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A Comparison of Methods for Ocean Reconstruction from Sparse Observations

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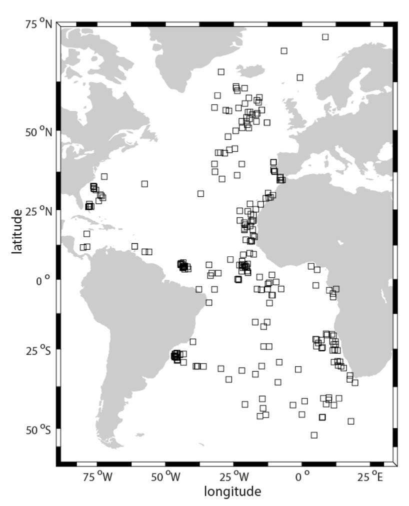
Introduction



- Problem: reconstructions from scattered observations of sediment cores distributed on the ocean floor in a sparse and irregular manner
- Data: measurements from benthic foraminifera in deep sea sediment cores (e.g., the data compiled by Peterson et al. [1])
- Solution: reconstruction methods useful for interpolating or approximating sparse scattered data
- Goal: comparison of the advantages and disadvantages of methods in order to enhance reconstruction quality

Methods

Reconstruction using a modified Moving Least Squares Approach

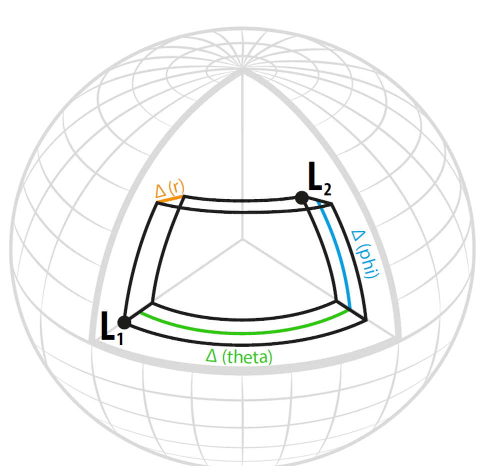
- Modified Moving Least Squares (MLS) approach without assuming any additional information (e.g., the flow field)
  - Input: A scalar field of observations **f**, precomputed weighting parameters α, β, γ (see Distance Measure section)
    - Computation of matrix **B** from quadratic basis functions **b**
    - Set up diagonal weight matrix $\mathbf{W}(\rho)$ with weight function ρ (depending on the weighted distance)
    - Evaluate MLS function[2]

$$MLS(x)=\mathbf{b}^T(x)\left(\mathbf{B}^T\mathbf{W}(\rho)\mathbf{B}\right)^{(-1)}\mathbf{B}^T\mathbf{W}(\rho)\,\mathbf{f},$$

$$\text{with } \rho(L_1,L_2)=1/\left(\text{distance}(L_1,L_2)^2+\varepsilon^2\right) \qquad \varepsilon \text{ is a smoothing parameter}$$

  - Output: Reconstructed values

Distance Measure

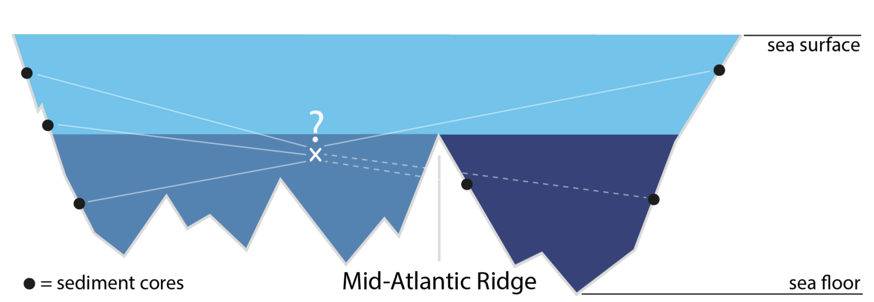


- Generalized distance measure considering spherical nature of the data set:
  - Input: Two locations L_1 and L_2

$$\text{distance}(L_1,L_2)=\alpha\cdot\Delta(\text{phi})+\beta\cdot\Delta(\text{theta})+\gamma\cdot\Delta(r)$$

  - α, β, γ are weights
  - **Δ(phi)** and **Δ(theta)** are geodesic distances between L_1 and L_2 (see figure)
  - **Δ(r)** is the depth difference between L_1 and L_2
- Machine-learning pre-processing step performed to estimate good values for α, β and γ

Physical Boundaries of the Ocean



- Consideration of ocean boundary to improve reconstruction results
- Core samples partitioned into bathymetry-based subsets
- Cores of not directly connected subsets are ignored

Reconstruction using a Flow-Based Approach

- Exploits correlations between the scalar field to be reconstructed and the vector field representing the ocean flow
- Input: A scalar field of observations **f** and a vector field representing flow
- Output: Reconstructed values

