

Regional Responses to Oceanic Variability Constrain Global Drought Synchrony

Corresponding Author: Dr Udit Bhatia

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Dr Bhatia,

Please accept our sincere apologies for the unusually long delay in sending a decision on your manuscript.

Your manuscript titled "Regional Responses to Oceanic Variability Constrain Global Drought Synchrony" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

In particular, please ensure that the revised manuscript meets the following editorial thresholds:

1. Ensure that your manuscript demonstrates a clear and significant contribution beyond the scope of existing literature, highlighting its novelty and relevance within the field.
2. Provide comprehensive methodological details, with particular emphasis on a well-substantiated justification for the selected drought indices.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

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Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Nicola Colombo, PhD
Associate Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The paper investigates the temporal evolution of global drought synchrony and its relationship with local temperature,

precipitation, and remote ENSO effects, using a combination of complex network analysis and EOF-based pattern diagnostics. The authors find that (1) increasing temperature enhances drought synchrony, (2) precipitation modulates it, producing short-term variations rather than a consistent long-term pattern, and (3) the overall degree of synchrony is smaller than expected.

This is an interesting study. The analysis is solid, and the paper is well written and organized. I also appreciate that the authors have made their entire code publicly available to reproduce the figures, which improves the transparency and reproducibility of the results. I recommend publication of this paper in the journal.

I suggest the following additional analyses to strengthen the depth and robustness of the study:

1. Statistical significance: I suggest performing statistical tests to demonstrate whether the changes across different periods are significant. For example, in Fig. 2(b), it is not clear whether the results for different periods differ significantly.
2. ENSO event stratification: For the ENSO–drought analysis, I suggest distinguishing between strong and moderate-to-weak events. I suspect that much of the correlation between ENSO and the drought index may be driven by exceptionally strong ENSO events (e.g., the 1997/98 El Niño). Separating these categories could clarify the nature of the relationship.

Reviewer #2 (Remarks to the Author):

Review comments are attached below.

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Version 1:

Decision Letter:

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Dear Dr Bhatia,

Your manuscript titled "Regional Responses to Oceanic Variability Constrain Global Drought Synchrony" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Nicola Colombo, PhD
Associate Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have satisfactorily addressed all of my comments. I have no further comments.

Reviewer #2 (Remarks to the Author):

The authors have satisfactorily addressed all the major and minor comments I had on the first version of manuscript. The clarity of the added explanations are exceptional and the revised manuscript presents a work worthy of prompt publication.

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Point-by-point response: Regional Responses to Oceanic Variability Constrain Global Drought Synchrony

Dear reviewers,

We deeply appreciate the thoughtful and encouraging comments made by all the reviewers. We have carefully addressed each comment and have revised the manuscript to reflect the suggested improvements. In doing so, we believe that the clarity, rigor, and overall quality of our work have been substantially enhanced.

Below, we present a point-by-point response to each comment. For clarity, the reviewers' comments are shown in **blue** and followed by our responses in **black**.

Where applicable, we also indicate how and where the manuscript has been updated to incorporate these changes.

Response to Reviewer 1

The paper investigates the temporal evolution of global drought synchrony and its relationship with local temperature, precipitation, and remote ENSO effects, using a combination of complex network analysis and EOF-based pattern diagnostics. The authors find that (1) increasing temperature enhances drought synchrony, (2) precipitation modulates it, producing short-term variations rather than a consistent long-term pattern, and (3) the overall degree of synchrony is smaller than expected. This is an interesting study. The analysis is solid, and the paper is well written and organized. I also appreciate that the authors have made their entire code publicly available to reproduce the figures, which improves the transparency and reproducibility of the results. I recommend publication of this paper in the journal.

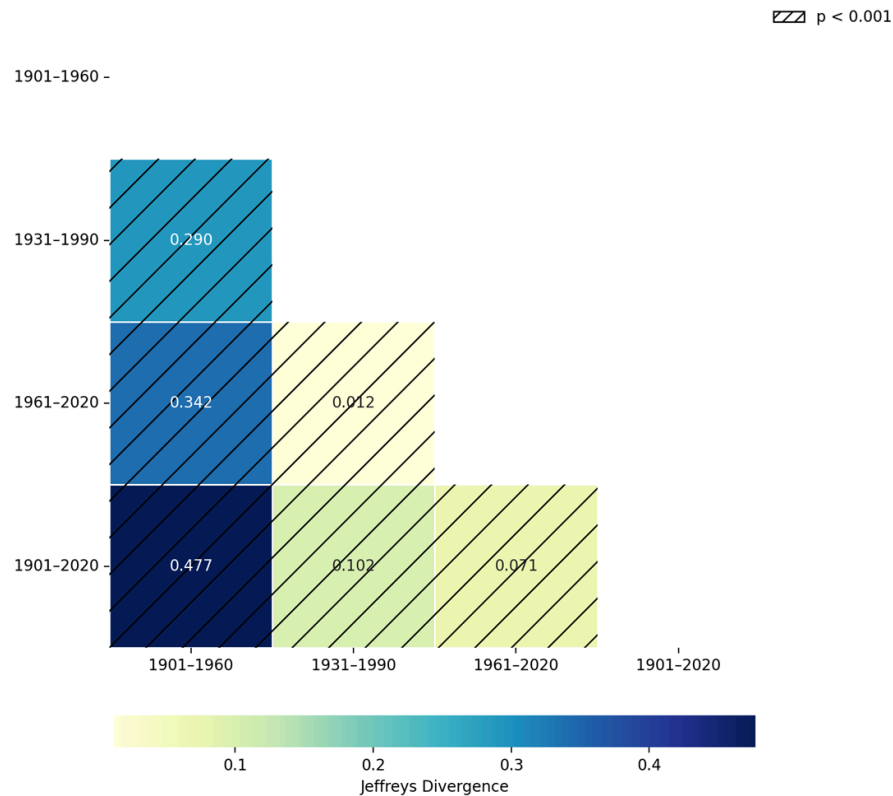
Thank you very much for your thoughtful and encouraging review. We sincerely appreciate your positive assessment of the study and the recognition of our efforts to ensure transparency through open-source code availability. Your comments are valuable to us, and all points raised have been fully addressed below.

