```
bedartha@Precision-5540:projects$ csvlook -d , presentation_schedule.csv
|       Date |  Time | Team                | Topic                                                                                        |
| ---------- | ----- | ------------------- | -------------------------------------------------------------------------------------------- |
| 2021-07-21 | 10.00 | Carmen & Michael    | Spatial pattern of West European surface temperatures from CNNs                              |
| 2021-07-21 | 10.15 | Stefan & Alexander  | Spatial pattern of average wind speeds over West Europe using CNNs                           |
| 2021-07-21 | 10.30 | Johannes & Adrian   | Regions of similar behaviour for West European rainfall from climate network communities     |
| 2021-07-21 | 10.45 | Dorothee & Frieder  | Latent factors underlying West European surface temperatures from EOFs                       |
| 2021-07-21 | 11.00 | Leonard & Rosanna   | Prediction of West Europe surface temperatures using LSTMs                                   |
| 2021-07-21 | 11.15 | Ludwig & Christian  | Rainfall over West Europe as a correlate of North Atlantic Oscillation (NAO)                 |
| 2021-07-21 | 11.30 | Merle & Mara        | Predicting spatial pattern of West European rainfall using CNNs                              |
| 2021-07-28 | 10.00 | Felix & Moritz      | Causal maps between NAO and WE precipitation                                                 |
| 2021-07-28 | 10.15 | Kari & Naman        | Mortality rates in West Europe modeled using cold / warm extremes                            |
| 2021-07-28 | 10.30 | Tim & Shiaw-Shiuan  | Predicting West European surface temperatures using Gaussian processes                       |
| 2021-07-28 | 10.45 | Effi & Ricarda      | Economic indicators of West European countries modeled using climatic observables             |
| 2021-07-28 | 11.00 | Jolanda & Robert    | Predicting West European rainfall using LSTMs                                                |
| 2021-07-28 | 11.15 | Gereon & Josua      | Regions of similar behaviour for average wind speeds over WE from climate network communities |
| 2021-07-28 | 11.30 | Julian & Dexter     | Latent factors underlying West European surface temperatures using VAEs                      |
|            |       |                     |                                                                                              |
bedartha@Precision-5540:projects$
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LECTURE 8:
Climate networks

ML-4430: Machine learning approaches in climate science

16 June 2021

What are climate networks

1

- How do we estimate climate networks?
- What do they tell us?

Avoiding potential pitfalls

2

- Autocorrelation (Palus et al., 2009)
- Boundary effects (Rheinwalt et al., 2011)
- Spatial embedding (Boers et al., 2019)

Networks from Graphical Models

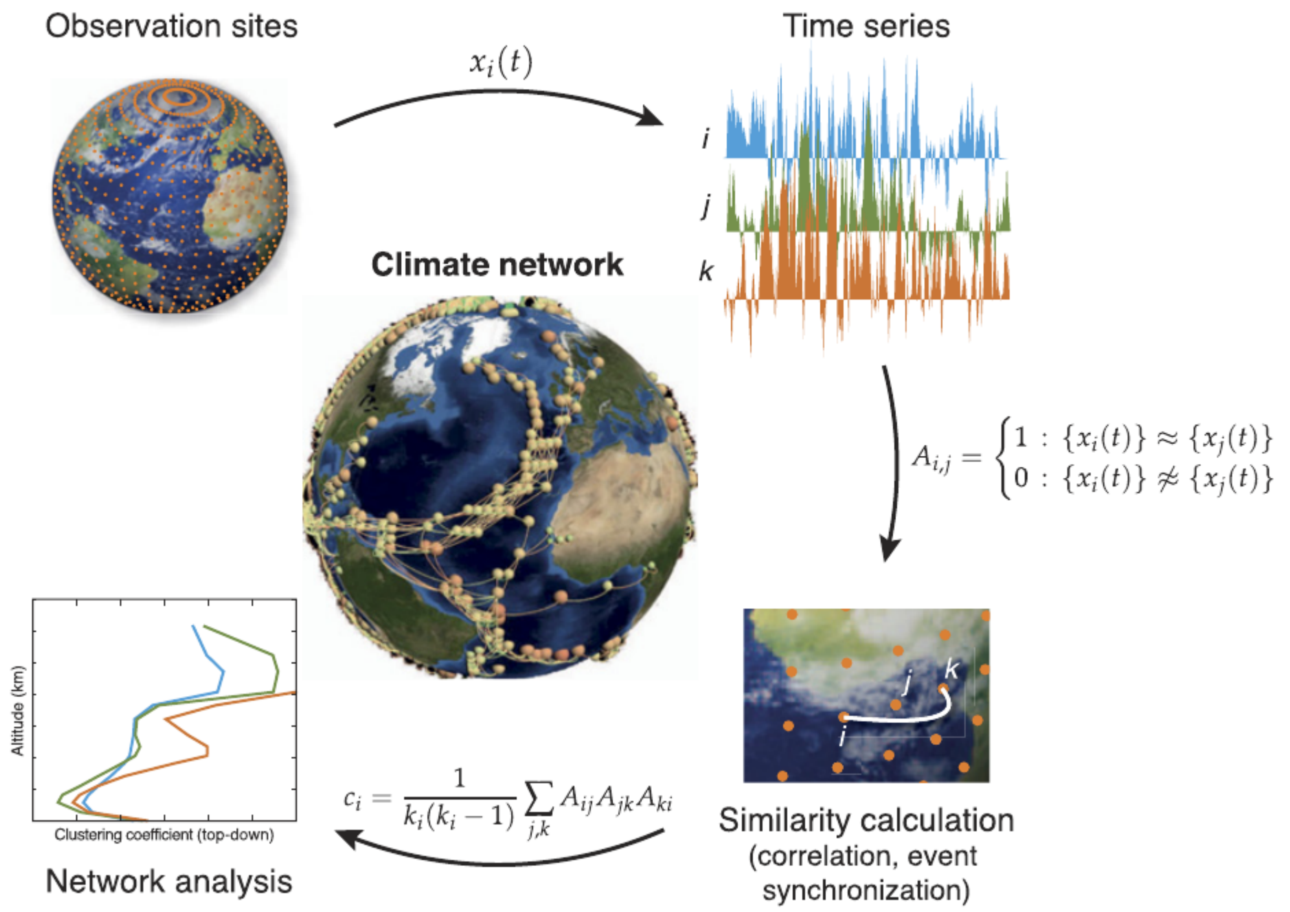
3

- Ebert-Uphoff & Deng, 2012
- Runge et al., 2015
- ~~Zerenner et al., 2012~~

Climate Networks with ML

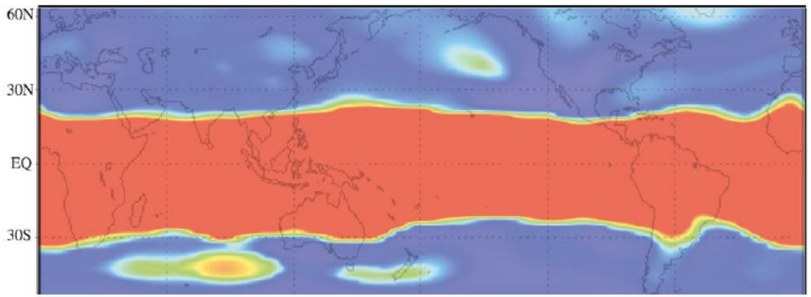
4

- Noteboom et al., 2018
- ~~Santos et al., 2020~~



