Bridging the gap between the terrestrial and marine paleoclimate reconstructions in the North Atlantic realm (PALEOBRIDGE)

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A state-of-the-art gridded reconstruction product for the annual sea surface temperature covering the northern North Atlantic region over the past two millennia.

Summary

In this ongoing project we are using two existing methods for climate field reconstruction (CFR) of gridded sea surface temperature (SST): one Bayesian hierarchical model and one proxy-surrogate reconstruction method. The ensemble-based reconstructions will be used to analyse past changes in marine to terrestrial teleconnections in the North Atlantic realm, and to improve the existing seasonal reconstructions of major climate indices such as the Atlantic multidecadal variability (AMV).

Time slice for example reconstruction - SST anomaly (K)

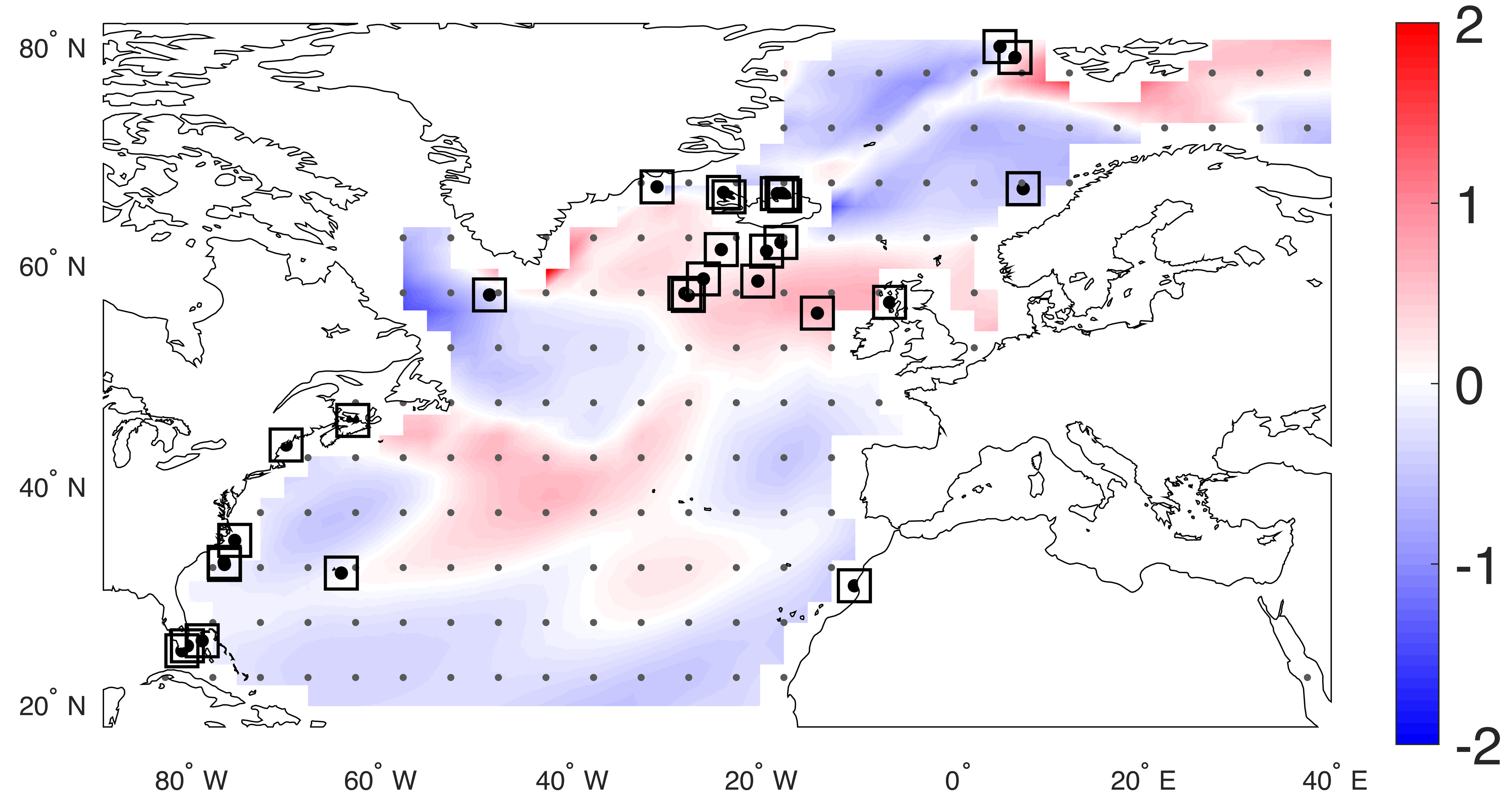

Fig. 1: Time slice at a given time for the reconstruction. Dots indicate the reconstruction target region. Squares denote proxy locations. Temperature in degrees Kelvin (K).

Input data:

- HadSST4 instrumental data: period 1850-present (Kennedy et al. 2019).
- Proxy records records with age-depth uncertainties sampled from marine sediment cores: foraminifera, alkenones, diatoms, dinocysts.
- Proxy records from marine layered archives: corals and bivalves.
- In total 30 proxy records used. Temporal resolution varying from 1-200 years
- Proxy records selected from Ocean 2k of the PAGES2k 2.0.0 database (PAGES2k Consortium 2017).

Please write me an e-mail if you have information on additional proxy records. Thank you.

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- Kennedy, J. J., Rayner, N. A., Atkinson, C. P., & Killick, R. E. (2019), *Journal of Geophysical Research: Atmospheres*, **124**, 7719– 7763, doi: 10.1029/2018JD029867
- PAGES2k Consortium (2017), *Scientific Data*, **4,** 170088, doi:10.1038/sdata.2017.88