Major Comments

1. Statistical significance: I suggest performing statistical tests to demonstrate whether the changes across different periods are significant. For example, in Fig. 2(b), it is not clear whether the results for different periods differ significantly.

We sincerely thank the reviewer for the insightful and constructive comment. Following your suggestion, we have conducted additional statistical analyses to assess the significance of changes in drought synchrony across different periods. Specifically, we evaluated the distributional differences using the Jeffrey's Divergence metric in combination with the Kolmogorov Smirnov (KS) test. Details of the Jeffrey's Divergence and Kolmogorov–Smirnov (KS) tests, which we apply here, can be found in *Geographical Trapping of Synchronous Extremes Amidst Increasing Variability of Indian Summer Monsoon Rainfall* (<https://doi.org/10.1029/2023GL104788>), and we have included the relevant clarifications in the

main text for improved clarity. The results of these analyses are now provided in the Supplementary Materials, which confirm the robustness of our main findings.



Supplementary Figure S5. Jeffrey's Divergence between degree distributions across the different analysis periods. Hatched boxes indicate pairwise comparisons that are statistically significant at the 0.001 level based on the two-sample KS test, confirming that the underlying generational processes of the distributions differ. Numerical values denote the magnitude of the divergence metric, with larger values reflecting stronger distributional separation.

The results shown in Figure 2(B), together with the additional analysis added to the Supplementary Materials, confirm that the distributions vary markedly across the study periods and that the median synchrony also shifts. These outcomes strengthen our conclusion of a systematic and overall increase in drought synchrony under a warming climate, and we have incorporated the relevant clarifications into the main text as follows:

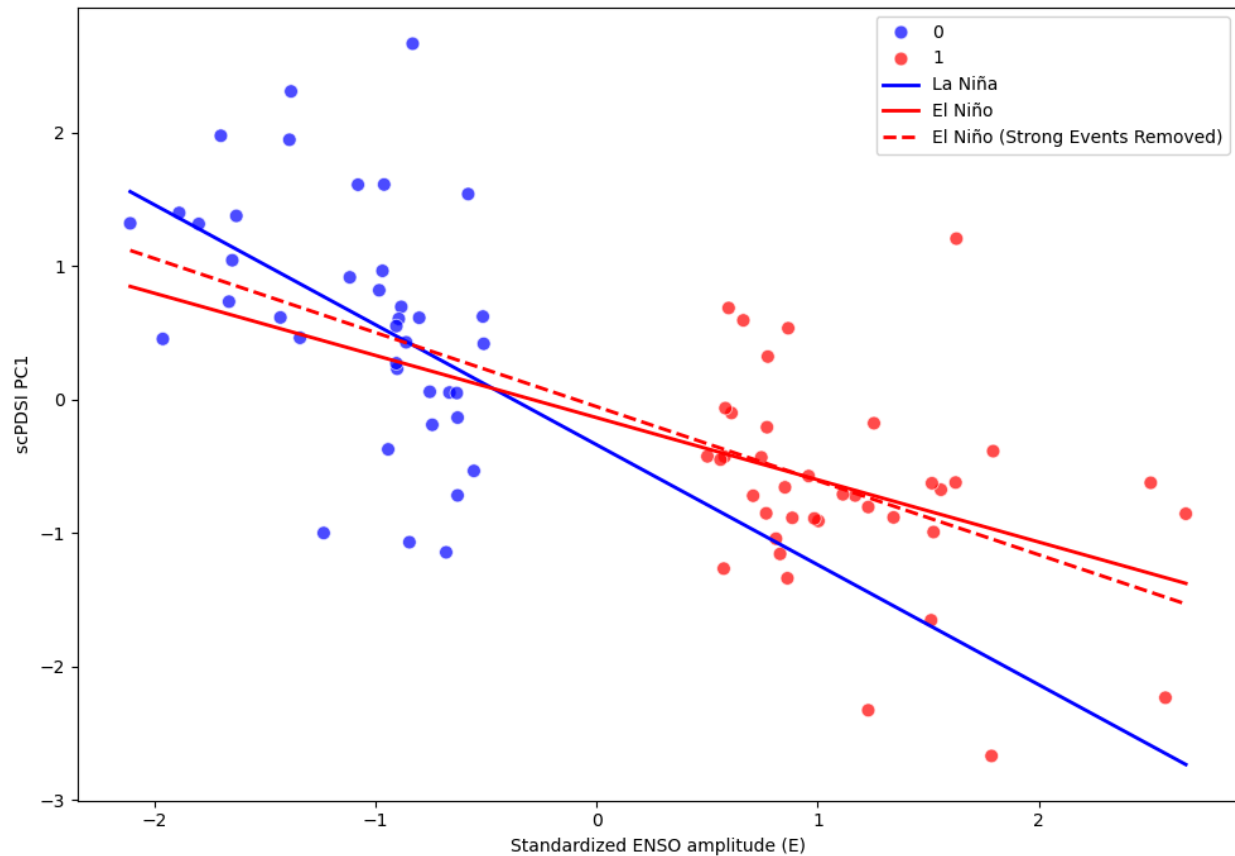
“To formally evaluate whether the degree distributions differ across historical periods, we quantified distributional divergence using Jeffrey's Divergence and assessed significance using the two-sample Kolmogorov–Smirnov (KS) test. Both metrics consistently indicate significant differences between periods ($p < 0.001$), demonstrating that the generative processes underlying drought synchrony have shifted over time. These results support our finding that drought synchrony has intensified in recent decades under a warming climate.”

