CAFE
Climate Advanced Forecasting of sub-seasonal Extremes

D3.5: Software to evaluate prediction of climate regime changes

Lead Beneficiary: Potsdam Institute for Climate Impact Research

Work Package: WP3

Dissemination level: PUBLIC

Type: Software

Due date: 31.08.2022

Submission date: 26.09.2022

Authors: Shraddha Gupta (*ESR9*), Prof. Jürgen Kurths (*supervisor*), Prof. Florian Pappenberger (*co-supervisor*)

Introduction:

Complex network is a powerful tool which encodes the interactions between the different components of a complex system, and helps to study the collective behaviour from such interactions, such as synchronization [1]. It has found wide applications in diverse fields such as spread of disease, protein structure, the internet, citation networks, etc [2]. Functional network analysis has been very successfully applied to the study of Earth's Climate system [3-6]. By considering every spatial location on the Earth's surface as a dynamical system with an associated time series, the interactions between the various locations are estimated by computing their pairwise statistical dependencies under the functional network framework. Climate networks have been used to gain better understanding of the mechanisms underlying various climate phenomena such as El Nino-Southern Oscillation [7-9], the South American Monsoon [10] and the Indian Monsoon [11-12] and have complemented the tools of predictability [13-14].

Climate networks are helpful to identify the most important regions of climate variability which can be then used to infer key regions that allow the construction of prediction schemes at different time scales. We provide the software for computing the climate network for precipitation data using event synchronization (ES) (Fig. 1) and calculating network measures such as degree (no. of connections one spatial location, here node, has with other grid points), which could be used to obtain a comprehensive picture of the patterns of spatial connectivity of extreme precipitation events either for a particular region or for the whole globe. We implement the python code on the TRMM 3B42 V7 satellite data [15] (0.25°×0.25° spatial resolution, daily data for the period 1998-2019, available from 50°N-50°S) to identify the dominant synchronization pathways between the Indian (ISM) and the East Asian Summer monsoon (EASM), and analyse variability of the ISM-EASM relationship at intra-seasonal timescales [16].

Since climate networks primarily depict the information of statistical connectivity between different regions, they can be used to evaluate these statistical interactions in the model predictions [17-18]. Therefore, we illustrate using an example the potential of climate networks to evaluate prediction of these spatio-temporal connections of extreme rainfall events by comparing the network topology of satellite-derived TRMM 3B42 V7 data [15] with ERA5 reanalysis data [19] for the same time period (1998-2019) at 1°×1° spatial resolution and daily temporal resolution.

CAFE project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813844.

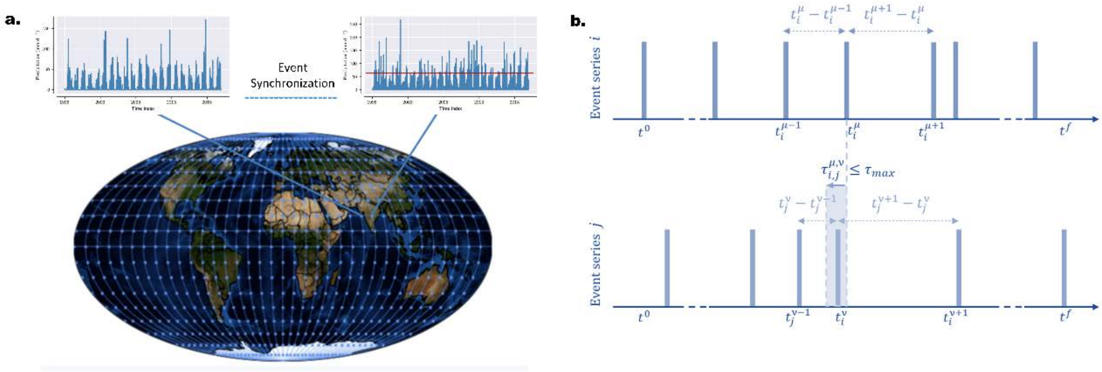

Fig. 1: (a) Schematic representation of climate network construction for extreme precipitation using Event Synchronization. (b) Illustration of calculation of Event Synchronization which counts the number of synchronized events between the two event series.