Methodology – Bayesian Algorithm for Reconstruction of Climate Anomalies in Space and Time (BARCAST)

<u>A Bayesian Hierarchial Model with 3 levels (Tingley & Huybers 2010)</u>

1) Process level – The temperatures are modelled as an AR(1) process in time:

$$\mathbf{T}_t - \mu = \alpha\,(\mathbf{T}_t - 1 - \mu\,) + \boldsymbol{\varepsilon}_t$$

The innovations (increments) $\boldsymbol{\varepsilon}_t$ are assumed to be IID normal draws $\boldsymbol{\varepsilon}_t \sim N(0,\boldsymbol{\Sigma})$ with exponentially decaying covariance structure: $\boldsymbol{\Sigma}_{ij} = \sigma^2 \exp(-\varphi|\mathbf{x}_i - \mathbf{x}_j|)$

Where t denotes time and i, j denotes locations in space.

2) Data level - model the instrumental ($W_{I,t}$) and proxy ($W_{P,t}$) observations as noisy realizations of the true climate:

$$\mathbf{W}_t = \begin{pmatrix} \mathbf{H}_{I,t} \\ \beta_1 \cdot \mathbf{H}_{P,t} \end{pmatrix} \mathbf{T}_t + \begin{pmatrix} \mathbf{e}_{I,t} \\ \mathbf{e}_{P,t} + \beta_0 \mathbf{1} \end{pmatrix}$$

Where **H** identfies each grid cell as empty or containing observations.

3) Prior level - weakly informative but proper prior distributions are used for the model parameters. The information from the data overwhelms the priors.

The probability for the observations, conditional on the true temperature field vector and the collection of all parameters denoted by Θ:

$$P(\mathrm{W}_1, \ldots \mathrm{W}_\kappa \,|\mathrm{T}_1, \ldots . \mathrm{T}_\kappa, \Theta) = \prod_{k=1}^{\kappa} P(\mathrm{W}_k \,|\mathrm{T}_k, \Theta),$$

Where time runs from 1 to κ.

Bayes rule is applied to estimate the posteriors for the temperatures and the scalar parameters given the observations.

TABLE 1. Forms of the priors and conditional posteriors, along with brief descriptions, for the unknowns inferred by BARCAST. MV stands for multivariate, and nonstandard indicates that the conditional posterior does not follow a well-known distribution.

