RESPONSES TO REVIEWER #2 COMMENTS

We are grateful to you and the reviewers for the constructive feedback that significantly enhanced our manuscript. We have comprehensively addressed all of the reviewers' comments. For ease of reference, we offer a detailed response to each comment below. The reviewers' remarks are presented in blue italics, while our responses are in standard black font. Modifications made in the revised manuscript, also quoted here, are highlighted in red.

The manuscript provides a comprehensive analysis of the climate system's evolution under the impact of global warming, employing climate network methods. The authors have effectively used climate network analysis and Louvain community detection to reveal a significant phenomenon: notable alterations in the climate network's structure. These changes include the network's modularization, the number of communities, and the average size of these communities. A particularly striking finding was the shift in the community structure around 1982, marked by a significant rise in isolated nodes, predominantly in the equatorial ocean regions.

Response: We thank the reviewer for the positive remarks regarding our results.

The study is engaging and well-articulated. Nonetheless, I have a few reservations that I believe, if addressed, could further solidify the scientific validity of this manuscript:
The field of complex network studies presents a variety of community detection algorithms, among which Louvain is a prominent choice. It would enhance the manuscript if the authors could elucidate their preference for the Louvain algorithm over other available options. Alternatively, to affirm the robustness of their findings, the authors might consider applying and comparing results from different algorithms.

Response: We thank the reviewer for the insightful comments. We have employed four different algorithms to detect community structures. Figure S3 below illustrates the modularity values obtained. The results highlight the robustness of the modularity transition around 1982 across different algorithms. Notably, the Louvain algorithm produces the highest modularity values, indicating its superior effectiveness in identifying community structures.

Correction: (Lines 141-144, Par 2, Page 7) Supplementary Figure S3 illustrates the modularity values obtained by four distinct algorithms, as outlined in Ref (Kittel et al., 2021). The results highlight the robustness of the modularity transition around 1982 across different algorithms. Notably, the Louvain algorithm produces the highest modularity values, indicating its superior effectiveness in identifying community structures.

Kittel, T., Ciemer, C., Lotfi, N. et al.: Evolving climate network perspectives on global surface air temperature effects of ENSO and strong volcanic eruptions, Eur. Phys. J. Spec. Top. 230, 3075–3100 , https://doi.org/10.1140/epjs/s11734-021-00269-9, 2021.

(Lines 194-197, Par 1, Page 10) To establish robustness, we conduct the analysis using different community detection algorithms, the maximum time lag of 365 days, the shuffled nodes and a 6-month shift for the time window. The obtained results are consistent, as illustrated in Supplementary Figures. S3-S12.

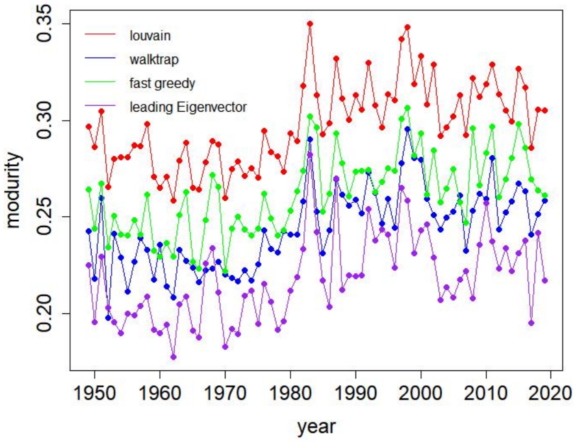

Figure S3: Time evolution of modularity for different algorithms, with red representing the Louvain algorithm, blue representing the Walktrap algorithm, green representing the Fast Greedy algorithm, and purple representing the Leading Eigenvector algorithm.

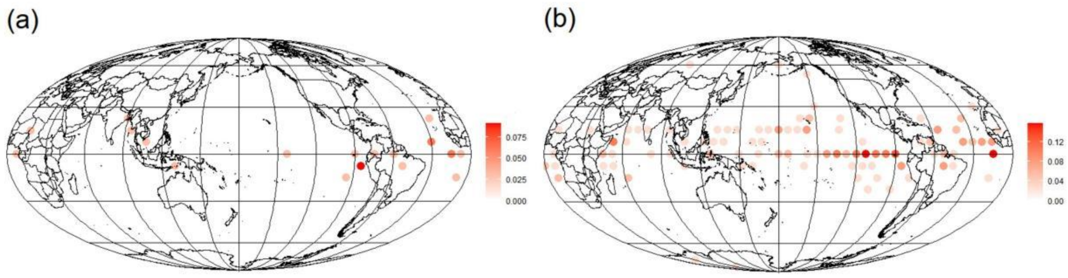

Figure S4: Probability graph of global isolated nodes using the Leading eigenvector algorithm for (a) 1949-1981 and (b) 1982-2019.