Details of the code:

The code is available at:
https://github.com/ShraddhaGupta28/AsianMonsoon_EventSynchronizationNetwork publicly and is licensed under the GNU General Public License v3.0. All coding files are implemented using Python 3.9 (Packages including: cython 0.29.32 + xarray 2022.6.0 + zarr 2.12.0 + netcdf4 1.6.0 + basemap 1.2.2 + cmocean 2.0). The code is based on Gupta *et al.*, 2022 [16], which can be referred to for more details.

It is an improved and modified version of the original code available at https://github.com/niklasboers/rainfall-teleconnections.git based on [20].

1. Data pre-processing

- Extreme.py – Loads the data and computes extreme events above predefined percentile thresholds.
- Extreme_Under_Box.py – Computes number of extreme events above predefined percentile thresholds for a particular region.

2. Network reconstruction

- Event_Sync_Null_Model_Cy.pyx – Cython function for computing the null model distribution for the Event Synchronization (ES) measure in parallel, based on surrogates with different event rates.

CAFE project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813844.

- Event_Sync2_Null_Model_Cy.pyx – Cython function for computing the null model distribution for the directed ES measure in parallel, based on surrogates with different event rates.
- Event_Sync_Udw_Cy.pyx – Cython function for computing the ES measure in parallel, and saves the slices as binary arrays (the link list of undirected networks with both endpoints being saved), with an entry equal to one if the corresponding ES value is above the significance threshold, chosen at the 95th percentile of the null model distribution.
- Task1_Ud_ES_Construction.pyx – An additional cython function to transform the link list by Event_Sync_Udw_Cy.pyx into quickly accessible graph structure.

3. Specific times of high extreme rainfall synchronicity – determines times of high extreme rainfall synchronization between two regions.

- Task1_Ud_ES_Regional_Sync_Corr.pyx – Cython function for computing the time series of synchronization between interested pairs of regions, based on the null model distribution obtained by Event_Sync2_Null_Model_Cy.pyx.
- ISM_EASM_IJC_Task1_Ud_ES_Reg_Sync_Corr.py – Python function for computing the specific days when the pair of regions is highly synchronized.

4. Composite anomalies of other climate variables for days when there is high synchronization between the two regions

- ISM_EASM_IJC_Task1_Ud_ES_Clim_ERA5_GPH_CAno_Mon.py
- ISM_EASM_IJC_Task1_Ud_ES_Clim_ERA5_OLR_CAno_Mon.py
- ISM_EASM_IJC_Task1_Ud_ES_Clim_ERA5_W_CAno_Mon.py
- ISM_EASM_IJC_Task1_Ud_ES_Clim_ERA5_WVF_CAno_Mon.py
- ISM_EASM_IJC_Task1_Ud_ES_Clim_TRMM_R_CAno.py

5. Visualization of figures of [16]

- Fig.1: ~ISM_EASM_IJC_Task1_Visual_ES_Reg_TPDeg_ASM_And_Mon.py
- Fig.2: ~ISM_EASM_IJC_Task1_Visual_Ud_ES_Reg_Sync_Corr_M.py
- Fig.3: ~ISM_EASM_IJC_Task1_Visual_Ud_ES_Clim_GPH_CAnoSN_MonRF.py
- Fig.4: ~ISM_EASM_IJC_Task1_Visual_Ud_ES_Clim_WVC_CAnoSN_Mon.py
- Fig.5: ~ISM_EASM_IJC_Task1_Visual_Ud_ES_Clim_WVF_CAnoSN.py
- Fig.6: ~ISM_EASM_IJC_Task1_Visual_Ud_ES_Clim_OLR_CAnoSN_Single.py
- Fig.7: ~ISM_EASM_IJC_Task1_Visual_Ud_ES_Reg_Sync_MJO_BSISO.py

CAFE project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813844.

