

Unexpected return of late-summer sea ice in the Pacific Arctic under persistent poleward-shifted cyclonic anomaly

Corresponding Author: Professor Xi Zhao

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This study argues that a shift in the PNA-like pattern favored sea ice recovery over the Pacific sector of the Arctic during the summers of 2020–2024. The question is interesting, and the study makes a strong argument for the proposed mechanism. I do not see any major issues with the analysis, and I believe this work is worthy of publication. My concerns are mainly related to the following points.

The PNA has strong internal variability and can also be influenced by tropical forcing. Since the authors found that the recent change was not tropically driven, this may indicate that the shift is primarily internally driven. If this is the case, the authors should emphasize that the recent pattern reflects internal or natural variability of the climate system (eg., in the abstract).

The study is based on only one observational sample. This limitation makes me feel that the conclusions require stronger support. I wonder whether it is possible to use model results to identify additional cases of this type of 4-year reversal and to test whether a similar PNA-shift mechanism can be found in the model world. Otherwise, for a single case study, there is considerable flexibility in framing the idea, and the physical and statistical robustness of the proposed mechanism becomes less clear.

I have also recently read quite a few papers that make similar arguments, linking regional sea ice recovery to tropical-extratropical SST variability or related processes. It would be helpful for the authors to clarify the key implication of this study. If a PNA-like pattern can favor sea ice recovery, why could it not also favor rapid sea ice decline during earlier periods? I feel that the current study still focuses too much on interpreting the results at a relatively surface level. A deeper discussion would help the community better understand the role of large-scale circulation in shaping summer Arctic sea ice changes.

Cloud variations during these 4 years can be quite sensitive to the choice of reanalysis product. If MERRA-2 or CALIPSO is used, does the low level cloud change signal still hold?

Reviewer #2

(Remarks to the Author)

This paper discusses a recent recovery in sea ice extent in the Pacific Arctic, which the authors propose was triggered by a poleward shift in the Pacific North American (PNA) teleconnection pattern. The authors present a detailed argument that supports this hypothesis. I found the work compelling, but there were several stylistic and technical issues that will require revision prior to publication.

Major Issues

1) Presentation of Results

I found many of the figures to have issues with the way there were presented. There were inconsistencies in the map projections used, which detracted from readers' ability to assess the results. Mercator, Lambert Conformal, Polar Stereographic projections and some sort of 'birds-eye view' (Fig 1b) are all used, often mixing projections within a single figure. I found this mixing disconcerting and made it a challenge to understand what is being presented. The Mercator

projection is especially problematic at high latitudes as it distorts the area. The authors have chosen to include labels in the colorbars. This was confusing and detracted from the important role that the colorbars play in allowing readers to understand the results presented. Many figures contain multiple subpanels that end up being quite small and difficult to read. Figure 1b is especially problematic as the authors present 2 fields (sea ice concentration and SST). The way the fields are presented makes it difficult to interpret what is going on.

2) Calculation of EOFs

EOFs are a function of the domain used to calculate them. The authors do not provide information on the domain used. Based on Fig. 2 and Fig. 3, it appears (though I could be wrong) that different domains are used for EOF1 and EOF3. If true, it is problematic and needs to be corrected. I assume that the same domain was used and the authors chose different domains. In this case, I don't see the reason why different domains were used. The Mercator projection is also an issue.

3) Excessive Supplementary Figures

There are 15 SFs. I assume that journal constraints forced the authors to have so many SFs. In my opinion, SFs should be used sparingly and curated to maximize impact. Given the number of SFs, it appears the authors did not follow this approach. I think it is asking a lot of readers to look at so many SFs and one is left with the opinion that many of the important results are delegated to SFs that many readers will not consider. This detracts from the paper's impact.

Minor Issues

1) Abstract. The 2007 sea ice extent minimum is not fully explained, which may confuse readers unfamiliar with Arctic sea ice variability.

2) The Introduction includes some results related to Fig. 2. I found this non-standard as I am a firm believer that the Introduction should summarize previous work and provide context for the results that follow.

3) Line 78: Moore et al (2025) emphasized the role that a large-scale convergence event in Feb 2024 played in the persistence of sea ice in the southern Chukchi Sea through the following summer.

Reviewer #3

(Remarks to the Author)

The paper documents an unusual five-year reappearance of summer sea ice in the Chukchi Sea during 2020–2024, culminating in the September 2024 congestion of the Northeast Passage. The authors argue that this recovery was driven by a poleward-shifted summer PNA pattern, which produced persistent northerly winds, enhanced cloud cover, reduced shortwave absorption, colder ocean and air temperatures, and a self-reinforcing cooling feedback. They further argue that the PNA index provides a unified framework for understanding both the 2007 extreme sea-ice retreat and the 2020–2024 recovery.