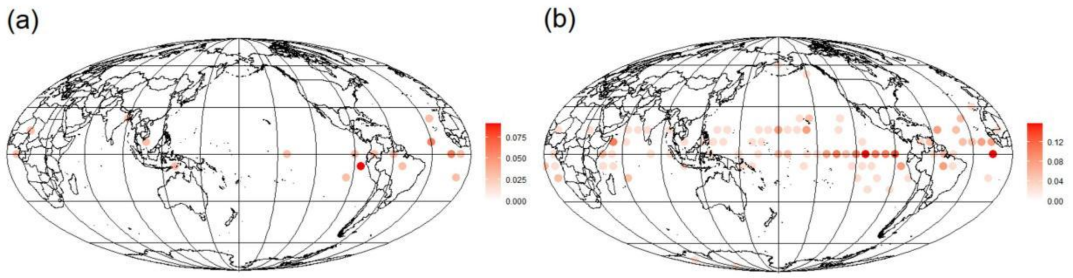

Figure S5: Probability graph of global isolated nodes using the Fast greedy algorithm for (a) 1949-1981 and (b) 1982-2019.

Lines 35-36: Previous papers have reported the collapse of AMOC; please provide more relevant references.

Response: We thank the reviewer for the comment and added the relevant refs in the revised manuscript.

Correction: (Lines 43-45, Par 2, Page 2) Additionally, the Atlantic Meridional Overturning Circulation (AMOC) may undergo a transition, with potential collapse having severe impacts on the climate in the North Atlantic and European regions (Rahmstorf et al., 2015; Boers, 2021).

Rahmstorf, S., Box, J., Feulner, G. et al.: Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation, Nature Clim Change 5, 475–480, https://doi.org/10.1038/nclimate2554, 2015.

Boers, N. Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. Nat. Clim. Chang. 11, 680–688, https://doi.org/10.1038/s41558-021-01097-4, 2021.

In lines 42-43, the statement "The climate system is highly complex, characterized by diversity, multiscale dynamics, and nonlinearity" is vague and should be clarified.

Response: We sincerely appreciate the reviewer for taking the time to provide insightful feedback on our manuscript. We have made additions to the revised manuscript based on your comments.

Correction:(Lines 50-53, Par 2, Page 3) Faced with these climatic systematic changes, the adoption of complex network analysis has become increasingly essential in the realm of climate science. The climate system is intricately complex, marked by multivariable and multiscale nonlinear dynamics. Unveiling the internal structure of the climate system necessitates the application of sound research methods.

In line 47, change to "(e.g., precipitation, temperature, and wind)."

Response: Thank you so much for your comment. Based on your suggestions, we have made the following adjustments.

Correction:(Lines 47-49, Par 1, Page 3) Understanding these systematic changes is imperative for predicting future climate scenarios (e.g., precipitation, temperature, wind) and formulating effective adaptation and mitigation strategies.

Line 49: The link of the climate network can be defined in various ways, such as synchronization and mutual information.

Response: We made changes as follows.

Correction:(Lines 56-60, Par 1, Page 3) In the climate network, nodes represent geographical locations where time series data for temperature (or other climate variables) are accessible. Links are established through bivariate similarity measures such as correlation, mutual information, or event synchronization between these time series (Tsonis et al., 2004; Donges et al., 2009; Quiroga et al., 2002).

A. A. Tsonis, and Paul J. Roebber.: The architecture of the climate network, Physica A, 333: 497-504. https://doi.org/10.1016/j.physa.2003.10.045, 2004.

F. Donges, Y. Zou, N. Marwan and J. Kurths: Complex networks in climate dynamics, Eur. Phys. J. Spec. Top. 174, 157 – 179, https://doi.org/10.1140/epjst/e2009-01098-2, 2009.

R. Quian Quiroga, T. Kreuz, and P. Grassberge: Event synchronization: A simple and fast method to measure synchronicity and time delay patterns, Phys. Rev. E 66, 041904, https://doi.org/10.1103/PhysRevE.66.041904, 2002.