	Prior form	Conditional posterior	Description
$\mathbf{T}_0$	MV normal	MV normal	Field values for the time step prior to the first observations.
$\mathbf{T}_{k=1\ldots\kappa}$	—	MV normal	Field values at each time step for which there are observations.
α	Uniform	Truncated normal	AR(1) coefficient in the field evolution equation.
μ	Normal	Normal	Mean of **T**.
σ^2	Inverse-gamma	Inverse-gamma	Partial sill of the spatial covariance matrix of the innovations that drive the AR(1) process.
ϕ	Log-normal	Nonstandard	Inverse range of this spatial covariance matrix.
τ_I^2	Inverse-gamma	Inverse-gamma	Error variance of instrumental observations.
τ_P^2	Inverse-gamma	Inverse-gamma	Error variance of proxy observations.
β_1	Normal	Normal	Scaling factor in the proxy observation equation.
β_0	Normal	Normal	Additive constant in the proxy observation equation.

Table 1 from Tingley & Huybers 2010 lists information about the model parameters

Accounting for age-depth uncertainties and miscounted layers

- An ensemble of age models is constructed for each core-based record using BACON (Bayesian accumulation histories for deposits, Blaauw & Christen, 2011) and used as input for the reconstruction.

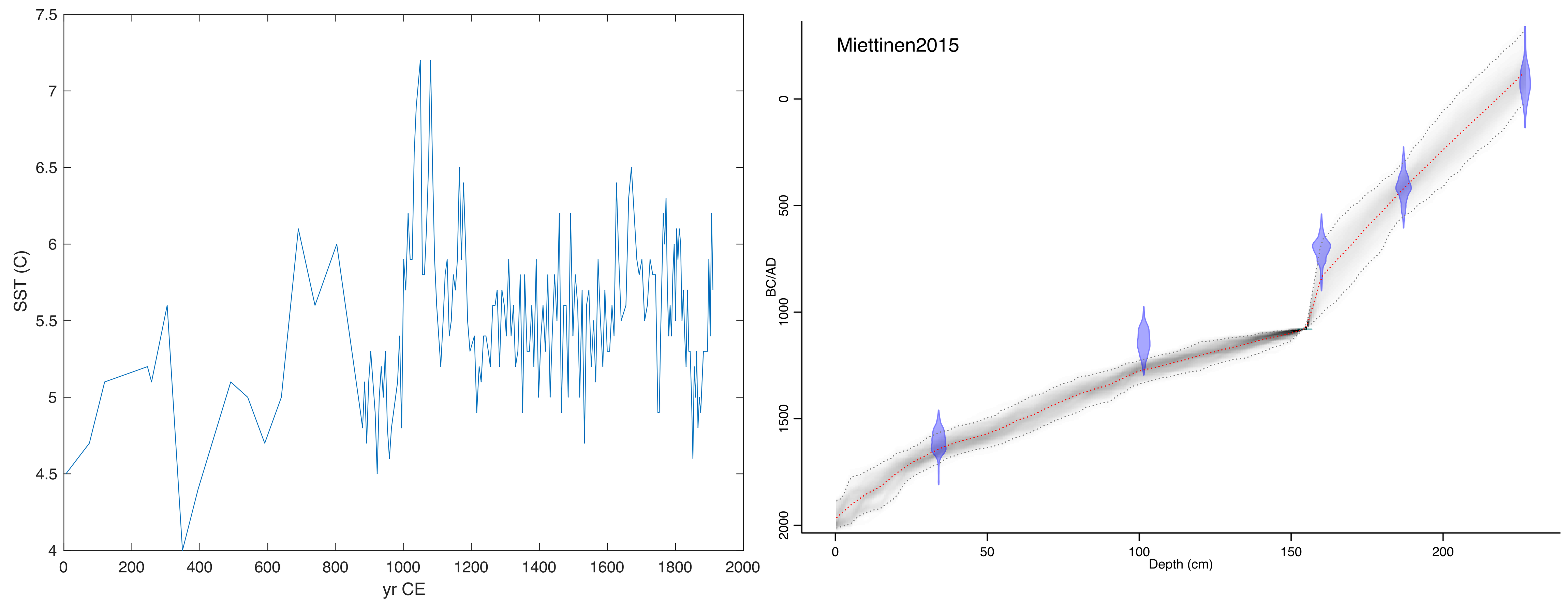