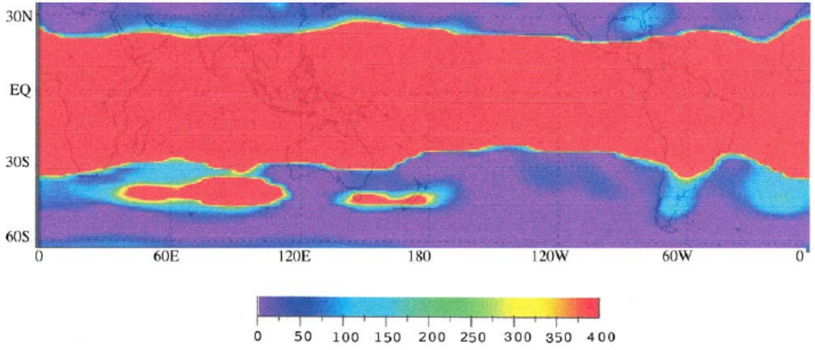
1. What are climate networks → How do we estimate climate networks?

Monthly Z500, 5 deg lat-lon grid, correlation coeff., 1% significance (threshold rho = 0.5)



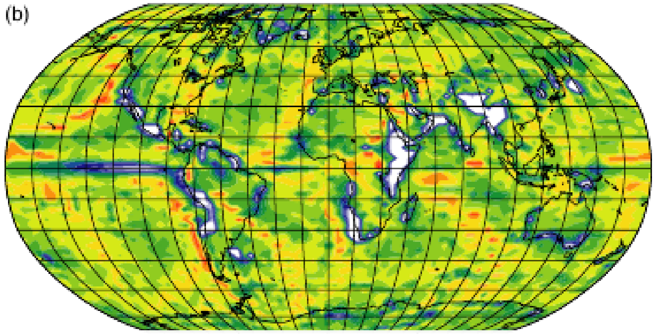
Degree

“The physical interpretation [...] is that the climate system exhibits properties of stable networks [...] where information is transferred efficiently [...] ‘information’ should be regarded as ‘fluctuations’ from any source ([e.g.] the tropics, El Niño, etc.). ”



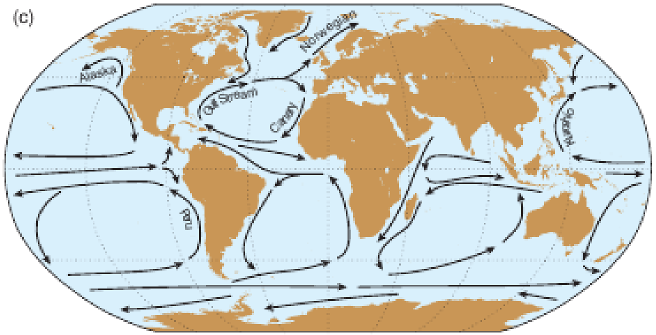
Degree > 5000 km

Monthly SAT, 2.5 deg lat-lon grid, Mutual Info., link density 0.5 %



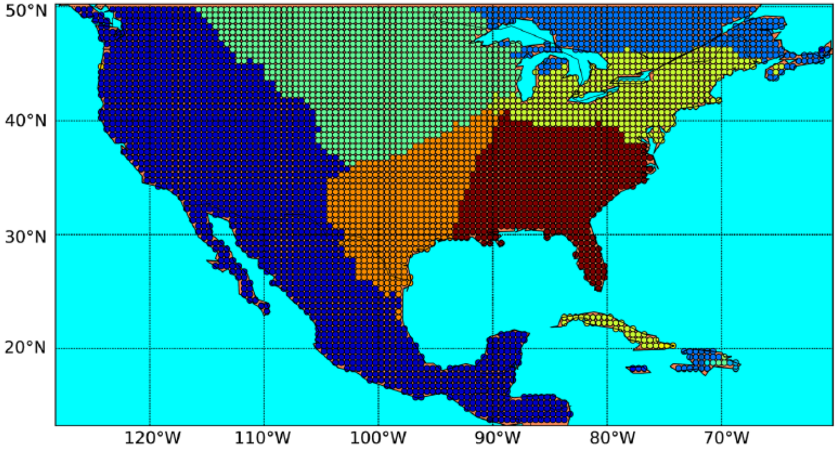
Shortest path betweenness

“In analogy with the internet, we call the network of these channels of high-energy flow the backbone of the climate network.”

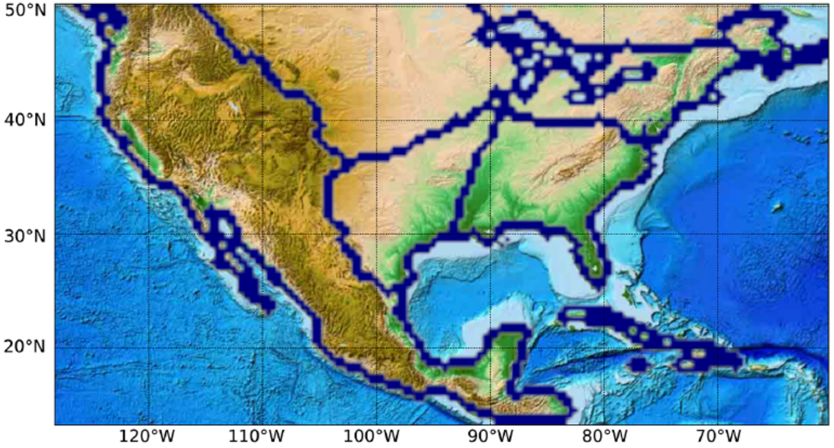


Ocean currents (schematic)

Monthly Surface T, 0.5 deg lat-lon grid, Cross correlation, link density 5 %



Network communities



Underlying topography

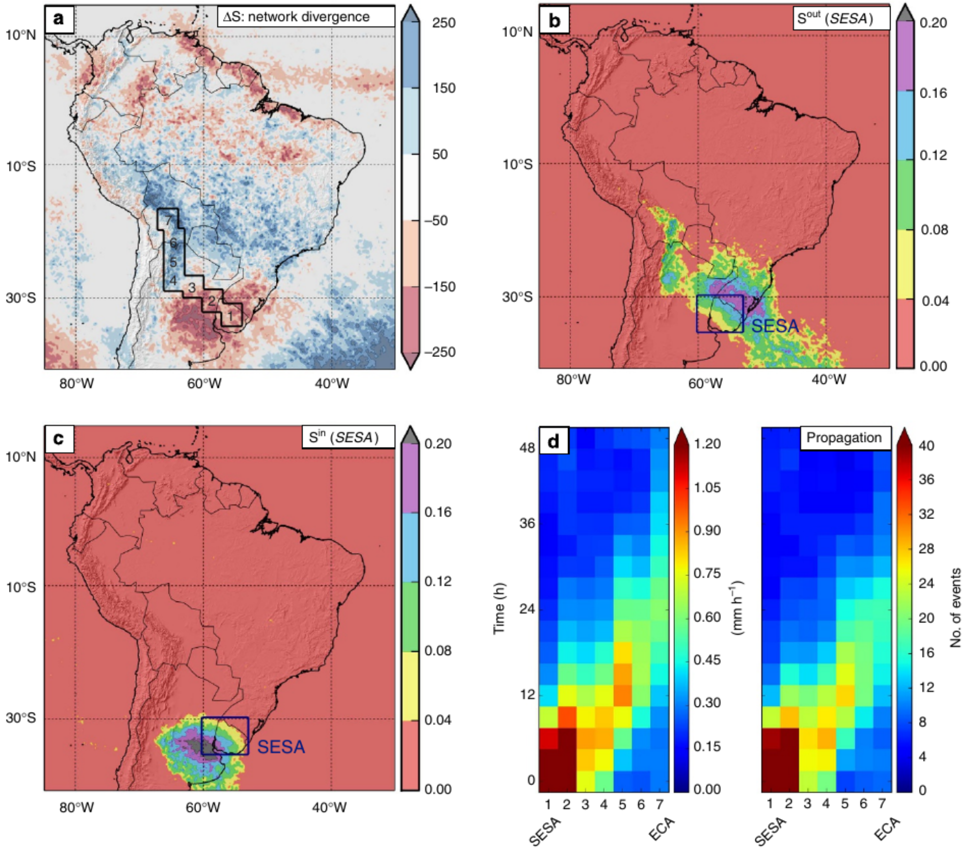
3-hourly extreme rainfall, 0.25 deg lat-lon grid, Event Synchronisation, link density 2 %

Network divergence

Outgoing links from SESA

Incoming links to SESA

Propagation of events