2. ENSO event stratification: For the ENSO–drought analysis, I suggest distinguishing between strong and moderate-to-weak events. I suspect that much of the correlation between ENSO and the drought index may be driven by exceptionally strong ENSO events (e.g., the 1997/98 El Niño). Separating these categories could clarify the nature of the relationship.

Thank you for this valuable suggestion. We fully agree that exceptionally strong ENSO events such as 1997-98 and 2015-16 could disproportionately influence the ENSO drought relationship, and we appreciate your recommendation to examine this explicitly. Instead of constructing a separate “strong-only” event-synchronization network (which is statistically limited due to the small number of strong events in 1901–2020), we conducted the requested robustness check using an amplitude-aware regression and composite framework. Specifically, we investigated how the leading drought mode (PC1 of sc-PDSI) responds across the full spectrum of ENSO amplitudes.

Our analysis shows that:

- The relationship between ENSO amplitude (Niño-3.4) and drought variability is robust and approximately linear across all event strengths.
- Excluding the major strong events (1982-83, 1997–98 and 2015–16) does not change the correlation or the regression slope.
- This confirms that the global ENSO–drought coupling is not dominated by a small set of extreme ENSO years, but instead reflects a broader and more consistent sensitivity across moderate and weak events as well.



Supplementary Fig S3: Relationship between ENSO amplitude and the leading global drought mode. Scatterplots show scPDSI PC1 regressed onto standardized Niño-3.4 amplitudes for La Niña (blue) and El Niño (red) events. Solid lines indicate ordinary-least-squares fits for all events, while the dashed red line shows the regression after excluding the major strong El Niño years (1982–83, 1997–98, 2015–16). The near-overlap of the two El Niño regression lines demonstrates that the ENSO–drought relationship is robust and not dominated by a small number of extreme events

We thank the reviewer again for this helpful suggestion, which has strengthened the clarity and robustness of the ENSO–drought analysis.

We have added the revised text in the manuscript as follows in the lines 201-207.

“Supplementary Fig. S3 presents our robustness check of the ENSO–drought relationship. We first performed a regression analysis between Niño-3.4 anomalies and the leading global drought mode (PC1 of sc-PDSI) to quantify the amplitude-dependent ENSO influence. We then repeated the analysis after removing the strong ENSO years (1982–83, 1997–98, 2015–16). The results show only minor changes in both the correlation and the regression slope, confirming that the ENSO–drought coupling is not driven by a handful of extreme events.”

Response to Reviewer 2

The manuscript presents a novel application of complex network analysis and maximum covariance analysis to assess whether there is synchrony in global drought occurrence. The results are interesting and appear to build on previous work by addressing their gaps. However, I need more convincing that the study presents a major contribution to the existing body of research on drought drivers and synchronous/asynchronous occurrences. The methodology is sound; however, the justification for using certain drought indices versus others needs more explanation. Also, it will be important to clearly distinguish how the work complements decades of research on El Niño Southern Oscillation (ENSO) teleconnections and drought/non-drought. I offer several major comments, and a few minor comments, for consideration by the authors when revising the manuscript.

Thank you for your careful and constructive review of our manuscript. We sincerely appreciate the depth of your feedback and the clear rationale behind each suggestion. Your comments have been extremely helpful in improving both the clarity and the scientific robustness of the paper. We have carefully addressed all major and minor points, and the corresponding revisions and analyses are detailed below. We are grateful for your positive assessment of the study, and we believe the manuscript is significantly strengthened as a result of your thoughtful input.

Major comments

1. Lines 36–37: Rapid onset droughts in recent years have caused severe impacts on agriculture. It is important to caveat the statement about droughts being slow onset events with an acknowledgement that rapid onset droughts do cause severe impacts in various parts of the Globe.

We thank the reviewer for this insightful comment. We agree that while droughts are generally characterized as slow-onset phenomena, rapid-onset or “flash droughts” have become increasingly frequent and can cause severe agricultural and ecological impacts. In response, we have revised the sentence to acknowledge both types of droughts as follows:

Revised Lines 36-37 : *Droughts manifest through diverse onset and progression rates ranging from slowly intensifying droughts that persist over several seasons to years to rapid-onset flash droughts that can develop within weeks. Both forms cause severe and widespread agricultural, hydrological, and ecological impacts in recent years, underscoring the growing complexity of drought dynamics in a warming climate.*

2. Line 81: Please explain how large-scale climate variability is defined.

Thank you for this helpful comment. We have now defined large-scale climate variability at its first use and added the relevant citations. The revised text clarifies that we refer to basin-scale atmospheric–oceanic modes such as ENSO, IOD, and PDO, which dominate variability on interannual to decadal timescales.

Revised text:

“Large-scale climate variability refers to basin-scale fluctuations in the coupled atmosphere–ocean system, expressed through recurring modes such as ENSO, the Indian Ocean Dipole, and the Pacific Decadal Oscillation, which operate on interannual to decadal timescales.” https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_AnnexIV.pdf

3. Line 85: Please provide the key citation for sc-PDSI on its first use.

Thank you for pointing this out. We have now added the key reference for the sc-PDSI at its first mention (line 85). The original formulation by Wells, Goddard, and Hayes (2004) is now cited appropriately (previously Reference 37). This correction has been incorporated into the revised manuscript.