Figure 2: left: example time series plot of SST reconstruction from Miettinen et al. 2015. Right: Age-depth models generated using information of C^{14} dating and absolute time markers.

- Layered proxy records exhibit dating uncertainties due to miscounting. An ensemble of age models is constructed for these records using BAM (banded archive modelling, Comboul et al. 2014).

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- Blaauw, M. and J. A. Christen, (2011), *Bayesian Analysis*, 6, 457-474, doi: 10.1214/11-BA618
- Comboul, M., Emile-Geay, J., Evans, M. N., Mirnateghi, N., Cobb, K. M., and Thompson, D. M., (2014), *Clim. Past*, 10, 825–841, doi:10.5194/cp-10-825-2014
- Miettinen, A., D. V. Divine, K. Husum, N. Koç, and A. Jennings (2015), *Paleoceanography*, 30, 1657?1674, doi: 10.1002/2015PA002849
- Tingley & Huybers (2010), *Journal of Climate*, 23 (10), doi: DOI: 10.1175/2009JCLI3015.1

Pseudoproxy experiments for BARCAST

- The BARCAST reconstruction skill for North Atlantic SST will be tested using known target data from one climate model simulation of the Last Millennium Ensemble of the CCSM4 model (Otto-Bliesner et al. 2016).
- The simulated SST is resampled to resemble real-world availability of SST observations, and perturbed with noise to simulate the observed noise of instrumental data and proxies.