Few illustrative examples:

1. **Dominant modes of synchronization between Indian and East Asian summer monsoon**: Two dominant synchronization pathways between ISM and EASM are identified (Fig. 2): (i) a southern mode between the Arabian Sea and southeastern China, which is related to the ISM onset in June, and (ii) a northern mode between the core ISM zone and northern China, which peaks in July. Thereafter, we determine the specific times of high extreme rainfall synchronization which confirms the intraseasonal variability of the ISM-EASM relationship (Fig. 3). Using these specific times of high extreme synchronization we were able to identify the distinctively different large-scale atmospheric circulation and moisture transport patterns associated with each mode and the role of intraseasonal oscillations in the intraseasonal variability of the ISM-EASM connection (For results related this, refer to Gupta *et al.,* 2022 [16]).

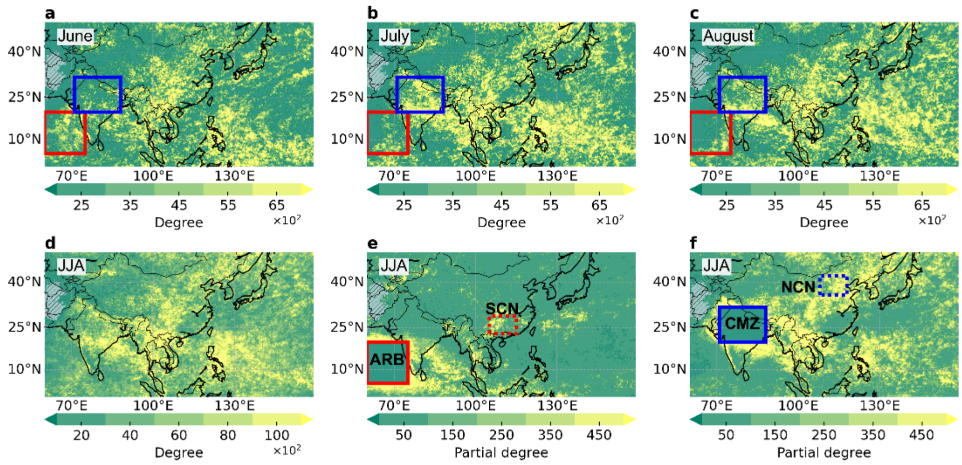

Fig. 2: Monthly evolution of network degree for networks constructed for June (a), July (b) and August (c), respectively. The solid red and blue boxes are positioned at the Arabian Sea (ARB) and core ISM zone (CMZ), respectively, to indicate noticeable changes in degree each month at different ISM regions. (d) Degree for the network constructed for the entire JJA season. (e) and (f): Partial degree for the regions, ARB and CMZ respectively, based on the network in (d) to indicate specific regions connected to each of them. From (e), it is seen that ARB has connections to Southern China (SCN) while from (f), CMZ is seen to be connected to parts in Northern China (NCN). These are the southern and northern modes of synchronization respectively. Taken from Figure 1 in Gupta *et al.*, 2022 [16].

CAFE project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813844.

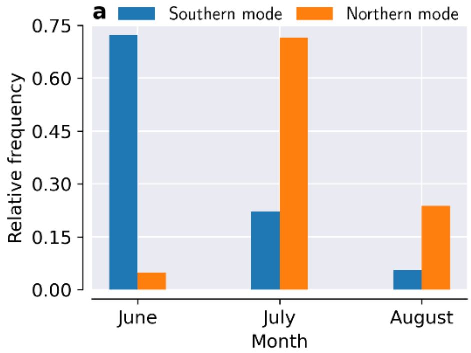

Fig. 3: The month-wise distribution of days with high ERE synchronization for the Southern mode (ARB → SCN) and the Northern mode (CMZ →NCN). Taken from Figure 2 in Gupta *et al.*, 2022 [16]. It can be seen that the Southern mode occurs prior to the northern mode of ISM-EASM interaction.