4. Line 135: Please explain what “projection distortions” are.

We thank the reviewer for pointing this out. The term “*projection distortions*” refers to the geometric bias introduced when gridded datasets on a latitude–longitude coordinate system are used for global analyses without accounting for the varying physical area represented by each grid cell. Specifically, grid cells near the poles cover much smaller surface areas than those near the equator, resulting in a higher density of nodes per unit area. This discrepancy can lead to artificial inflation of network measures such as node degree toward higher latitudes.

To address this, we applied an area correction factor by multiplying each grid cell DC by the cosine of its latitude, following the standard approach recommended in recent studies (e.g., Chauhan et al., 2024). This correction ensures that each spatial node contributes proportionally to its true surface area on the globe, thereby mitigating the projection-related bias.

Revised line 135:

Fig 2A The degree centrality (DC) estimated in this study has been corrected for errors introduced by projection distortions. Polar regions inherently have a higher node density per unit area than equatorial regions, which can lead to overestimation of network measures. To correct this, each grid cell DC was weighted by the cosine of its latitude (Chauhan et al., 2024). As shown in Supplementary Fig. 2, applying this correction reduces the apparent degree values at higher latitudes, providing a more physically consistent spatial representation of drought synchrony.

5. Line 153–156: Please clarify where it is observed that: “...La Niña tends to drive more dispersed and fragmented drought patterns, whereas El Niño induces more concentrated but intense droughts.” If available, please provide a citation to back this observation/statement.

The statement that “La Niña tends to drive more dispersed and fragmented drought patterns, whereas El Niño induces more concentrated but intense droughts” is an interpretation arising directly from our network diagnostics. In Fig. 3 we observe regions with high node degree but low Average Link Length, which corresponds to high local clustering and therefore clustered, intense droughts in confined regions. Conversely, during La Niña phases our maps show a larger number of smaller, High Average Link Length and lower local clustering, consistent with more fragmented and spatially dispersed drought occurrence. This interpretation is consistent with previous findings that El Niño tends to produce spatially coherent, nearly synchronous drought anomalies across teleconnected regions, while La Niña’s impacts are often more spatially variable and regionally heterogeneous.

We added the key citation for the statement in the text and revised the text.

Revised text

“This shift in the geographic distribution of droughts during La Niña supports the observation that La Niña tends to drive more dispersed and fragmented drought patterns, whereas El Niño induces more concentrated but intense droughts. Our network diagnostics show that El Niño years are characterized by high node degree and low Average Link Length, indicating strong local clustering and spatially coherent drought conditions. In contrast, La Niña years exhibit higher Average Link Length and reduced local clustering, consistent with more spatially heterogeneous and regionally dispersed drought occurrence. This interpretation is in line with previous findings that stronger El Niño events produce more spatially coherent drought anomalies, while La Niña impacts are typically more heterogeneous (Lyon, 2004).”

6. Lines 165–170: Provide citations that highlight well-established teleconnections between the El Niño Southern Oscillation (ENSO) phases and drought in different regions of the globe, and include a discussion of how the study corroborates or challenges previous findings. Suggest adding explanations to the manuscript that highlight the study’s contribution to improving understanding of global drought teleconnections.

We thank the reviewer for this thoughtful and constructive suggestion. To improve clarity and strengthen the contextual grounding of our results, we have added a revised paragraph in this section that (i) incorporates a broader set of citations documenting well-established ENSO–drought teleconnections across multiple regions of the globe, and (ii) explicitly explains how our findings corroborate and extend previous work. The newly added paragraph also highlights the study’s contribution by demonstrating how ENSO phases reorganize global drought synchrony from a complex-network perspective. This expanded discussion now appears in the revised manuscript from lines 165 -201 where multiple citations are added as well as an additional paragraph has been added for clarity.

Revised Text line 165- 201:

“Taken together, these ENSO-stratified network results align well with established teleconnection behaviour. The increased drought degree over Australia during El Niño and the higher degree across Africa and South America during La Niña match the phase-asymmetric hydroclimatic responses reported in earlier studies. Likewise, the weak and inconsistent ENSO signals seen over Europe are consistent with findings that ENSO influence in mid-latitudes is indirect and strongly seasonal. By quantifying ENSO-phase-specific changes in DC, and spatial propagation (ALL), we reveal how ENSO reorganizes the coherence of drought events rather than only where droughts occur.”

7. Line 169: The citation #30 (i.e., Mondal et al., 2020) does not refer to Australia and South Africa and does not indicate that regions with high clustering coefficients indicate local-scale synchronization. Please provide a different citation or explain how relevant findings of Mondal et al., 2020 corroborate findings of the study.

We thank the reviewer for catching this and sincerely apologize for the inadvertent miscitation. The reference to *Mondal et al., 2020* was indeed a typographical oversight. The correct citation should be *Mondal et al., 2023* (*Nature Communications*, 14:144; <https://doi.org/10.1038/s41467-022-35531-8>), which presents a global complex-network analysis of drought synchronization and explicitly discusses the role of the clustering coefficient (CC) in identifying local-scale or spatially contiguous drought regions.

In particular, *Mondal et al. (2023)* show that regions with high CC values represent spatially continuous drought behaviour and thus correspond to local-scale synchronization. As noted in their text (page 5, paragraph beginning “Once DC and BC are employed...”),

“A high value of CC primarily indicates spatial continuity of the regional drought events... high CC value locations possibly act as peripheral nodes... Comparatively high CC values (>0.3) are present in desert regions and regions sandwiched between high topographies (in Australia), showing that drought events over these regions are spatially continuous and limited” (*Mondal et al., 2023, p. 5, Fig. 2a–c*).

They further identify South Africa and the Sahel as examples where high CC coexists with high DC and BC, implying locally coherent but spatially contiguous droughts:

“Exceptions are the Sahel and South Africa (high DC, high BC), where high CC values suggest that drought events are typically spatially contiguous” (*Mondal et al., 2023, p. 5*).