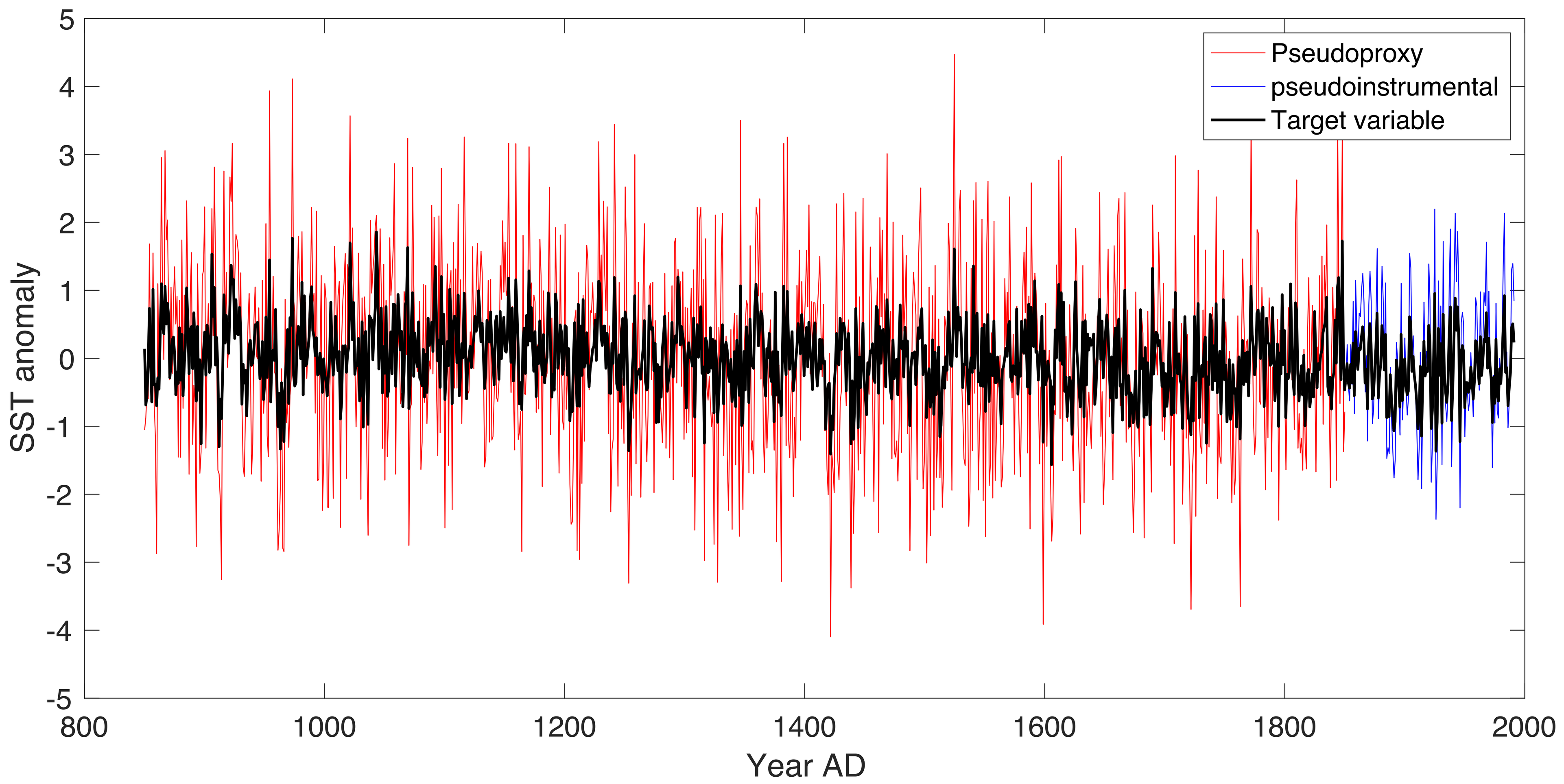

Figure 3: Example time series used for pseudoproxy experiments. Target variable perturbed with white noise to obtain a proxy signal-to-noise ratio of 0.7

Methodological challenges

- BARCAST models the target variable as an AR(1) process in time, and cannot assess the long-range memory that real SST data exhibit (Franzke et al. 2019).
- BARCAST parameters are originally designed for data over land.
- BARCAST is computationally demanding and probabilistic in nature. Generating a full ensemble of reconstructions is CPU- and time-consuming.

Proxy surrogate reconstruction method (the analogue method)

The second reconstruction method is a learning technique with proxy records as predictors, and climate model time slices as the learning set (the pool of possible analogues). For each time point to reconstruct, the distance between the vectors of the proxy network and each model time slice is calculated. The reconstruction at time *t* is the mean of the N closest analogues.

Euclidian distance between the proxy network T^P at time t_1 and a possible analogue T^M at time t_i:

$D(T^P, T^M)=\sqrt{\sum_{j=1}^{K}(T_j^P - T_j^M)}$, where *j* denotes proxy locations.

