# *Evaluation of Global Teleconnections in CMIP6 Climate Projections using Complex Networks*

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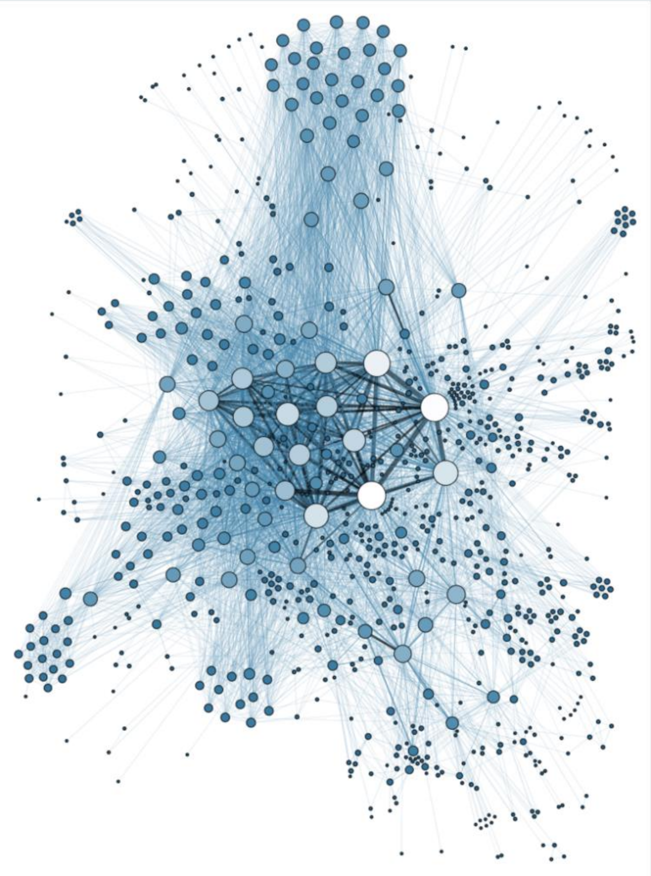
# *Teleconnections--Complex Networks*

- **Teleconnections** are interactions between **geographically separated regions** that are **persistent** and **recurrent**.
- Caused by **energy transport** and **wave propagation** in **atmosphere** and **ocean**, necessary for balancing the **equator-to-pole** insolation difference (Bollasina&Wilcox 2022)
- Teleconnections track low-dimensional manifolds of climate → indespensable to understand **climate variability** and **climate senitivity** (Ricard et al. 2024)

- Complex Networks can describe teleconnections in **complementation to linear methods** (Donges et al. 2015)
- A **Complex Network** is a **graph** having non-trivial topological properties characterized by **non-linear dynamics** (nonnormality, long-range dependence, fractal geometry, self-organised criticality, chaotic behavior…)