In line 52, use past tense in "Donges et al. employed..." and ensure consistency with tenses in surrounding sentences.

Response: Done! We rewrote the sentence as follows.

Correction:(Lines 56-67, Par 1, Page 3-4) In the climate network, nodes represent geographical locations where time series data for temperature (or other climate variables) are accessible. Links are established through bivariate similarity measures such as correlation, mutual information, or event synchronization between these time series (Tsonis et al., 2004; Donges et al., 2009; Quiroga et al., 2002). Climate network techniques have proven effective in enhancing our understanding of various climate and weather phenomena, including ENSO, teleconnection patterns of weather, and atmospheric pollution (Tsonis et al., 2008; Yamasaki et al., 2008; Fan et al., 2017; Kittel et al., 2021; Zhou et al., 2015; Boers et al., 2019; Di Capua et al., 2020; Zhang et al., 2019). Notably, complex network analysis has unveiled the weakening of tropical circulation under global warming (Geng et al., 2021; Fan et al., 2018). Furthermore, these techniques have demonstrated utility in forecasting climate events (Boers et al., 2014; Ludescher et al., 2014; Meng et al., 2018; Ludescher et al., 2021).

A. A. Tsonis, and Paul J. Roebber.: The architecture of the climate network, Physica A, 333: 497-504. https://doi.org/10.1016/j.physa.2003.10.045, 2004.

K. F. Donges, Y. Zou, N. Marwan and J. Kurths: Complex networks in climate dynamics, Eur. Phys. J. Spec. Top. 174, 157 – 179, https://doi.org/10.1140/epjst/e2009-01098-2, 2009.

R. Quian Quiroga, T. Kreuz, and P. Grassberge: Event synchronization: A simple and fast method to measure synchronicity and time delay patterns, Phys. Rev. E 66, 041904, https://doi.org/10.1103/PhysRevE.66.041904, 2002.

A. A. Tsonis and Kyle L. Swanson: Topology and predictability of El Niño and La Niña networks, Phys. Rev. Lett. 100, 228502, https://doi.org/10.1103/PhysRevLett.100.228502, 2008.

K. Yamasaki, A. Gozolchiani, and S. Havlin: Climate networks around the globe are significantly

Affected by El Niño, Phys. Rev. Lett. 100, 228501, https://doi.org/10.1103/PhysRevLett.100.228501, 2008.

J. Fan, J. Meng, Y. Ashkenazy, S. Havlin and H. J. Schellnhuber: Network analysis reveals strongly localized impacts of El Niño, Proc. Natl. Acad. Sci. U.S.A. 114, 7543 – 7548, https://doi.org/10.1073/pnas.1701214114, 2017.

Kittel, T., Ciemer, C., Lotfi, N. et al.: Evolving climate network perspectives on global surface air temperature effects of ENSO and strong volcanic eruptions, Eur. Phys. J. Spec. Top. 230, 3075 – 3100 , https://doi.org/10.1140/epjs/s11734-021-00269-9, 2021.

Zhou, Dong, et al.: Teleconnection paths via climate network direct link detection, Phys. Rev. Lett. 115, 268501, https://doi.org/10.1103/PhysRevLett.115.268501, 2015.

Niklas Boers, Bedartha Goswami, Aljoscha Rheinwalt, Bodo Bookhagen, Brian Hoskins and Jürgen Kurthsl: Complex networks reveal global pattern of extreme-rainfall teleconnections, Nature 566, 373 – 377, https://doi.org/10.1038/s41586-018-0872-x, 2019.

Di Capua, G., Kretschmer, M., Donner, R. V., van den Hurk, B., Vellore, R., Krishnan, R., and Coumou, D.: Tropical and mid-latitude teleconnections interacting with the Indian summer monsoon rainfall: a theory-guided causal effect network approach, Earth Syst. Dynam., 11, 17 – 34, https://doi.org/10.5194/esd-11-17-2020, 2020.

Zhang, Y., J. Fan, Chen, X., Ashkenazy, Y., and Havlin, S.: Significant impact of Rossby waves on air pollution detected by network analysis, Geophys. Res. Lett., 46, 12476 – 12485, https://doi.org/10.1029/2019GL084649, 2019.

Z. Geng, Y. Zhang, B. Lu, J. Fan, Z. Zhao and X. Chen: Network-Synchronization analysis reveals the weakening tropical circulations, Geophys. Res. Lett. 48, e2021GL093582, https://doi.org/10.1029/2021GL093582, 2021.