This directly supports our interpretation that regions with high clustering coefficients indicate local-scale synchronization, and that such behavior is characteristic of spatially coherent drought regimes such as those over Australia and South Africa.

Accordingly, the sentence at Line 169 has been corrected to cite *Mondal et al. (2023)* instead of *Mondal et al. (2020)*. The revised sentence now reads:

“Regions exhibiting high clustering coefficients (CC) generally indicate locally coherent or spatially continuous drought behaviour, consistent with the findings of Mondal et al. (2023), who reported high CC values (>0.3) over Australia and South Africa corresponding to spatially contiguous droughts with limited large-scale synchronization.”

8. Line 175: Please provide a citation to back the statement that the ALL range indicates connections from regional to global scales.

We thank the reviewer for this important comment and have revised the text to provide a more detailed explanation of how the *average link length (ALL)* represents the spatial scale of drought connectivity. In our analysis, ALL quantifies the mean geographical distance between pairs of nodes that are significantly synchronized in terms of drought occurrence. A low ALL value indicates that drought connections are mostly confined within nearby or regional grids, whereas higher ALL values represent long-distance linkages spanning continents having circumglobal extent, thus signifying large-scale or global synchronization patterns. Therefore, the observed range of ALL from several hundred to nearly 20,000 km captures the continuum of spatial connectivity from regional to global scales. This interpretation is consistent with the findings of Mondal et al. (2023), who introduced the concept of *mean synchronization distance (MSD)* to measure the spatial scale of drought teleconnections. They reported MSD values ranging from 2,000 to 10,000 km, highlighting that drought events can be spatially correlated over regional to circumglobal extents.

Revised text (Line 175):

“The average link length (ALL) represents the mean geographical distance among significantly synchronized nodes in the drought network. Lower ALL values correspond to regionally confined drought linkages, while higher values reflect teleconnections extending across continents and ocean basins. In our analysis, ALL values range from several hundred to nearly 20,000 km, indicating spatial connections spanning regional to global scales. Similar spatial ranges were reported by Mondal et al. (2023).”

9. Lines 203–204: Please include a brief explanation on why it is inferred that: “...the more modest increase in degree during the second period (1961–2020) suggests that oceanic and regional variability may constrain global drought synchronization.”

We thank the reviewer for this valuable observation and agree that the inference required clearer justification. We have now expanded the text to briefly explain the reasoning behind this interpretation.

Specifically, the increase in mean degree centrality between 1901–1960 and 1961–2020 (Fig. 2D) indicates that drought-affected regions have become more interconnected overall, consistent with the intensification of global warming. However, the smaller relative rise in degree during the later period—despite stronger global temperature trends—suggests that enhanced regional and oceanic variability acts as a limiting mechanism. Our Maximum Covariance and Singular Value Decomposition (MCA/SVD) analyses show that large-scale

sea-surface-temperature (SST) oscillations such as ENSO, IOD, and AMO introduce asynchronous drought responses across different basins (Figs. 4–6). These opposing SST-driven anomalies generate regionally out-of-phase drought and wet conditions, thereby preventing further expansion of globally synchronous drought networks even under stronger thermodynamic forcing.

Accordingly, the revised text now reads:

“Although mean degree increased between 1901–1960 and 1961–2020, the relatively modest rise during the latter period suggests that enhanced oceanic and regional variability, expressed through out of phase SST oscillations and associated precipitation anomalies, acts to constrain further growth in global drought synchronization”

10. Line 205: Is 6.5% considered to be extensive connectivity, or is the reference here to the degree centralities reported in previous studies?

We thank the reviewer for this helpful clarification request. Our intention was not to describe 6.5% as a typical or consistently “extensive” level of global connectivity. Rather, this value represents a single-time-window peak in our analysis. Across all other periods, the proportion of global land exhibiting synchronous drought is considerably lower, underscoring that high connectivity is not the norm but an occasional upper bound.

Revised Line 205:

“The maximum degree centrality observed in our analysis was 3,871 (6.5% of all grid cells) during the 1942–2001 window; this value represents an isolated upper bound, with all other periods showing substantially lower connectivity. This contrasts with earlier studies that reported degree centralities approaching 15,000, which appear considerably higher than what we obtain using the same data source and network construction procedure.”

11. Lines 236–242: ENSO teleconnections do lead to different responses in drought/wet patterns across the globe. How different is “synchrony” to teleconnection patterns? One could argue that wet and dry patterns in different regions are synchronized when there is a strong ENSO event underway.

This is an excellent point. We clarify that while teleconnections can drive synchrony, they are not the only mechanism responsible for temporally aligned drought or wet events. Teleconnections refer to *physical and dynamical linkages* in the climate system, how a perturbation in one region (such as an ENSO-related SST anomaly) propagates through atmospheric and oceanic circulation to influence remote areas. They are directional and mechanistic, describing cause-and-effect relationships, such as Rossby wave trains or shifts in the Walker circulation, that mediate large-scale rainfall anomalies.

In contrast, synchrony, as used in our study, is a *statistical manifestation* of temporal coherence. It quantifies whether drought onsets occur within a short time window across different locations,

irrespective of whether they share the same physical driver. Synchrony is therefore an emergent property of the climate system, integrating both causally linked (teleconnected) and coincident but independent responses. For instance, a strong ENSO event can indeed create synchronous drying in some regions (e.g., Australia, southern Africa) and wet anomalies elsewhere (e.g., equatorial South America). However, the presence of opposite responses in sign implies that ENSO produces both synchronous and asynchronous behavior globally. Thus, synchrony captures the *temporal alignment of drought occurrences*, not necessarily their *phase or causal pathway*.