- Optimal Interpolation used as the underlying reconstruction method
- Modification of underlying method: utilize a non-Euclidean distance measure defined using the input flow field:

$$\text{distance}(L_1,L_2)=\sqrt{\left(\alpha\cdot(\text{distance along streamline})^2+(\text{distance across streamline})^2\right)}$$

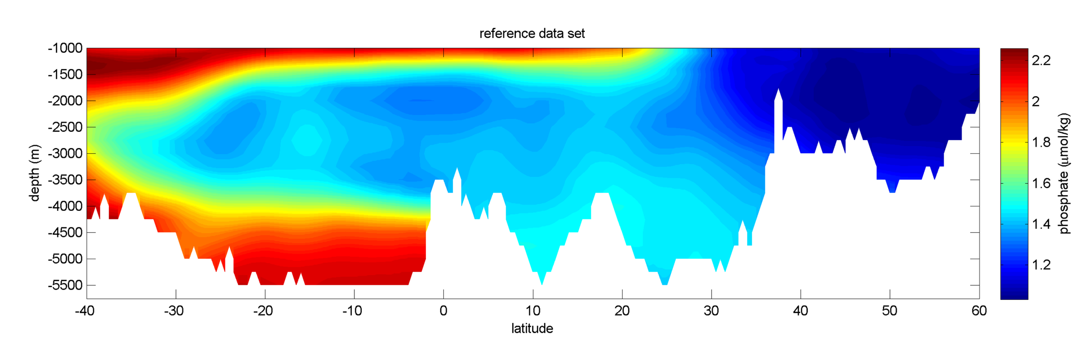
- Streamlines are calculated for the flow field using a fourth-order Runge Kutta method
- Parameters: α, correlation length
- Parameters optimized dynamically using an objective function defined with respect to the RMS error for a leave-one-out cross validation using the given observations

Results

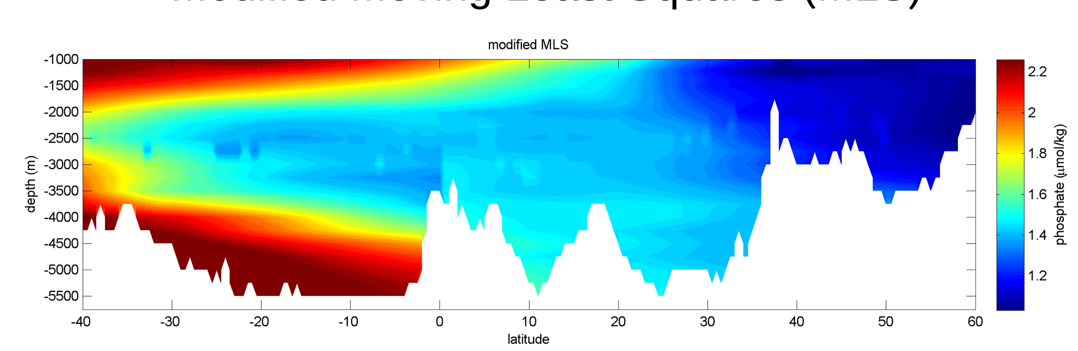
Modern day

- Comparisons of the Reconstructions for the modern-day Atlantic Ocean based on a gridded data product [3] as reference data
- Reconstructions based on a subset of 186 data points corresponding to the distribution of the sediment cores
- Due to lack of a gridded climatology of modern-day $\delta^{13}C$ data we used phosphate, because of its nearly linear relation to $\delta^{13}C$

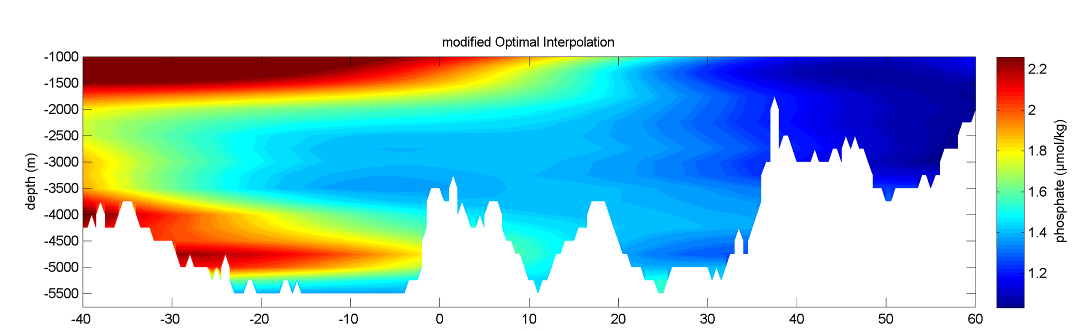
WOCE data set



Modified Moving Least Squares (MLS)