J. Fan, Meng, J., Ashkenazy, Y., Havlin, S., Schellnhuber and H.J.: Climate network percolation reveals the expansion and weakeningof the tropical component under global warming, Proc. Natl. Acad. Sci. USA , 115, E12128 – E12134, https://doi.org/10.1073/pnas.1811068115, 2018.

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, https://doi.org/10.1038/ncomms6199, 2014.

J. Ludescher, A. Gozolchiani, M. I. Bogachev, A. Bunde, S. Havlin and H. J. Schellnhuber: Very early warning of next El Niño, Proc. Natl. Acad. Sci. U.S.A. 111, 2064 – 2066, https://doi.org/10.1073/pnas.1323058111, 2014.

J Meng, J. Fan, Y. Ashkenazy, A. Bunde and S. Havlin: Forecasting the magnitude and onset of El

Niño based on climate network, New J. Phys. 20, 043036, https://doi.org/10.1088/1367-2630/aabb25, 2018.

J. Ludescher, Martin, M., Boers, N., Bunde, A., Ciemer, C., J.Fan, Havlin, S., Kretschmer, M., Kurths, J., Runge, J.; et al.: Network-based forecasting of climate phenomena, Proc. Natl. Acad. Sci. USA , 118, e1922872118, https://doi.org/10.1073/pnas.1922872118, 2021.

Line 70: Remove "deeper."

Response: Thanks. We rewrote the sentence as follows.

Correction:(Lines 68-71, Par 2, Page 4) Complex systems naturally exhibit partitioning into multiple modules or communities, a significant feature of complex networks (Palla et al., 2005). In the context of climate networks, each community serves as a representation of a climate subsystem, shedding light on the interrelationships between different components (Tsonis et al., 2011).

Palla, G., Derényi, I., Farkas, I. et al.: Uncovering the overlapping community structure of complex networks in nature and society, Nature 435, 814 – 818, https://doi.org/10.1038/nature03607, 2005.

A. A. Tsonis, Wang, G., Swanson, K.L. et al.: Community structure and dynamics in climate networks, Clim Dyn 37, 933 – 940, https://doi.org/10.1007/s00382-010-0874-3, 2011.

Line 95: Clarify why 726 nodes were chosen in detail.

Response: Thanks. The homogeneity of the spatial density of the considered nodes within the sphere has been a deliberate focus in our study. This rationale guides our selection of 726 nodes, strategically spaced to ensure uniform coverage of the Earth in Euclidean space, as depicted in the below Figure S1(a). The nodes are equally distributed in Euclidean space with distances between any two neighboring nodes approximately 850 km, as illustrated in Figure S1(b).

Correction: (Lines 91-96, Par 1, Page 5) We select 726 nodes to construct the network and maintain the spatial density homogeneity within the climate network nodes in the sphere as suggested in previous studies (Zhou et al., 2015; Guez et al., 2014). These nodes are strategically spaced to ensure uniform coverage of the Earth in Euclidean space, as depicted in Supplementary Figure S1(a). The nodes are equally distributed, with distances between any two neighboring nodes approximately 850 km, as illustrated in Supplementary Figure S1(b).

Guez, O. C., Gozolchiani, A. and Havlin, S.: Influence of autocorrelation on the topology of the climate network, Phys. Rev. E, 90(6), 062814, https://doi.org/10.1103/PhysRevE.90.062814, 2014.

Zhou, Dong, et al.: Teleconnection paths via climate network direct link detection, Phys. Rev. Lett. 115, 268501, https://doi.org/10.1103/PhysRevLett.115.268501, 2015.