1. What are climate networks → What do they tell us?

What are climate networks

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- Runge et al., 2015
- ~~Zerenner et al., 2012~~

Climate Networks with ML

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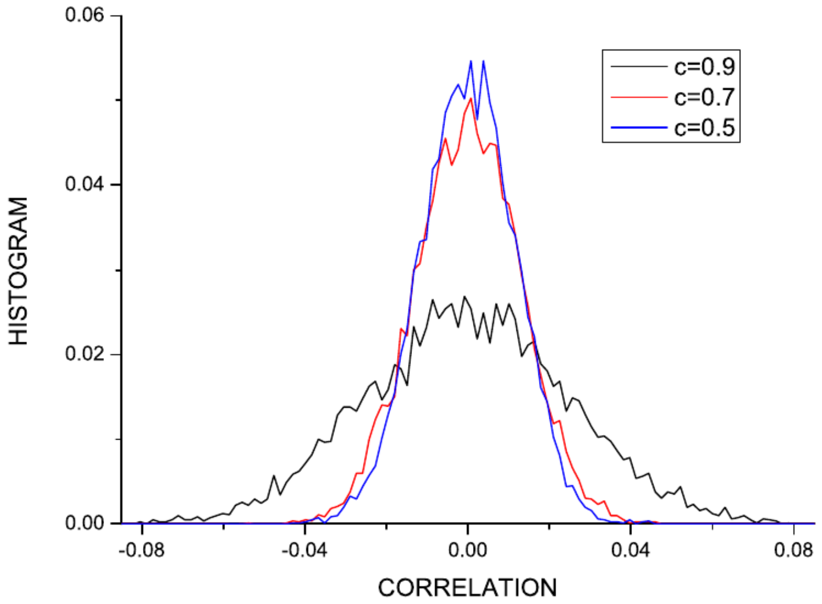
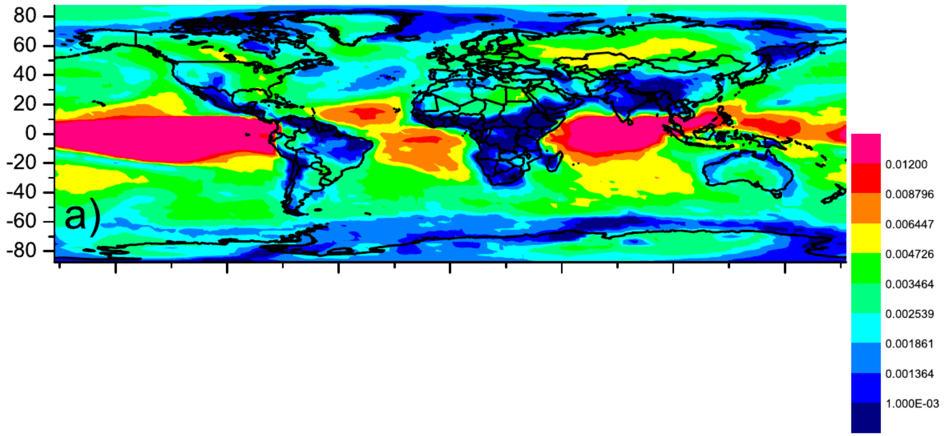
- Noteboom et al., 2018
- ~~Santos et al., 2020~~

Correlations between 8192 independent AR(10) processes for different AR coefficients



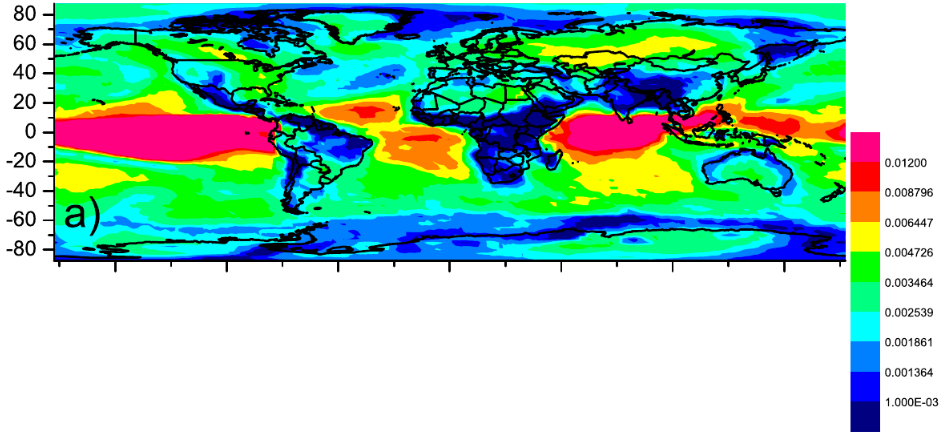
Monthly SAT, 2.5 deg lat-lon grid, absolute correlation coeff., link density 0.5 %

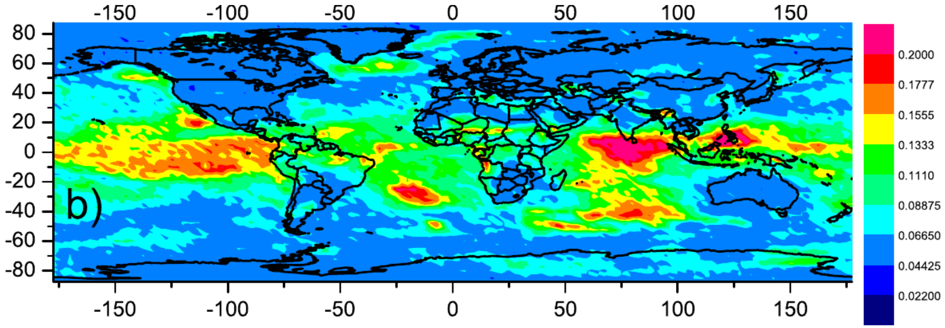
Area-weighted degree (original data)