*Quelle: Wikipedia*

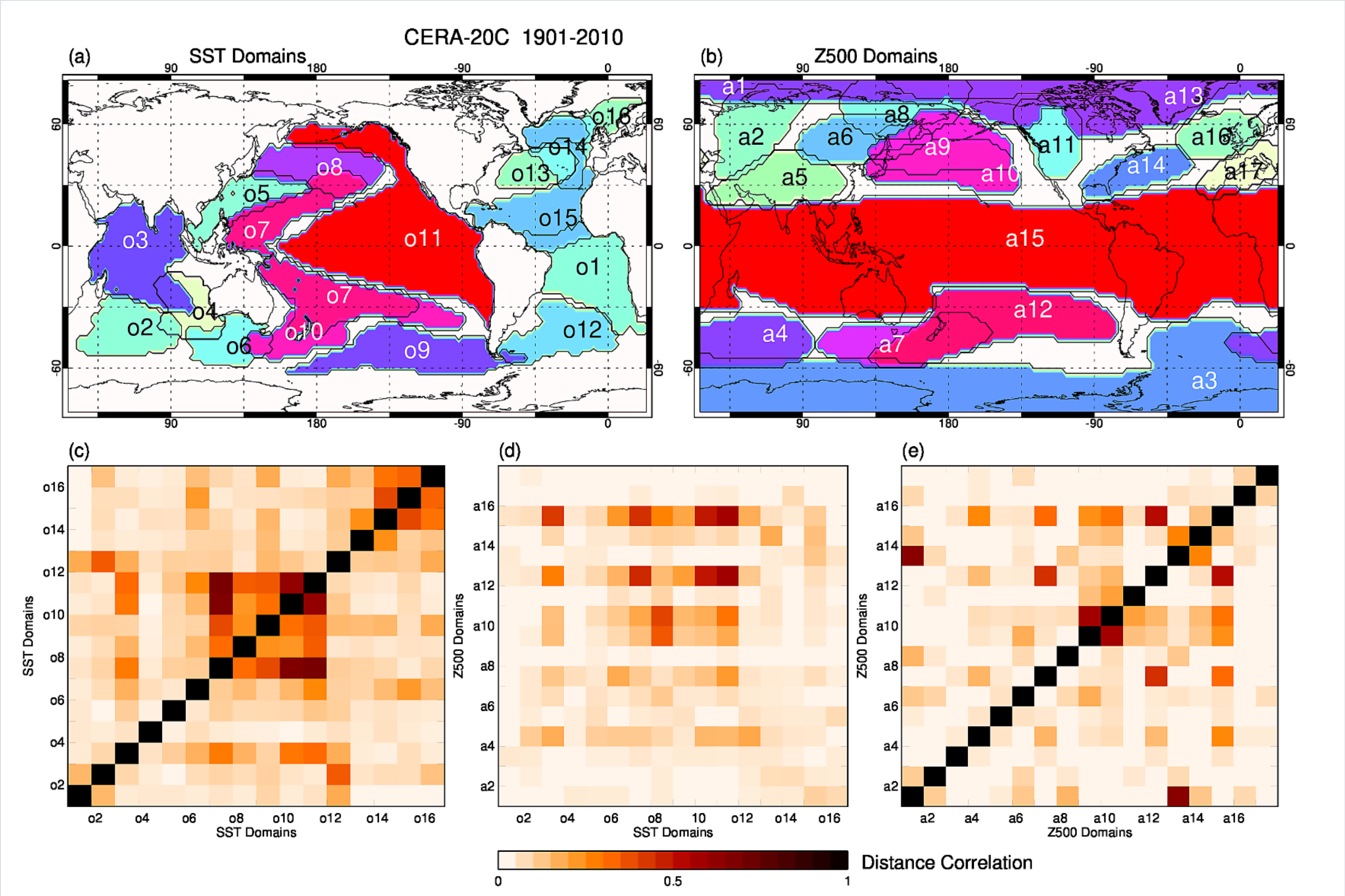
# *Data and Methods*

- **Data:** CMIP6 historical simulations vs. CERA-20C, 20CRv3 seasonal means of **SST, Z500**
- **Trend-EOFs** extract global nonlinear trend patterns (Hannachi et al. 2007)
- **δ-Maps :** data mining tool, identifies all teleconnections according to specification (Fountalis et al. 2018)
  - Domain identification=non-linear **dimension reduction**=coherent grid cells
  - **Network inference**=lagged links between domains based on **Distance correlation**--robust measure of nonlinear dependence (Székely et al. 2007)
  - Depencence of >2 domains: **Distance multicorrelation** (Böttcher et al. 2017) → detect Lancaster interaction=synergy
  - Controle of **False Discovery Rate** in multiple testing (Benjamini & Hochberg 1995)
- **Evaluation: Structural Simularity** for comparison between model/reanalysis networks