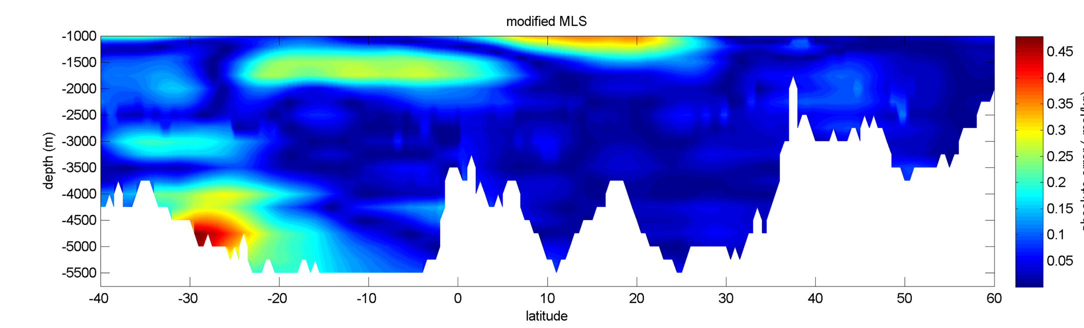


Modified Optimal Interpolation (OI)

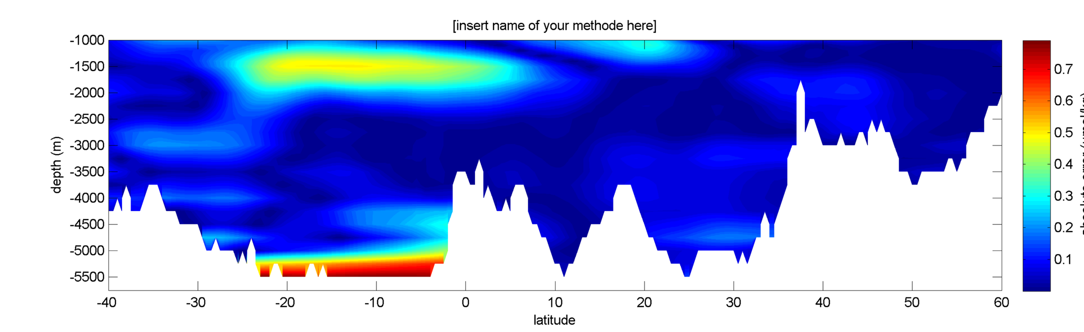


- Difference images between reconstructions and WOCE data set

Modified Moving Least Squares (MLS)

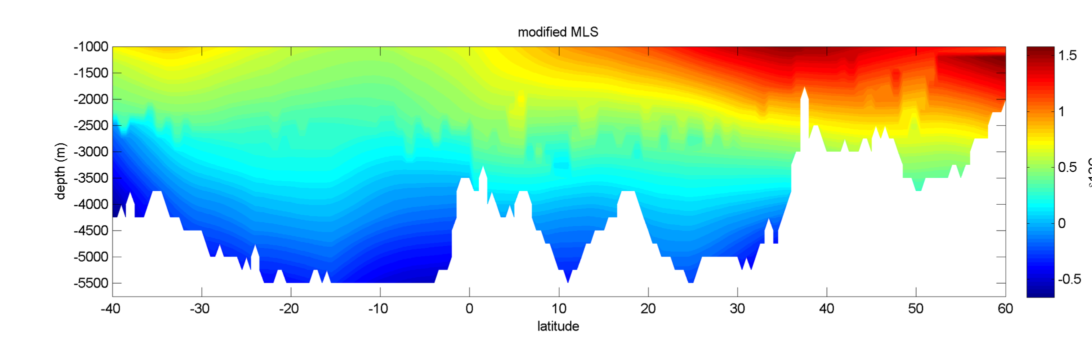


Modified Optimal Interpolation (OI)



LGM

- A reconstruction for the LGM



Summary and Future Work

- Both methods show promising results
- They have advantages and disadvantages in different regions
- In the future a combination of both may merged to a more precise reconstruction
- Further improvements may allow a estimating the glacial changes in multiple seawater properties and guide the analysis of existing and the future collection of sediment cores

References

[1] Peterson, C., Lisiecki, L., and Stern, J. Deglacial whole-ocean $\delta^{13}C$ change estimated from 493 benthic foraminiferal records. Submitted to *Paleoceanography*.

[2] Agranovsky, A., Garth C. and Joy, K., (2011) Extracting Flow Structures Using Sparse Particles. *Vision, Modeling and Visualization Workshop 2011*

[3] Gouretski, V., and K. Koltermann (2004), WOCE global hydrographic climatology, *Bericht des Bundesamtes für Seeschifffahrt und Hydrogr.*