Monthly SAT, 2.5 deg lat-lon grid, absolute correlation coeff., link density 0.5 %

Area-weighted degree (original data)

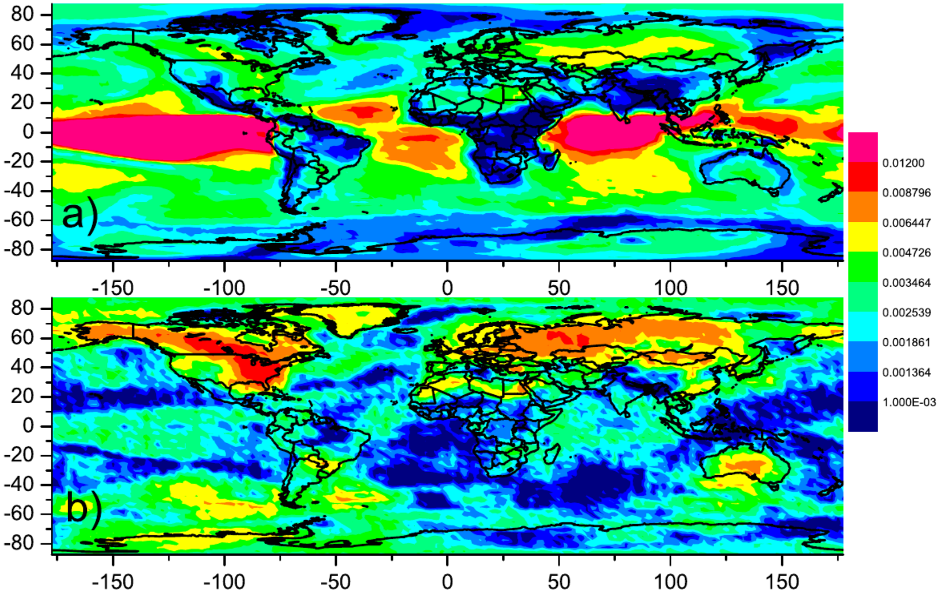




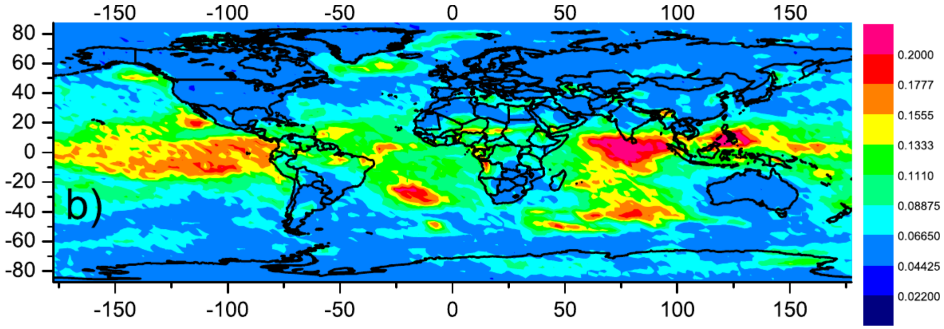
Area-weighted degree (randomised data)

Monthly SAT, 2.5 deg lat-lon grid, absolute correlation coeff., link density 0.5 %

Area-weighted degree (original data)



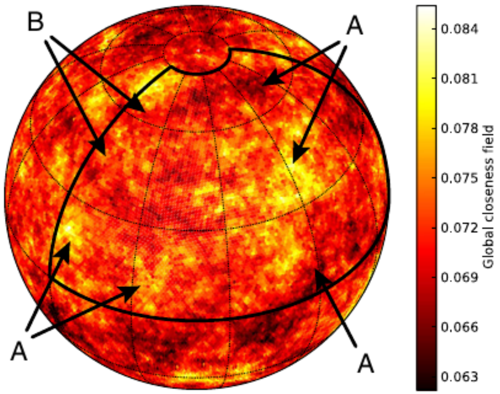
Z-score of area-weighted degree (original data)
(w.r.t. the distribution from randomised data)



Area-weighted degree (randomised data)

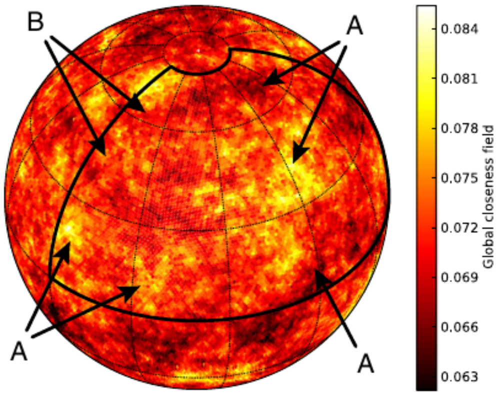
Closeness centrality on a random network on a sphere

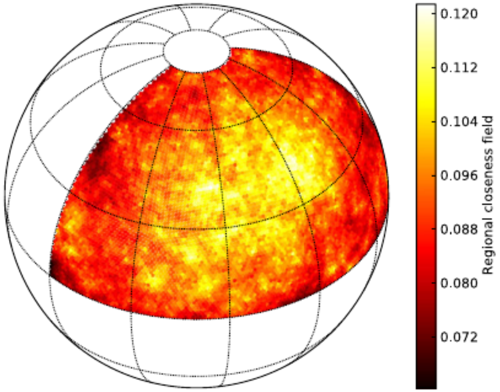
Closeness centrality
(Full data)