# *δ-Maps*

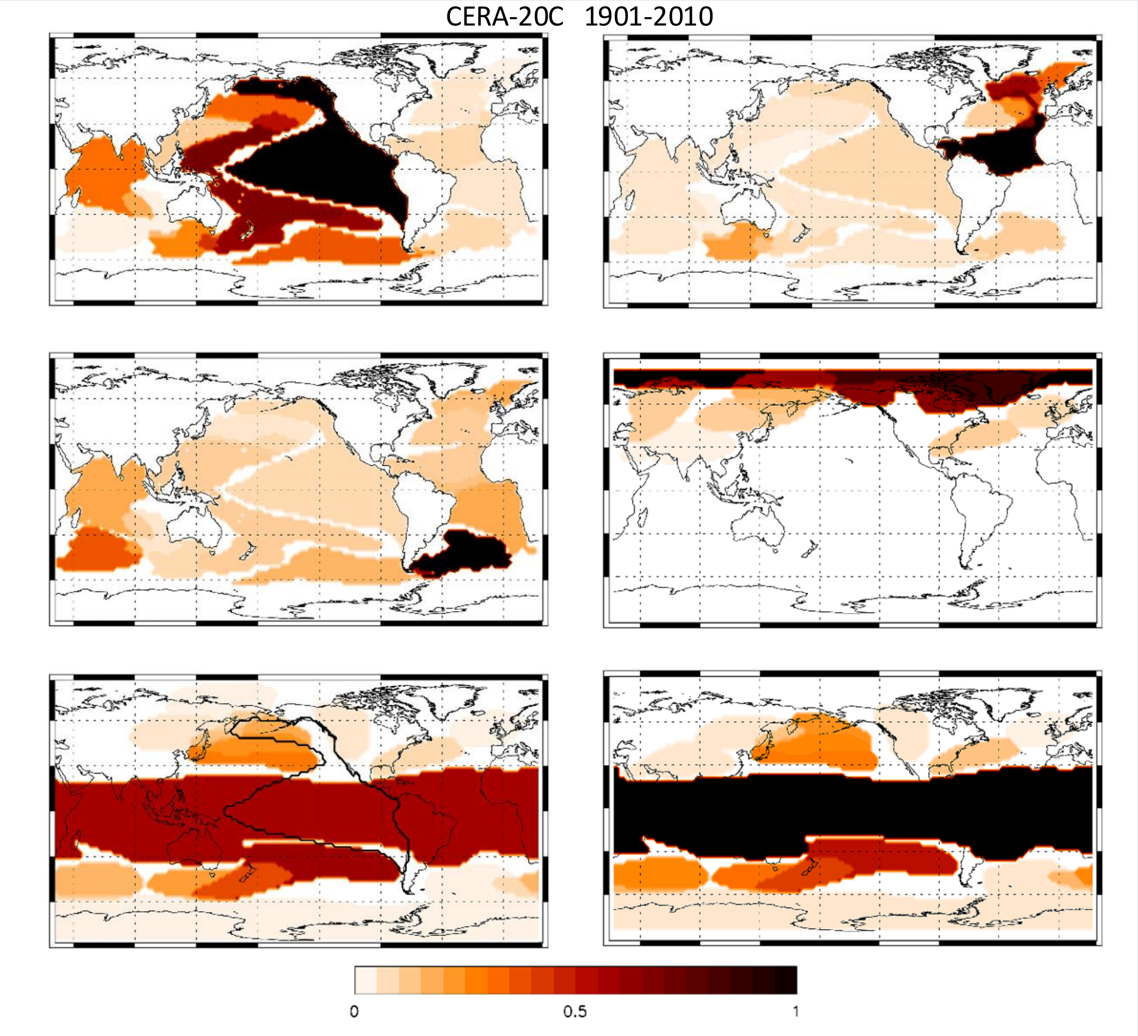
- **Domains**=grid cells with average pairwise (rank) correlation >δ
- Consistent with known teleconnections ENSO, AMO, PDO …

- **Links**=Distance correlation between domains=Correlation between pairwise distances $|x_i-x_j|$ and $|y_i-y_j|$ of two time series
  - $0 \leq \text{Dcor} \leq 1$
  - Dcor=0 ⇔ x,y independent
  - Dcor=1 ⇔ y=ax+b
  - Robust against nonlinearity and autocorrelation



