delta^{18}O_{prec}$-PSM

- Precipitation weighting for annual $\delta^{18}O$
- Height correction (isotopic lapse rate)
- Diffusion

Speleothem $\delta^{18}O_{prec}$-PSM

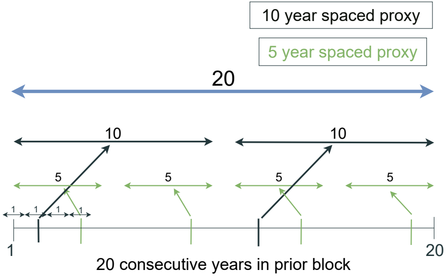
- Infiltration weighting for annual $\delta^{18}O$
- Height correction (isotopic lapse rate)
- Fractionation
- Karst filter

Algorithm sketch for Paleoclimate Data Assimilation



Multi-timescale DA approach following Steiger and Hakim 2016

Idea:



- Reconstruct (sub-)blockwise instead of annually.

Caveats

- assign proxies to (sub-)blocks
  $\rightarrow$ resampling to median resolution
- additional calculations

Advantages:

- Proxies representing mean state over several years can be used
- Use timescale appropriate covariances
- Get more reconstruction out of proxies

What the heck are Ensemble Square Root Kalman Filters?

STACY

Kalman Filter and posterior covariance P^{post} (Kalman 1960)

$$\mathrm{X}^{post} = \mathrm{X}^{prior} + \mathrm{K}(Y - \mathrm{H}X^{prior}) \quad (1)$$

$$\mathrm{K} = \mathrm{P}^{prior} H^T (\mathrm{H}P^{prior} H^T + \mathrm{R})^{-1} \quad (2)$$

$$\mathrm{P}^{post} = (\mathrm{I} - \mathrm{K}H)\mathrm{P}^{prior} \quad (3)$$

Problem dimensions

- N_e Ensemble members in prior
- N_y Number of proxies
- N_x State vector length (grid $\times$ vars)

- Nonlinear H, unknown prior covariance P^{prior}? $\rightarrow$ Ensemble Kalman Filter (Evensen 1994)
- Original EnKF gets P^{post} too small $\rightarrow$ EnKF in square root form

$$\mathrm{P}^{post} = \frac{\mathrm{X}^{post}(\mathrm{X}^{post})^T}{N_e - 1} \quad (4)$$

$$= \mathrm{X}^{prior} T (\mathrm{X}^{prior} T)^T \quad (5)$$

$$= \mathrm{X}^{prior} (T T^T) X^{prior\,T} \quad (6)$$

Find the matrix T

- not uniquely defined, use Lin Alg tools: SVD, EVD ...
- Best solution depends on problem dimensions

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