2. **Evaluate climate interactions and teleconnections in model predictions.** We illustrate this by comparing the global network topology obtained from satellite derived TRMM data with the ERA5 reanalysis data (Fig. 4). It can be seen that due to uncertainties in the observation data the TRMM network patterns of spatial

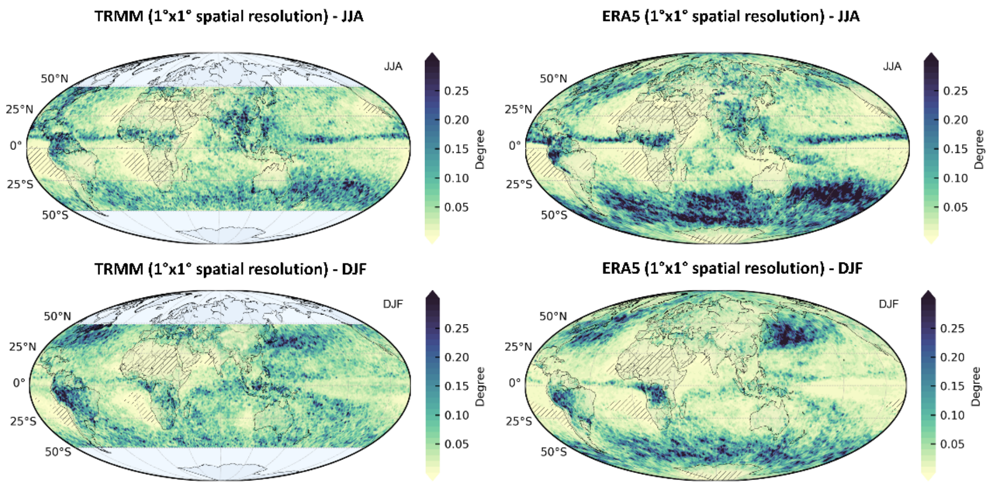

Fig. 4: Comparison of spatial Patterns of degree (normalised) between TRMM (left) and ERA5 (right) extreme precipitation events for the seasons June-July-August (JJA) and December-January-February (DJF). It can be observed clearly that the patterns of degree are better defined in the ERA5 reanalysis data than the TRMM observation data and appear less noisy.

connectivity are more scattered than the ERA5 reanalysis precipitation network. Also, there are large differences in spatial connectivity for some regions such as the Southern Ocean in both seasons, the equatorial Indian Ocean in boreal winter and the Asian Monsoon region in the boreal summer, to name a few. This method of evaluation based on complex networks can be used to get a comprehensive

CAFE project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813844.

overview of the model performance at the preliminary stage in order to identify the key regions affected by the model errors. The python code can also be implemented for other model data, such as 10-day forecast data produced from the ERA5 system, or the SEAS5 seasonal forecast data.

Conclusions:

We show that the developed code based on python for complex networks of extreme rainfall can reveal variability of climate interactions at different timescales and be used to evaluate the predictions of statistical interactions and global teleconnections in models.

References

[1] Alex Arenas, Albert Díaz-Guilera, Jurgen Kurths, Yamir Moreno, Changsong Zhou, *Synchronization in complex networks*, Physics Reports, Volume 469, Issue 3, 2008, Pages 93-153, ISSN 0370-1573, DOI: 10.1016/j.physrep.2008.09.002.

[2] Albert R, Barabasi AL, *Statistical mechanics of complex networks*, Rev. Mod. Phys. **74,** 47-97 (2002); DOI: 10.1103/RevModPhys.74.47.

[3] Tsonis A, Roebber P, *The architecture of the climate network*, Physica A: Statistical Mechanics and its Applications **333**, 497-504 (2004);
DOI: 10.1016/j.physa.2003.10.045.

[4] Tsonis AA, Swanson KL, Roebber PJ, *What Do Networks Have to Do with Climate?*, Bulletin of the American Meteorological Society **87**(5), 585-595 (2006);
DOI 10.1175/BAMS-87-5-585.

[5] Tsonis AA, Swanson KL, *Topology and predictability of El Nino and La Nina networks*, Phys. Rev. Lett. **100**, 228502 (2008);
DOI 10.1103/PhysRevLett.100.228502.

[6] Donges J, Zou Y, Marwan N, Kurths J, *Backbone of the climate network*, EPL (Europhysics Letters) **87** (2010); DOI 10.1209/0295-5075/87/48007.

[7] Ludescher J, Gozolchiani A, Bogachev MI, Bunde A, Havlin S, Schellnhuber HJ, *Improved El Nino forecasting by cooperativity detection*, Proceedings of the National Academy of Sciences **110**(29), 11742-11745 (2013);
DOI 10.1073/pnas.1309353110.