# *δ-Maps*

- Links are tested with control of FDR
- Distributed adjacency tensors **M** on grid cell level: slices showing the teleconnections of various SST and Z500 domains
  - $\mathbf{M}_{ijkl} = 0 \Leftrightarrow x_{ij}$ or $x_{kl} \notin$ domain
  - $\mathbf{M}_{ijkl} = 1 \Leftrightarrow x_{ij}$ and $x_{kl} \in$ same domain
  - $\mathbf{M}_{ijkl}$ = average of all links between domains $\ni$ $x_{ij}$ and $x_{kl}$



# *δ-Maps Network Comparison*

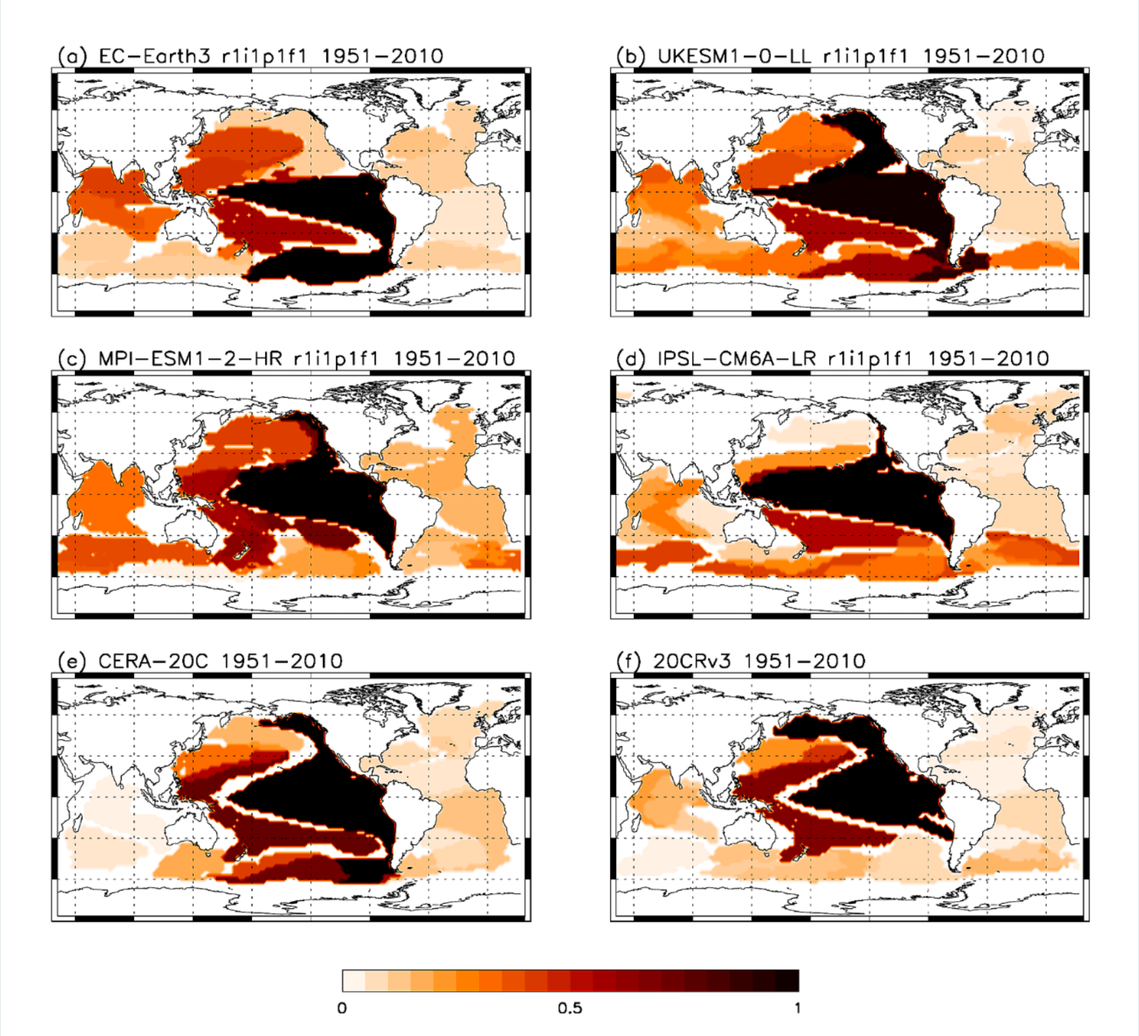
- Comparison of model/reanalysis adjacency tensors using Structural Similarity Index **SSIM**: combination of strength, variability and pattern correlation