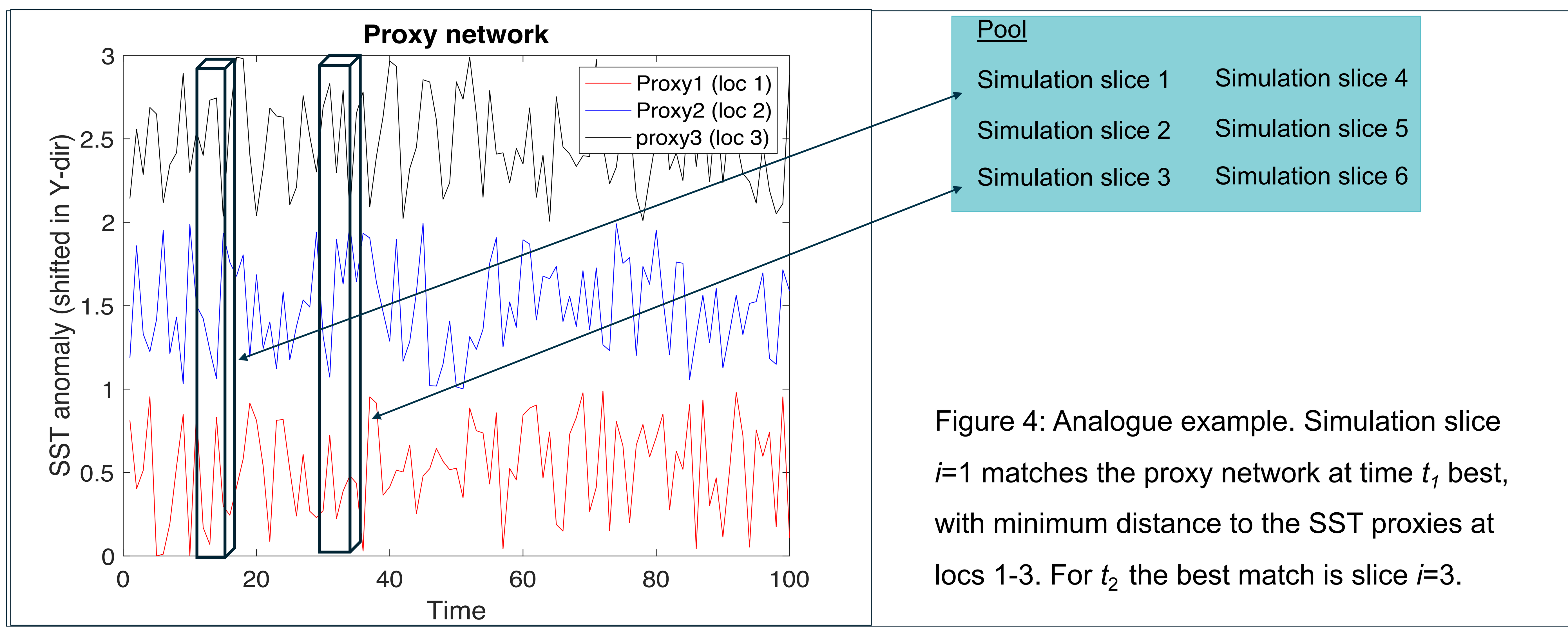

Figure 4: Analogue example. Simulation slice *i*=1 matches the proxy network at time t_1 best, with minimum distance to the SST proxies at locs 1-3. For t_2 the best match is slice *i*=3.

Results to come!

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- Franzke, C. L. E., Barbosa, S., Blender, R., Fredriksen, H.-B., Laepple, T., Lambert, F., et al., (2020). *Reviews of Geophysics*, 58, e2019RG000657, doi: 10.1029.2019/RG000657.
- Otto-Bliesner et al. (2016) , *Bull. Amer. Meteor. Soc.* **97**, 735-754, doi: 10.1175/BAMS-D-14-00233.1

Project timeline

2019	2020	2021	2022
Method implementation, configuration, data preparation	Pseudoproxy experiments, generating reconstructions (both methods), initial data analysis		Data analysis, impact studies

Novelties of the PALEOBRIDGE project

- This will be the first ensemble-based climate field reconstruction of SST using marine proxies for the larger northern North Atlantic region.
- BARCAST reconstructs target values even at locations without observations, and takes age-model uncertainties properly into consideration.

Why do we need SST reconstructions for the northern North Atlantic?

- To gain knowledge and better understanding of the natural climate variability on time scales extending beyond the instrumental period.
- To improve the existing reconstructions of the AMV. The variability of the North Atlantic SST is currently reconstructed from terrestrial proxy data (Fig 1a and 2a of Wang et al. 2017).

Expected output and how to access it

The reconstructed data sets and the associated numerical code will be uploaded to NOAA NCEI and the UiT Open Research Data Portal upon publication*. In the meantime, contact me by e-mail for updates and requests.

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The Research Council of Norway

- Wang, J., Yang, B., Ljungqvist, F. et al. (2017). *Nature Geosci*, 10, 512-517, doi:10.1038/ngeo2962

* https://dataverse.no/dataverse/uit