Closeness centrality on a random network on a sphere

Closeness centrality
(Full data)

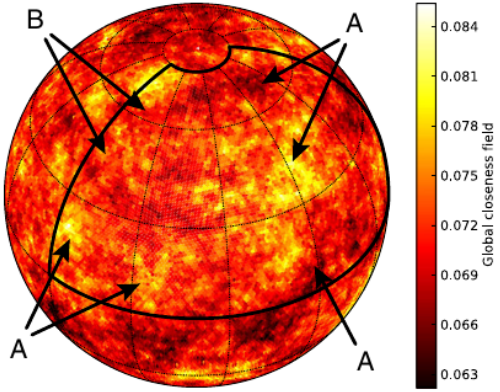




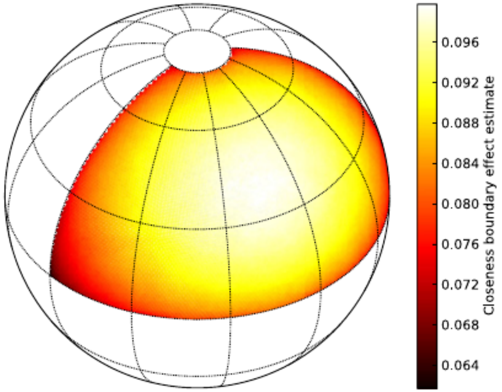
Closeness centrality
(boxed data)

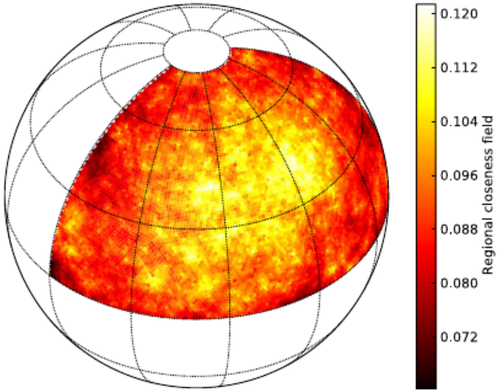
Closeness centrality on a random network on a sphere

Closeness centrality
(Full data)



Closeness centrality
(random model
preserving link length
distribution)



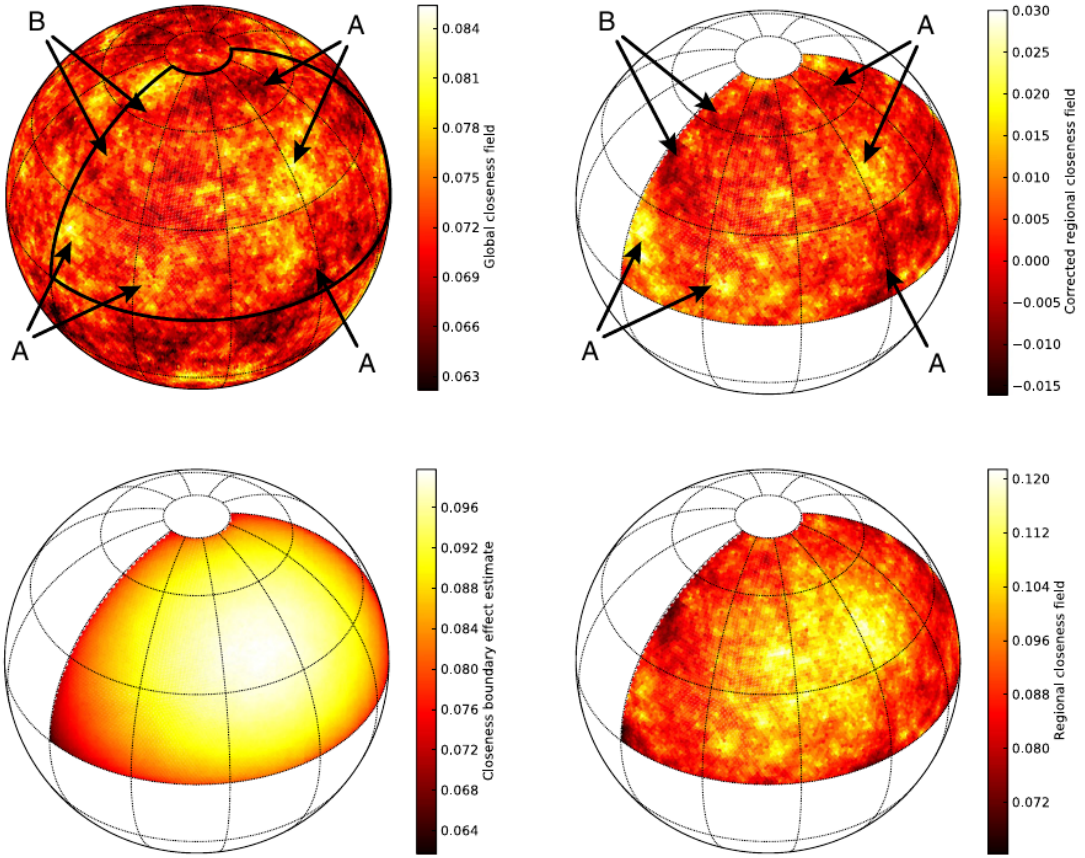


Closeness centrality
(boxed data)

Closeness centrality on a random network on a sphere

Closeness centrality (Full data)

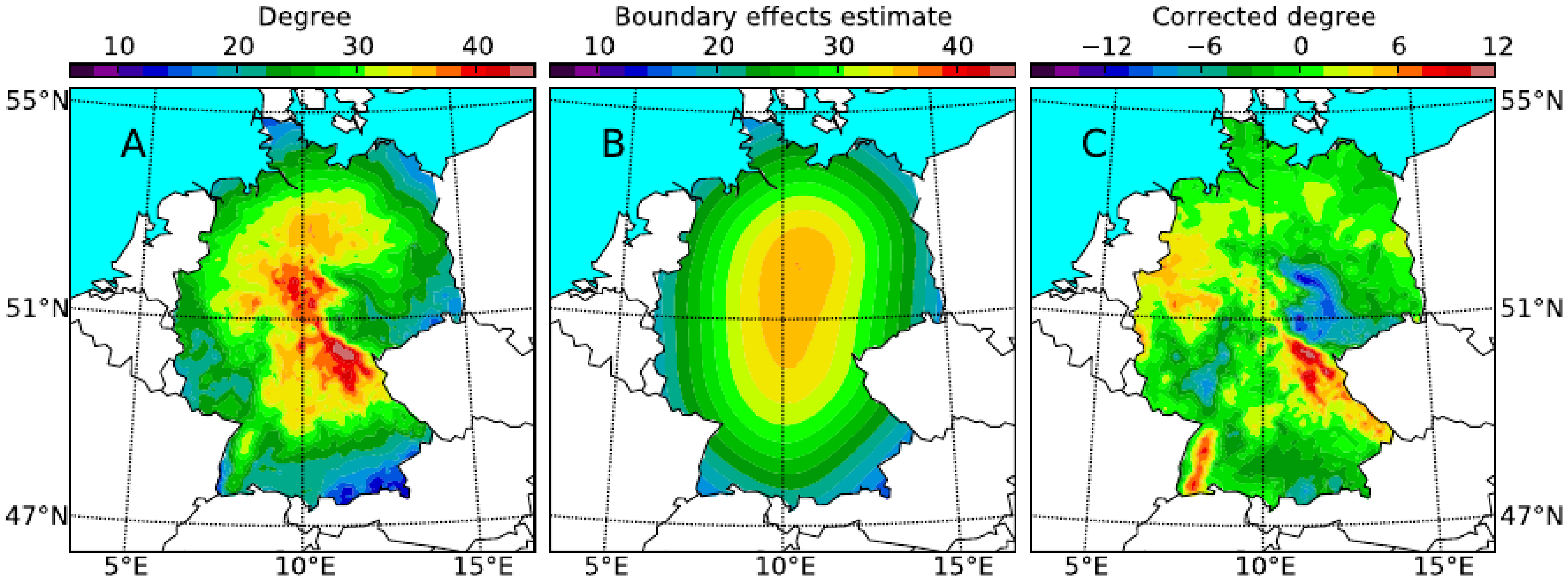
Closeness centrality (boxed data, corrected)



Closeness centrality (random model preserving link length distribution)