- -1 ≤ SSIM ≤ 1, SSIM = 1 identity

$$\mathrm{SSIM} = \frac{2\mu_1\mu_2 + c_1}{\mu_1^2 + \mu_2^2 + c_1} \cdot \frac{2\sigma_1\sigma_2 + c_2}{\sigma_1^2 + \sigma_2^2 + c_2} \cdot \frac{Cov + c_3}{\sigma_1\sigma_2 + c_3}$$

- Exponential transform → **Network Quality Score**

$$\mathrm{NQS} = \exp\left\{-\left(\frac{1-\mathrm{SSIM}}{2}\right)^2\right\}$$ (1=ideal SSIM value)



# *δ-Maps Network Comparison*

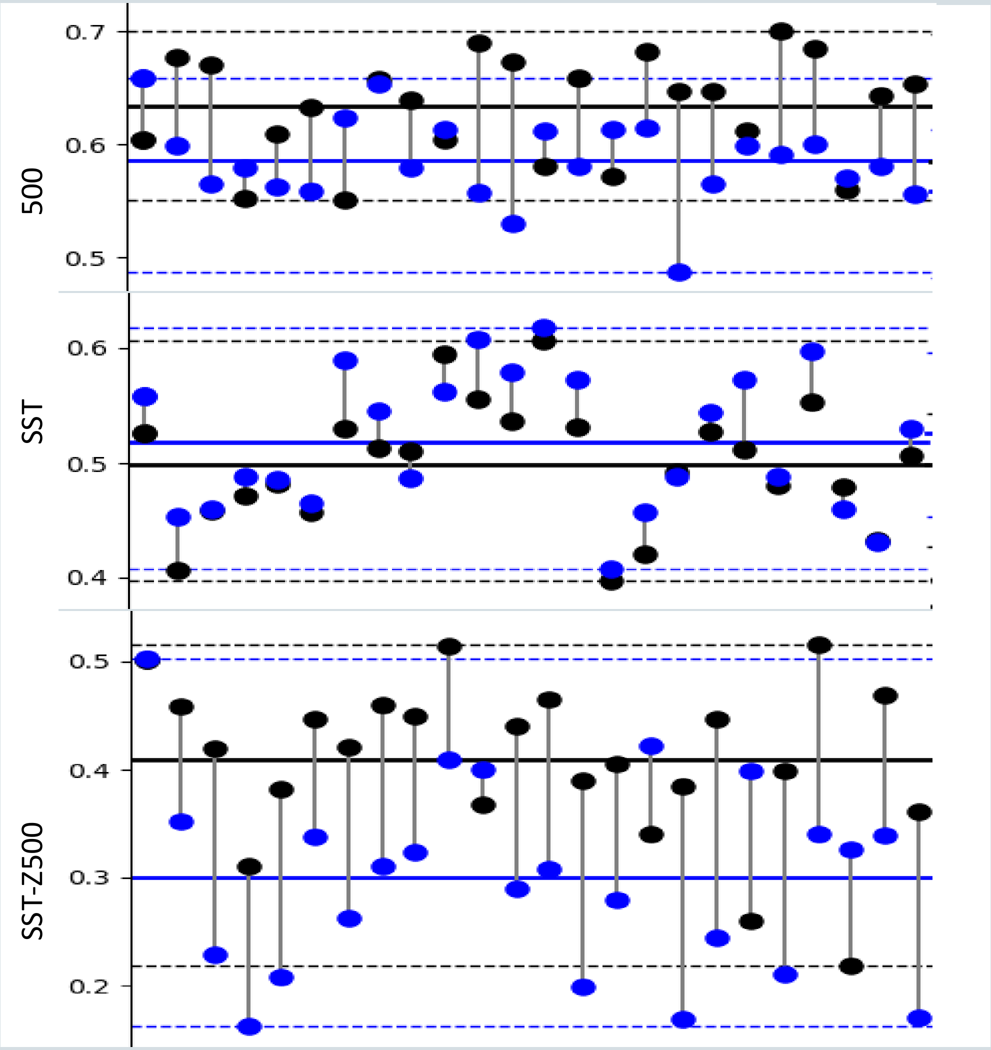
- **24 historical CMIP6 simulationen** – driving data for RCM downscaling provided