This conceptual distinction also explains why we emphasized the percentage variance explained plots and the coupled SST–scPDSI modes in Figs. 4–6. These analyses explicitly quantify how much of the global drought variability can be statistically attributed to oceanic forcing and where this coupling weakens or reverses. The spatial heterogeneity in explained variance and correlation patterns demonstrates that while ENSO teleconnections impose large-scale organization, regional modes (e.g., Indian Ocean Dipole, North Atlantic Oscillation, Tropical Atlantic SSTs) often produce out-of-phase or compensatory responses. These asynchronous behaviors act as natural constraints on global drought synchrony, explaining why, despite warming and more frequent extremes, the extent of globally simultaneous droughts remains limited.

This has been added at appropriate place in Discussion:

“We note that teleconnections and synchrony are related but distinct concepts. Teleconnections describe the physical and directional linkages between distant regions mediated through atmospheric and oceanic circulation anomalies such as those associated with ENSO. Synchrony, in contrast, is a statistical measure of the temporal co-occurrence of drought onsets across locations, regardless of whether the underlying mechanisms are shared or independent. While teleconnections can therefore generate synchrony, they are not its sole driver, as coincident regional anomalies or compensating ocean–atmosphere interactions can also align drought timing. This distinction motivates our use of percentage variance explained plots with SST anomalies (Figs. 4–6), which demonstrate that although ENSO accounts for a substantial portion of coupled SST–drought variability, spatial heterogeneity in these relationships indicates that regional oceanic and atmospheric variability constrains the overall degree of global drought synchronization.”

12. Lines 256–257: There are also some marked differences in the Central Pacific region; please comment on the potential significance (if any) of changes in correlation patterns in the Central Pacific, besides the Atlantic and Indian Oceans.

Thank you for this valuable point. We have now added a discussion on the significance of the correlation changes in the Central Pacific. Warming in the Central Pacific is closely associated with the emergence of Central Pacific El Niño (also called El Niño Modoki), which differs dynamically and teleconnection-wise from the canonical Eastern Pacific (EP) El Niño. Central Pacific warming is therefore an important feature influencing global drought connectivity, precipitation shifts, and atmospheric circulation anomalies. We have incorporated these points into the revised text.

“Beyond the Atlantic and Indian Oceans, we note enhanced correlations in the Central Pacific alongside a higher squared covariance fraction (SCF) of the leading SST–T mode. This co-occurrence indicates that a larger portion of the joint variability is being organized by Central-Pacific (CP) El Niño dynamics, wherein SST anomalies peak near the dateline and convection shifts westward. Observational analyses show increasing CP El Niño intensity and greater prevalence in recent decades, while process-based studies tie future CP frequency to background-state features such as cold-tongue strength. These results suggest that ENSO diversity has evolved, with CP events increasingly modulating global teleconnections and, by extension, the spatial structure of drought synchrony in our network analysis.”

13. Lines 270–274: Figure 5B does not show temperature-SST correlations. Please correct the figure reference to Figure 6B.

We thank the reviewer for pointing this out. The figure reference has now been corrected.

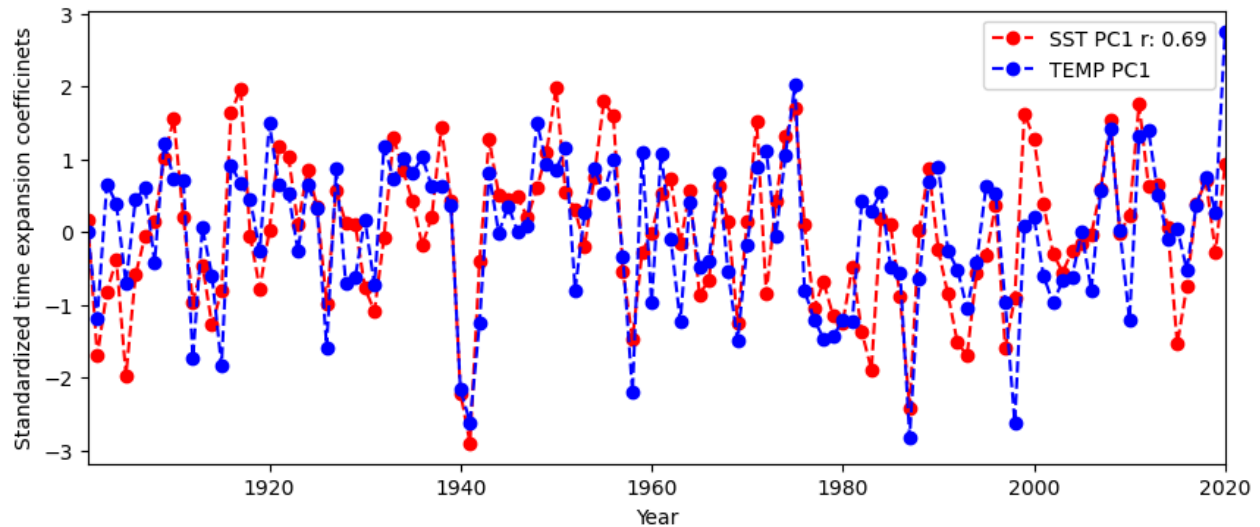
14. Lines 284–286: It is unclear how this inference is made. Please include the normalized time series of the expansion coefficients of the leading mode of T-SST to back this statement.

Thank you for the question. We clarify that the inference about “consistent temperature–SST correlations between regions” is based on the spatial loading pattern of the leading T–SST mode, not only on the temporal expansion coefficients. In the MCA spatial field (Fig. 6B), temperature loadings maintain the same sign globally, indicating that SST anomalies exert a spatially uniform warming influence across continents. In contrast, the P–SST mode displays mixed positive and negative signs across different regions (Fig. 6A), revealing a heterogeneous precipitation response to SST variability.