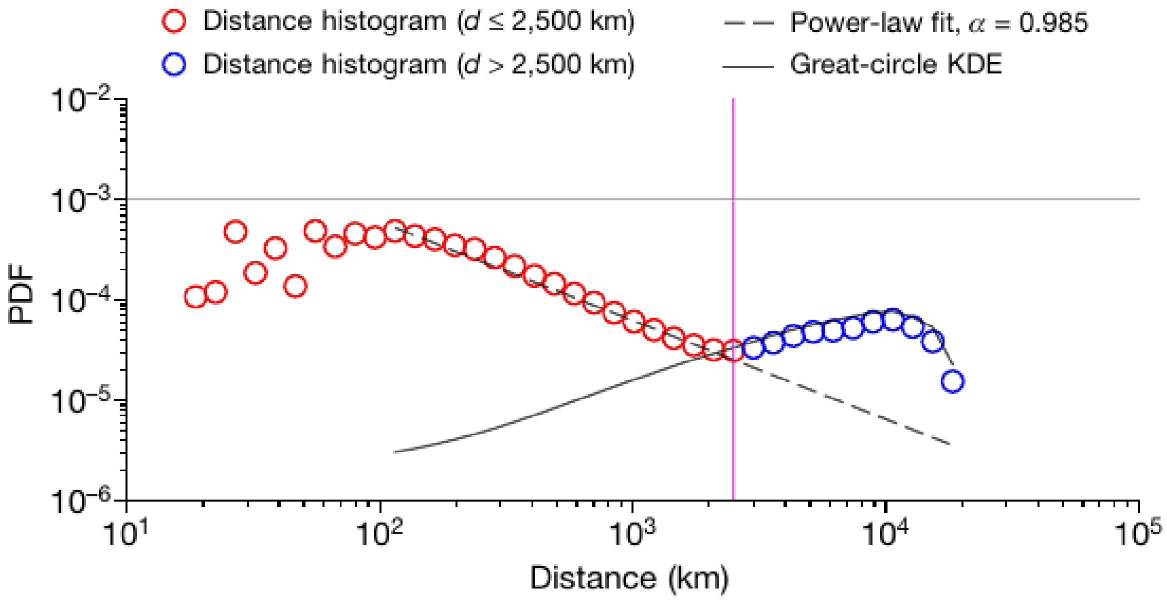
Closeness centrality (boxed data)

Daily extreme rainfall, 2000 weather stations, Event Synchronisation, 50 % link density

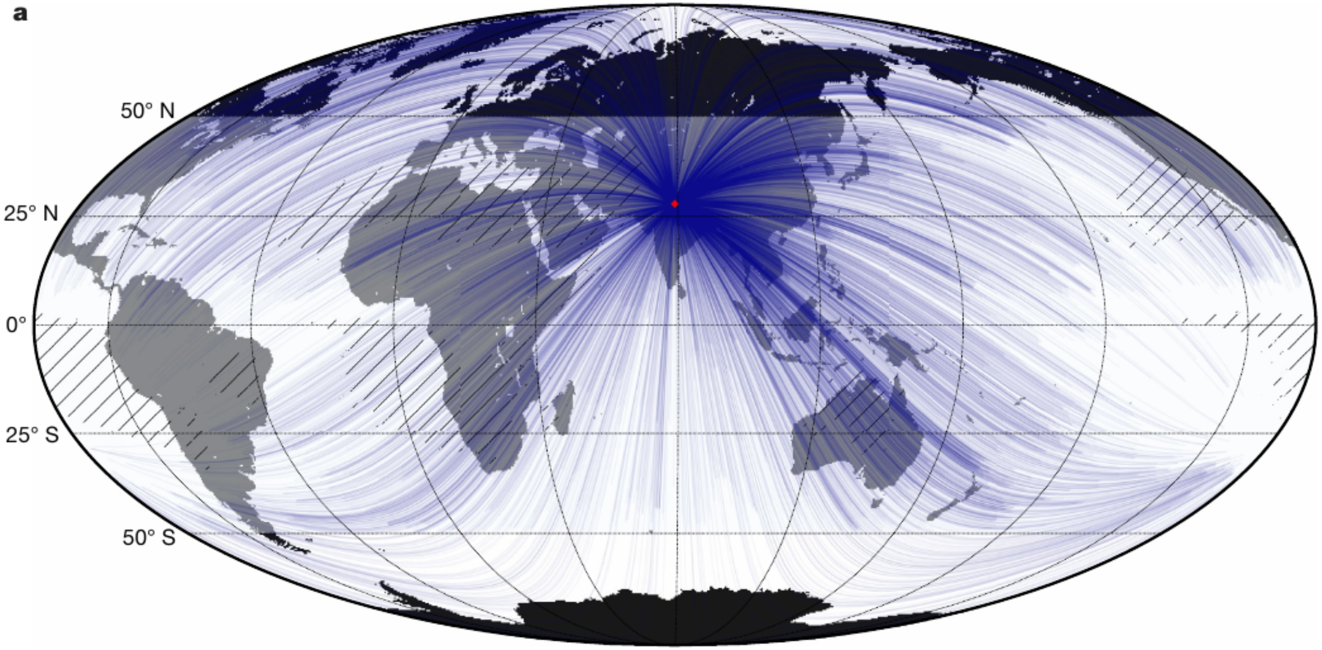


2. Avoiding potential pitfalls → Boundary effects

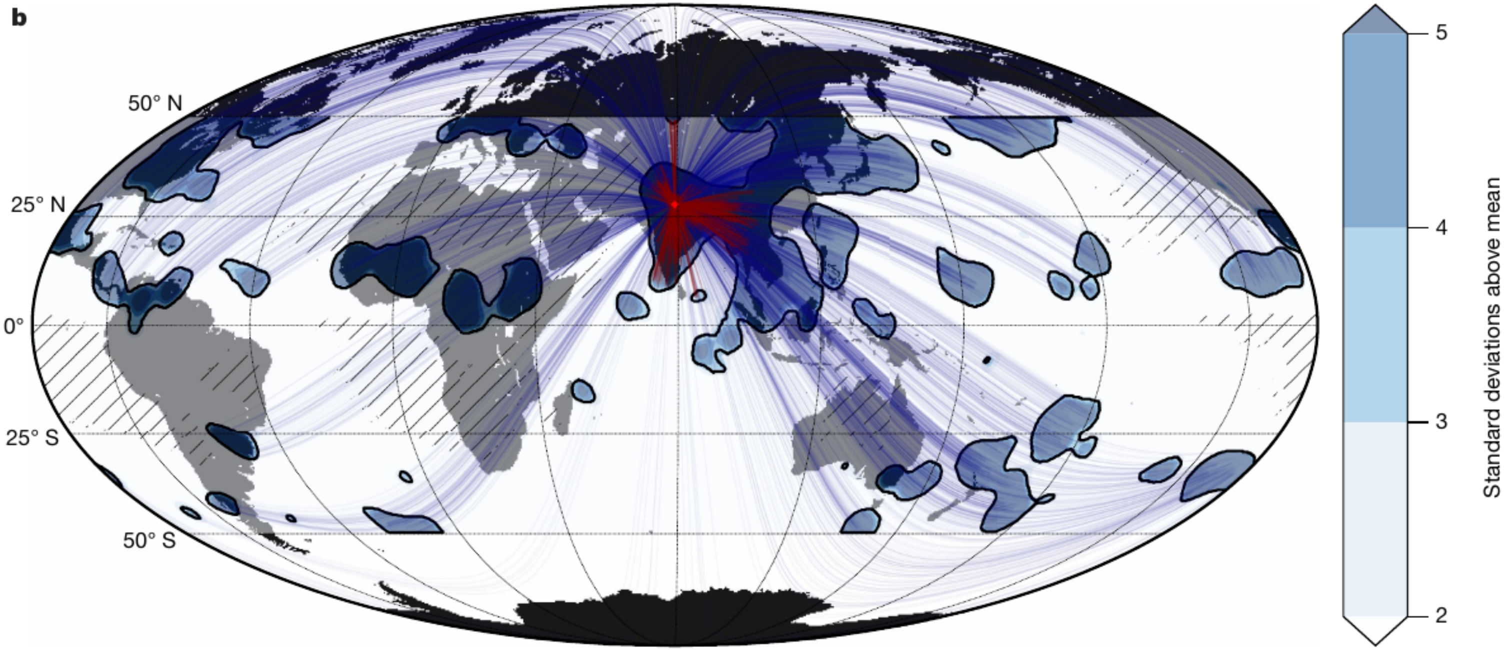
Daily extreme rainfall, 0.25 deg lat-lon grid, Event Synchronisation, 0.5 % significance



Daily extreme rainfall, 0.25 deg lat-lon grid, Event Synchronisation, 0.5 % significance



Daily extreme rainfall, 0.25 deg lat-lon grid, Event Synchronisation, 0.5 % significance



2. Avoiding potential pitfalls → Spatial embedding

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Networks from Graphical Models

3