- Network Quality scores wrt. **CERA-20C** and **20CRv3** in 1951-2010
- similar scores ⬄ no contradictions between reanalyses

- Z500 networks: similar to all reanalyses ⬄ interactions in Z500 fields well represented
- SST networks: some satisfactory, some less so
- SST-Z500 networks: some low scores

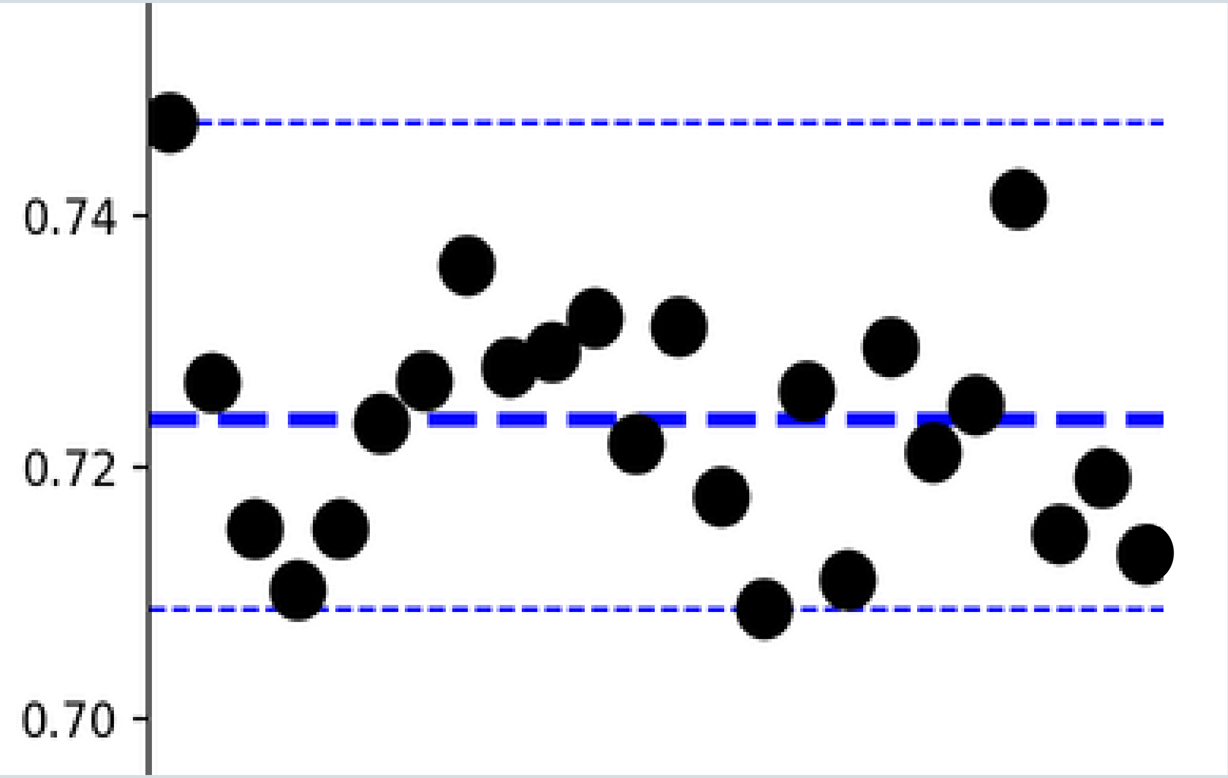
- Geometric mean → **Multivariate** Network Quality Score

$$\mathrm{MNQS} = \sqrt[3]{\mathrm{NQS}(SST) \cdot \mathrm{NQS}(Z500) \cdot \mathrm{NQS}(SST{-}Z500)}$$