[8] Ludescher J, Gozolchiani A, Bogachev MI, Bunde A, Havlin S, Schellnhuber HJ, *Very early warning of next El Nino*, Proceedings of the National Academy of Sciences **111**(6), 2064-2066 (2014); DOI 10.1073/pnas.1323058111.

[9] Meng J, Fan J, Ashkenazy Y, Havlin S, *Percolation framework to describe El Nino conditions*, Chaos: An Interdisciplinary Journal of Nonlinear Science **27**(3), 035807 (2017); DOI 10.1063/1.4975766.

CAFE project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813844.

[10] Boers, N., Bookhagen, B., Marwan, N., Kurths, J. and Marengo, J. (2013) *Complex networks identify spatial patterns of extreme rainfall events of the South American monsoon system*. Geophysical Research Letters, 40, 4386–4392. DOI: 10.1002/grl.50681.
[11] Malik N, Bookhagen B, Marwan N, Kurths J, *Analysis of spatial and temporal extreme monsoonal rainfall over South Asia using complex networks*, Climate Dynamics **39**, 971-987 (2012); DOI 10.1007/s00382-011-1156-4.
[12] Stolbova V, Martin P, Bookhagen B, Marwan N, Kurths J, *Topology and seasonal evolution of the network of extreme precipitation over the Indian subcontinent and Sri Lanka*, Nonlinear Processes in Geophysics **21**(4), 901-917 (2014); DOI 10.5194/npg-21-901-2014.
[13] Boers, N., Bookhagen, B., Barbosa, H. et al. *Prediction of extreme floods in the eastern Central Andes based on a complex networks approach*. Nat Commun 5, 5199 (2014). DOI: 10.1038/ncomms6199
[14] Stolbova, V., Surovyatkina, E., Bookhagen, B., and Kurths, J. (2016), *Tipping elements of the Indian monsoon: Prediction of onset and withdrawal*, Geophys. Res. Lett., 43, 3982– 3990, DOI:10.1002/2016GL068392.
[15] Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., Hong, Y., Bowman, K. P., & Stocker, E. F. (2007). *The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales*, Journal of Hydrometeorology, 8(1), 38-55.
[16] Gupta, S., Su, Z., Boers, N., Kurths, J., Marwan, N. and Pappenberger, F. (2022), *Interconnection between the Indian and the East Asian Summer Monsoon: spatial synchronization patterns of extreme rainfall events*. International Journal of Climatology, 1-16. DOI: 10.1002/joc.7861.
[17] Steinhaeuser, K., Tsonis, A.A. *A climate model intercomparison at the dynamics level*. Clim Dyn 42, 1665–1670 (2014). DOI: 10.1007/s00382-013-1761-5
[18] Di Capua, G., Coumou, D., van der Hurk, B., Weissheimer, A., Turner, A. G., and Donner, R. V.: *Validation of boreal summer tropical-extratropical causal links in seasonal forecasts*, Weather Clim. Dynam. Discuss. [preprint], DOI:10.5194/wcd-2022-48, in review (2022).
[19] Hersbach H, Bell B, Berrisford P, Hirahara S, Horanyi A, Munoz-Sabater J, Nicolas J, Peubey C, Radu R, Schepers D, Simmons A, Soci C, Abdalla S, Abellan X, Balsamo G, Bechtold P, Biavati G, Bidlot J, Bonavita M, De Chiara G, Dahlgren P, Dee D, Diamantakis M, Dragani R, Flemming J, Forbes R, Fuentes M, Geer A, Haimberger L, Healy S, Hogan RJ, Holm E, Janiskova M, Keeley S, Laloyaux P, Lopez P, Lupu C, Radnoti G, de Rosnay P, Rozum I, Vamborg F, Villaume S, Thepaut JN, *The ERA5 global reanalysis*, Quarterly Journal of the Royal Meteorological Society **146**(730), 1999-2049 (2020); DOI: 10.1002/qj.3803.
[20] Boers, N., Goswami, B., Rheinwalt, A., Bookhagen, B., Hoskins, B., & Kurths, J. (2019). *Complex networks reveal global pattern of extreme-rainfall teleconnections*. Nature, 566(7744), 373-377.

CAFE project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813844.