- Ebert-Uphoff & Deng, 2012
- Runge et al., 2015
- ~~Zerenner et al., 2012~~

Climate Networks with ML

4

- Noteboom et al., 2018
- ~~Santos et al., 2020~~

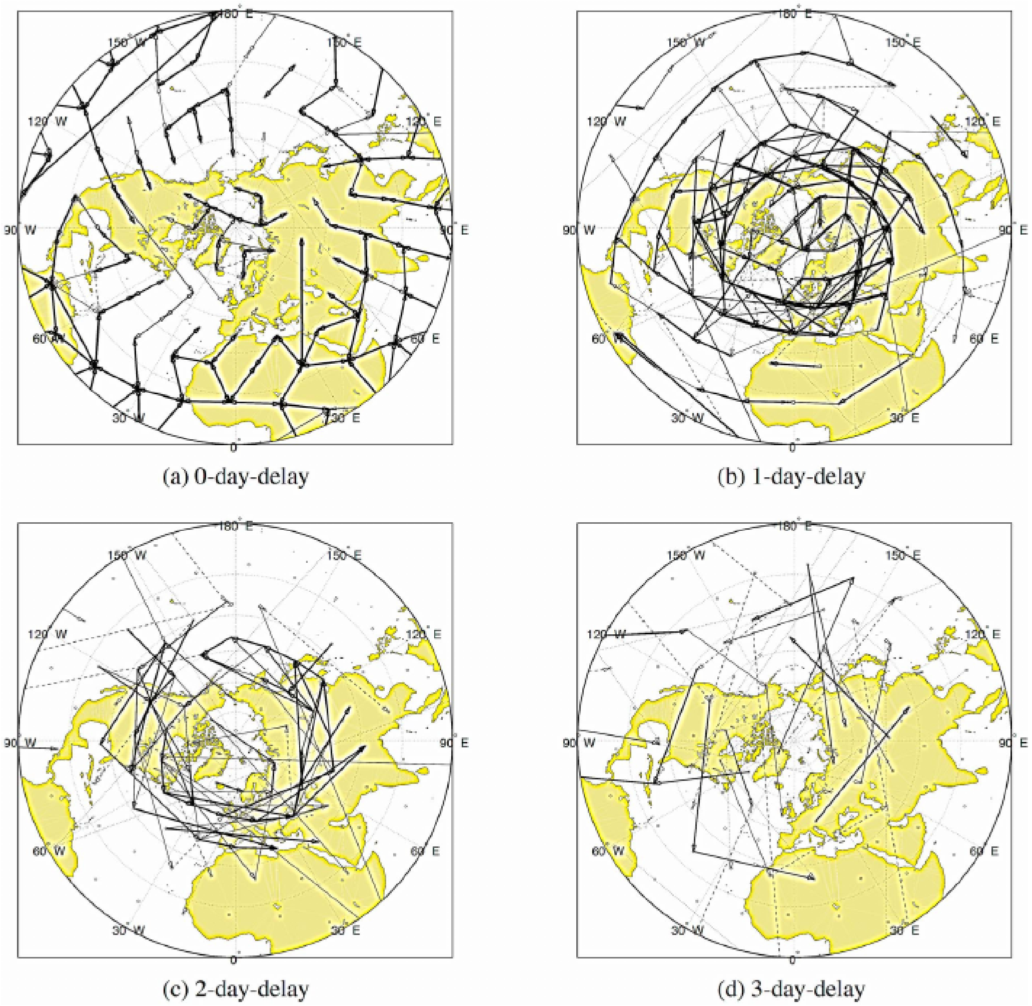
Construction of the network ...

- Z500 geopotential height in the northern hemisphere from 1948 – 2011
  - 200 locations / time series

- PC algorithm (Spirtes & Glymour, 1991) to construct the graphical model
  - S = 15 time delays
  - Fischer’s Z-test at 10 % confidence

- Data transformed to equidistant grid on the sphere using the Fekete algorithm (Bendito et al., 2007)

- Directed climate network of 15 x 200 = 3000 nodes



3. Networks from Graphical Models → Ebert-Uphoff & Deng, 2012

Construction of the network ...