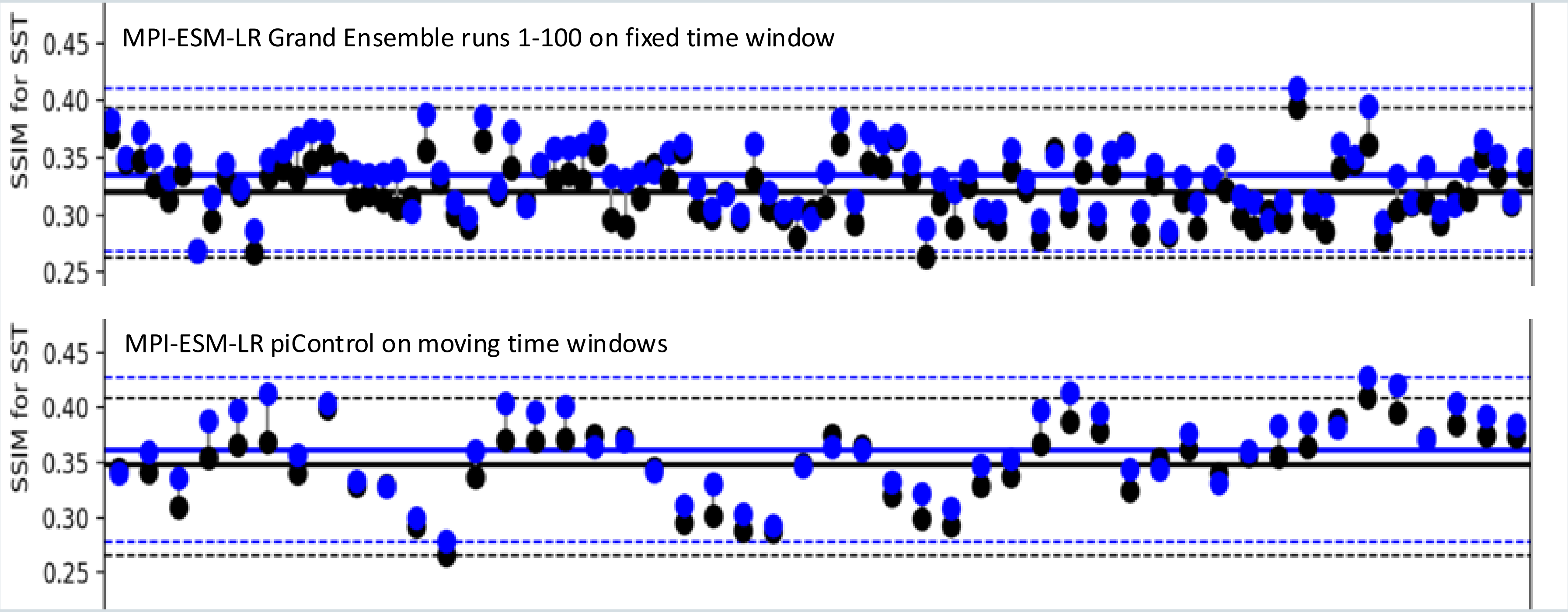
# *δ-Maps Network Comparison*

- **Average** Multivariate Network Quality Score over both references in 1951-2010
- Input for ensemble selection using the **Independent Ensemble Quality Score** (Sanderson et al. 2015, Brunner et al. 2020)



# ***δ-Maps Extensions***

- **Vector-valued** time series: e.g. (SST, SSS, SSH), (Z850, Z500, Z200)…
- **Multi-scale networks** with wavelet decomposition
- **Higher-order** networks with multiple-domain interactions
- **Causal Networks**
- **Evolving networks** on moving windows




Climate networks are subject to **multidecadal variability** → multiple runs to evaluate model, choose simulation runs that are in phase with reality for downstream applications

# *Thank you*

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