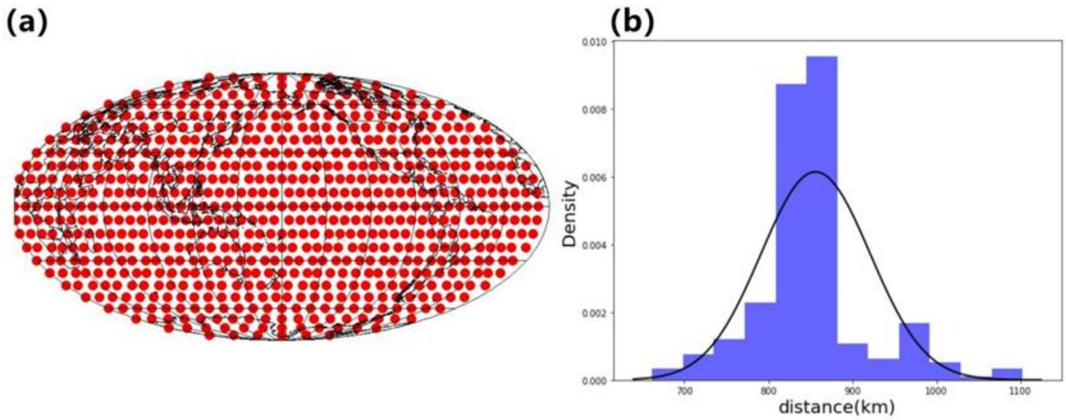

Figure S1: (a) Spatial distribution of 726 network nodes in Earth and (b) the PDF of distances between neighboring nodes.

Line 108: Add the unit of the time lag.

Response: Done.

Correction:(Lines 107-108, Par 1, Page 6) t represents time and the time lag is denoted as $\tau \in [0{,}200]$ days.

Lines 112-114: The statement "The strength W_{ij} reflects the deviation and serves to eliminate the effect of autocorrelation, aiming for a more desirable outcome." needs additional support or citation of a relevant study.

Response: Thanks for the comment. In accordance with your request, we have added the relevant references.

Correction: (Lines 112-116, Par 2, Page 6) Strong autocorrelation can inflate the significance of cross-correlation. In contrast, the link strength $W_{i,j}^{y}$ is more effective in mitigating the effects of autocorrelation, offering a more reasonable reflection of the relationship between two nodes (Guez et al., 2014). This approach has proven valuable in predicting climate phenomena (Ludescher et al., 2021).

Guez, O. C., Gozolchiani, A. and Havlin, S.: Influence of autocorrelation on the topology of the climate network, Phys. Rev. E, 90(6), 062814, https://doi.org/10.1103/PhysRevE.90.062814, 2014.

J. Ludescher, Martin, M., Boers, N., Bunde, A., Ciemer, C., J.Fan, Havlin, S., Kretschmer, M., Kurths, J., Runge, J.; et al.: Network-based forecasting of climate phenomena, Proc. Natl. Acad. Sci. USA , 118, e1922872118, https://doi.org/10.1073/pnas.1922872118, 2021.

Lines 221-224: The conclusion mentions enhanced connectivity between nodes in the equatorial region and the European continent due to changes in atmospheric circulation patterns. Consider citing relevant literature to support this claim.

Response: Thank you for your valuable comments. We have made corresponding revisions to these statements and have included appropriate references to support our claims.

Correction: (Lines 222-229, Par 1, Page 11) Previous studies have suggested the weakening of tropical circulations such as the Hadley cell and the Walker circulation, in response to increasing greenhouse gases (Lu et al., 2007; Tokinaga et al., 2012; Cai et al., 2021). This weakening may contribute to the amplified isolation of nodes in tropical oceans. Additionally, the weakened tropical circulation could potentially trigger extreme climate phenomena, such as the intensification of El Niño, with more pronounced teleconnection impacts on distant regions (Fan et al., 2017; Hu et al., 2021). This could, in turn, strengthen the linkage between equatorial regions and continents in climate networks.

Lu, J., G. A. Vecchi, and T. Reichler: Expansion of the Hadley cell under global warming, Geophys. Res. Lett., 34, L06805, doi:10.1029/2006GL028443, 2007.

Tokinaga, H., Xie, SP., Deser, C. et al.: Slowdown of the Walker circulation driven by tropical Indo-Pacific warming, Nature 491, 439 – 443, https://doi.org/10.1038/nature11576, 2012.

Cai, W., Santoso, A., Collins, M. et al.: Changing El Niño – Southern Oscillation in a warming climate, Nat Rev Earth Environ 2, 628 – 644, https://doi.org/10.1038/s43017-021-00199-z, 2021.

J. Fan, Meng, J., Ashkenazy, Y., Havlin, S., and Schellnhuber, H. J.: Network analysis reveals strongly localized impacts of El Niño. Proceedings of the National Academy of Sciences, 114(29), 7543-7548, https://doi.org/10.1073/pnas.1701214114, 2017.

Hu K., Huang, G., Huang, P. et al.: Intensification of El Niño-induced atmospheric anomalies under greenhouse warming, Nat. Geosci. 14, 377 – 382, https://doi.org/10.1038/s41561-021-00730-3, 2021.