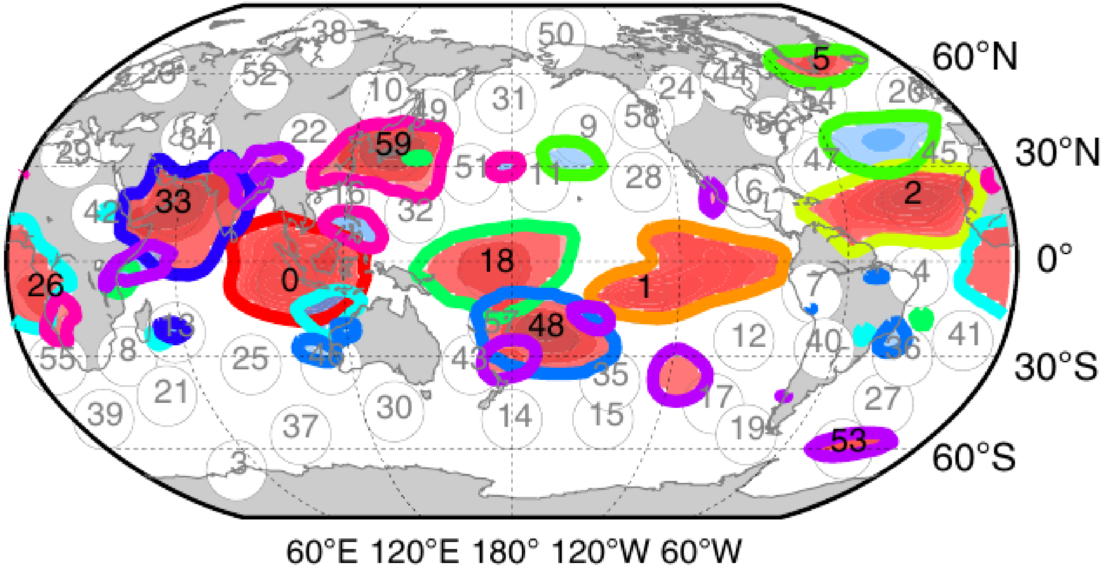
- Global weekly surface pressure at 2.5 deg lat-lon grid from 1948 – 2012
  - 10512 time series, each 3339 points long

- Data dimensionality reduction using PCA with Varimax rotation
  - Top 60 components retained

- Modifed PC algorithm (Runge et al., 2012) to construct the network based on graphical model
  - Delay considered = 4 (weeks)

- Quantifying causal effect:
  - Path coefficient: regression coefficient for the link $X^i_{t-\tau} \rightarrow X^j_t$

Top 60 components of Varimax rotated PCA, areas defined by 98% of loading

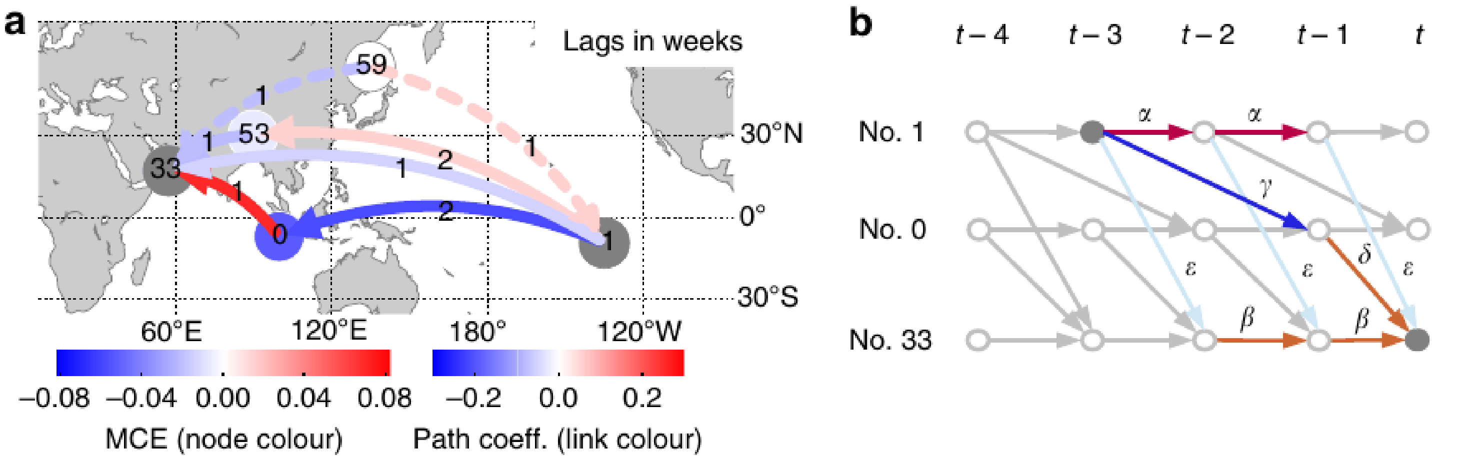


Bedartha Goswami

Quantifying causal effect ...

- Path coefficient:
  - Regression coefficient for the link $X^i_{t-\tau} \rightarrow X^j_t$
- Total causal effect:
  - Sum over the products of path coefficients along indirect causal paths, i.e., all paths between X^i and X^j at lag τ
- Mediated Causal Effect (MCE):
  - MCE of a node is the sum over products of path coefficients that pass through that node

MCE and path coefficients of nodes in the Indo-Pacific region



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Climate Networks with ML

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Main idea ...

- Use climate networks + ANNs to forecast the Niño 3.4 index

- $Z_t = Y_t + N_t$
  - Z_t := Niño 3.4 index to be predicted
  - Y_t := ARIMA process
  - N_t := residual of the ARIMA fit, predicted with an ANN

- Simple ANN structure: 3 layers: 2 neurons x 1 neuron x 1 neuron

- Input features:
  - Warm water volume (WWV)
  - C_2 := fraction of components of size 2
  - Seasonal cycle
  - Second principal component of EOF analysis of wind stress

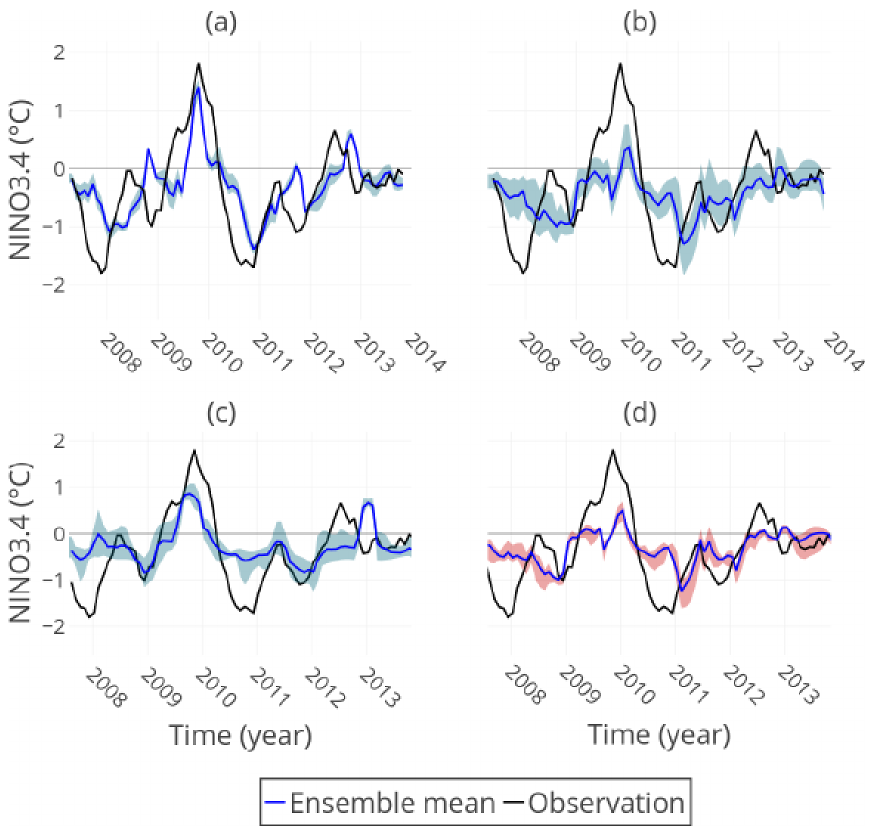
- Zebiak-Cane model used to test climate network features

ANN spread, 4-month lead

6-month lead, ANN spread

ANN spread, 12-month lead

6-month lead, ARIMA spread



4. Climate networks with ML → Noteboom et al., 2018

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Q
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