To complement this, we now include the standardized time expansion coefficients in the supplementary figure S10, which show a strong correlation ($r = 0.69$), confirming the temporal coherence of the T–SST mode. However, it is the globally uniform spatial structure, rather than the temporal correlation itself, that supports the statement regarding regional consistency.

To make the inference clearer for readers we now add another line as

“The corresponding normalized expansion coefficients are presented in Supplementary Fig. S9, confirming the temporal coherence of the leading T–SST mode. Critically, however, the inference of regional consistency is grounded in the spatial loading pattern, whose globally uniform sign indicates a continent-wide and directionally consistent temperature response to SST variability”



Supplementary Fig. S11. Standardized time series of the leading Maximum Covariance Analysis (MCA) modes derived from global land surface temperature and sea surface temperature (SST) fields. The red curve shows the expansion coefficients of the SST leading mode, while the blue curve shows those of the temperature leading mode. Both series are standardized to allow direct comparison of their temporal variability. The two leading modes exhibit a correlation of $r = 0.69$, indicating a strong and coherent co-evolution between global SST anomalies and land surface temperature anomalies over the past century. This shared variability reflects large-scale coupled ocean–atmosphere processes: warm or cool SST patterns tend to be accompanied by corresponding warming or cooling of continental regions. Thus, the leading MCA mode captures the dominant pattern of joint SST–temperature variability, highlighting the tight coupling between oceanic forcing and land climate response.

15. Lines 344–345: Please provide citations to back the statement that mid-latitude regions in Europe and Asia are experiencing rapid warming.

We thank the reviewer for this helpful comment. We have now added citations supporting the statement that mid-latitude regions in Europe and Asia are undergoing rapid warming. Multiple studies document that these regions have warmed at rates exceeding the global average. For instance, Huang et al. (2012) report that mid-latitude semi-arid regions in Europe and Asia experienced warming of 1.41°C and 2.42°C respectively over 1901–2009, highlighting pronounced and accelerated temperature increases. Similarly, Chen et al. (2009) demonstrate significant long-term warming across mid-latitude Central Asia, while Yin et al. (2024) show enhanced and anthropogenically amplified warming across mid-latitude Europe.

We have incorporated these references into the revised manuscript.

16. Lines 396–403: Please comment on the appropriateness of using sc-PDSI to identify drought onset given that there can be a lag of several months before the PDSI picks up a drought signal. (WMO 2016)

We thank the reviewer for this important observation. We agree that the sc-PDSI can exhibit a lag of several months before capturing the onset of drought conditions, as documented by WMO (2016). We have now clarified this limitation in the manuscript and explained why the sc-PDSI remains appropriate for the goals of our study. Specifically, our work focuses on large-scale, persistent drought dynamics rather than short-lived or flash-drought events. For such persistent droughts, the integrating behavior of sc-PDSI is advantageous, as it reflects cumulative soil moisture deficits and produces spatially and temporally comparable metrics (Dai, 2011; van der Schrier et al., 2013). We have also emphasized that our synchrony and network-based analysis relies on spatial patterns of sustained drought rather than precise month-to-month onset timing, making the sc-PDSI's known lag less critical. These clarifications have now been incorporated into the revised manuscript.

In this study, we define the onset of moderate drought using a threshold-based approach, adopting a threshold of -2 on the self-calibrating Palmer Drought Severity Index (sc-PDSI). We acknowledge that the sc-PDSI may exhibit a lag of several months before fully detecting emerging drought conditions (WMO, 2016). However, our analysis focuses on large-scale and persistent drought behavior rather than rapid-onset or short-duration events, for which sc-PDSI is well suited due to its cumulative accounting of soil moisture deficits (Dai, 2011). We employ the sc-PDSI because of its widespread use in global drought assessments, its Penman–Monteith–based potential evapotranspiration formulation, and its ability to provide spatially and temporally comparable measures of drought severity under climate warming (van der Schrier et al., 2013). Moreover, the synchrony and network analyses in this study rely on spatial patterns of persistent drought rather than precise month-to-month onset timing, making the sc-PDSI's lag less critical for our research objectives. And it has been used in the previous network studies (Mondal et al. (2023)) So we use scPDSI to make a direct comparison.

These limitations and lines are now added in the discussion section.

“Although the sc-PDSI can exhibit a lag of several months before fully capturing drought onset (WMO, 2016), its integrative treatment of soil moisture deficits makes it well suited for the large-scale and persistent drought behavior examined here. Because our synchrony and network analyses rely on spatial patterns of sustained drought rather than precise onset timing, this lag does not materially affect our conclusions. Moreover, the sc-PDSI provides spatially comparable drought metrics and is widely employed in global drought studies, including previous network-based analyses, thereby ensuring methodological consistency and facilitating comparison across studies”.

Minor comments

1. Spell out all acronyms on first use (e.g., sc-PDSI).

We have made the changes in the manuscript and now all acronyms, including sc-PDSI and others, are now spelled out upon first use.

2. Line 230: Please define on first use and provide key citations for the IOD.

The Indian Ocean Dipole (IOD) is now defined at its first appearance, and the key reference is cited in the text.

3. Lines: 383–386: Please include the citation for the ERSST v5 dataset.

The citation for the ERSSTv5 dataset (Huang et al., 2017) has been included in the revised manuscript.

References:

- Otkin, J. A., Svoboda, M., Hunt, E. D., Ford, T. W., Anderson, M. C., Hain, C. R., & Basara, J. B. (2018). Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bulletin of the American Meteorological Society*, 99(5), 911–919. <https://doi.org/10.1175/BAMS-D-17-0149.1>
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- Weng, H., Ashok, K., Behera, S. K., Rao, S. A., & Yamagata, T. (2007). Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific Rim during boreal summer. *Climate Dynamics*, 29(2–3), 113–129. <https://doi.org/10.1007/s00382-007-0234-0>
- Kao, H.-Y., & Yu, J.-Y. (2009). Contrasting Eastern-Pacific and Central-Pacific types of ENSO. *Journal of Climate*, 22(3), 615–632. <https://doi.org/10.1175/2008JCLI2309.1>

**Point-by-point response R(2): Regional Responses to Oceanic Variability Constrain
Global Drought Synchrony**

Dear Reviewers,

We are delighted that you and the referees find the revisions satisfactory and that our clarifications have strengthened the paper. Thank you again for your support and the opportunity to contribute to Communications Earth & Environment.

Sincerely,
Udit Bhatia
On behalf of all co-authors

Point-by-point response to reviewers' final comments:

Reviewer #1

Comment:

The authors have satisfactorily addressed all of my comments. I have no further comments.

Response:

We sincerely thank the reviewer for the positive evaluation of our manuscript and for confirming that all comments have been satisfactorily addressed. We truly appreciate the time and effort invested in reviewing our work.

Reviewer #2

Comment:

The authors have satisfactorily addressed all the major and minor comments I had on the first version of manuscript. The clarity of the added explanations are exceptional and the revised manuscript presents a work worthy of prompt publication.

Response:

We sincerely thank the reviewer for the generous and encouraging comments on the revised manuscript. We are grateful for the appreciation of the clarity and quality of the revisions, and we highly value the constructive feedback that helped improve our work.

Review of **Regional Responses to Oceanic Variability Constrain Global Drought Synchrony**

By Udit Bhatia, Hemant Poonia, Danish Mansoor Tantary, Vimal Mishra, and Rohini Kumar.

The manuscript presents a novel application of complex network analysis and maximum covariance analysis to assess whether there is synchrony in global drought occurrence. The results are interesting and appear to build on previous work by addressing their gaps. However, I need more convincing that the study presents a major contribution to the existing body of research on drought drivers and synchronous/asynchronous occurrences. The methodology is sound; however, the justification for using certain drought indices versus others needs more explanation. Also, it will be important to clearly distinguish how the work complements decades of research on El Niño Southern Oscillation (ENSO) teleconnections and drought/non-drought. I offer several major comments, and a few minor comments, for consideration by the authors when revising the manuscript.

Major comments

1. Lines 36–37: Rapid onset droughts in recent years have caused severe impacts on agriculture. It is important to caveat the statement about droughts being slow onset events with an acknowledgement that rapid onset droughts do cause severe impacts in various parts of the globe.
2. Line 81: Please explain how large-scale climate variability is defined.
3. Line 85: Please provide the key citation for sc-PDSI on its first use.
4. Line 135: Please explain what “projection distortions” are.
5. Line 153–156: Please clarify where it is observed that: “....La Niña tends to drive more dispersed and fragmented drought patterns, whereas El Niño induces more concentrated but intense droughts.” If available, please provide a citation to back this observation/statement.
6. Lines 165–170: Provide citations that highlight well-established teleconnections between the El Niño Southern Oscillation (ENSO) phases and drought in different regions of the globe, and include a discussion of how the study corroborates or challenges previous findings. Suggest adding explanations to the manuscript that highlight the study’s contribution to improving understanding of global drought teleconnections.
7. Line 169: The citation #30 (i.e., Mondal et al., 2020) does not refer to Australia and South Africa and does not indicate that regions with high clustering coefficients indicate local-scale synchronization. Please provide a different citation or explain how relevant findings of Mondal et al., 2020 corroborate findings the study.
8. Line 175: Please provide a citation to back the statement that the ALL range indicates connections from regional to global scales.
9. Lines 203–204: Please include a brief explanation on why it is inferred that: “...the more modest increase in degree during the second period (1961–2020) suggests that oceanic and regional variability may constrain global drought synchronization.”

10. Line 205: Is 6.5% considered to be extensive connectivity, or is the reference here to the degree centralities reported in previous studies?
11. Lines 236–242: ENSO teleconnections do lead to different responses in drought/wet patterns across the globe. How different is "synchrony" to teleconnection patterns? One could argue that wet and dry patterns in different regions are synchronized when there is a strong ENSO event underway.
12. Lines 256–257: There are also some marked differences in the Central Pacific region; please comment on the potential significance (if any) of changes in correlation patterns in the Central Pacific, besides the Atlantic and Indian Oceans.
13. Lines 270–274: Figure 5B does not show temperature-SST correlations. Please correct the figure reference to Figure 6B.
14. Lines 284–286: It is unclear how this inference is made. Please include the normalized time series of the expansion coefficients of the leading mode of T-SST to back this statement.
15. Lines 344–345: Please provide citations to back the statement that mid-latitude regions in Europe and Asia are experiencing rapid warming.
16. Lines 396–403: Please comment on the appropriateness of using sc-PDSI to identify drought onset given that there can be lag of several months before the PDSI picks up a drought signal. (WMO 2016)¹

Minor comments

1. Spell out all acronyms on first use (e.g., sc-PDSI)
2. Line 230: Please define on first use and provide key citations for the IOD.
3. Lines: 383–386: Please include the citation for the ERSST v5 dataset.

Recommendation

I recommend that the manuscript undergoes a major revision to address all the major and minor comments addressed above.

¹ World Meteorological Organization and Global Water Partnership. Handbook of Drought Indicators and Indices. In Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2; Svoboda, M., Fuchs, B.A., Eds.; WMO: Geneva, Switzerland, 2016.