The observation is interesting and the paper brings together a useful set of atmospheric, oceanic, and sea-ice diagnostics. However, the manuscript repeatedly makes claims that are stronger than the evidence supports. In particular, it treats a short regional anomaly as evidence for a structural shift in a hemispheric teleconnection pattern, relies heavily on correlations and EOF-based arguments, and does not sufficiently establish causality or future predictive value. I think the paper could be much stronger if reframed as a diagnostic case study of a recent regional anomaly, rather than as evidence for a robust new PNA-driven sea-ice recovery mechanism. Below are some major comments.

- The period of interest is very short. The main result is based on only five summers, and much of the signal appears to be dominated by 2024. The authors should test whether the results hold if 2024 is removed, or through a leave-one-year-out analysis across 2020–2024.
- The causal language is too strong. Terms such as “triggered,” “drove,” and “self-reinforcing feedback” require more than contemporaneous composites and correlations.
- The PNA argument is conceptually unclear. The canonical positive PNA is described as promoting Chukchi sea-ice loss, but the 2020–2024 recovery is also attributed to the PNA because its structure shifted poleward. It is unclear whether the PNA index is measuring canonical PNA amplitude, anomaly latitude, or simply covarying with another regional circulation pattern.
- The MZD argument is weak as currently presented. EOF3 explains only 16.3 percent of Z500 variance, and the authors acknowledge that the MZD has only a weak relationship with SIC over the full record. They should test EOF mode separation, for example using a North et al. eigenvalue separation test, and clarify whether this mode is statistically robust.
- The 26-year running correlation needs much more justification. The window length appears arbitrary, adjacent windows share 25 years of data, and significance is likely overstated without accounting for autocorrelation and overlapping samples. Sensitivity to 15-, 20-, and 30-year windows would help.
- The 2002–2019 baseline may exaggerate the apparent recovery because it is the period of rapid sea-ice decline. Key figures should be repeated using a standard climatology such as 1991–2020 to test whether the recovery framing survives.
- The paper does not sufficiently engage with the broader slowdown in Arctic sea-ice loss literature. Recent work is directly relevant, including England et al. 2025 on the post-2005 pause in September sea-ice area decline, doi:10.1029/2025GL116175; Wang et al. 2025 on the post-2012 slowdown and summer NAO phase shift, doi:10.1038/s41467-025-63520-0; Yu et al. 2025 on decelerated Arctic sea-ice loss linked to North Pacific warming, doi:10.1038/s43247-025-02882-1; and Zhang 2021 on the slowdown in Arctic sea-ice volume decline during 2007–2020, doi:10.1029/2021GL094780. The authors should clarify whether the Chukchi anomaly is part of a broader Arctic or Pacific-sector slowdown, distinct from it, or simply internal variability.
- The broader significance is unclear. The manuscript gestures toward improved prediction and future shipping risks, but it does not show that this mechanism has predictive skill. If this is short-lived internal variability, its future relevance may be limited. If it reflects a structural PNA change, the authors need much stronger evidence.
- Overall, the paper would be more convincing if the central claim were softened and the statistics more robust. The authors can reasonably argue that the 2020–2024 Chukchi sea-ice retention was associated with unusual circulation, northerly

winds, and cloud-radiative cooling. They have not yet shown that a structurally shifted PNA triggered a robust sea-ice recovery or provides a reliable framework for future prediction.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The paper has been greatly improved and is ready for publication.

Reviewer #2

(Remarks to the Author)

The authors have addressed all the issues I have. I thank them for their diligence.

Reviewer #3

(Remarks to the Author)

The authors have sufficiently addressed my main concerns.

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Reviewer #1

General Comments: This study argues that a shift in the PNA-like pattern favored sea ice recovery over the Pacific sector of the Arctic during the summers of 2020–2024. The question is interesting, and the study makes a strong argument for the proposed mechanism. I do not see any major issues with the analysis, and I believe this work is worthy of publication. My concerns are mainly related to the following points.

Response:

We sincerely thank the reviewer for the positive evaluation and constructive suggestions. In the revised manuscript, we have clarified the interpretation of the recent Pacific–Arctic circulation anomaly, emphasized its relation to natural atmospheric variability, and added further analyses and discussion to strengthen the interpretation of the 2020–2024 Chukchi Sea sea-ice recovery.

Specific comments:

1. The PNA has strong internal variability and can also be influenced by tropical forcing. Since the authors found that the recent change was not tropically driven, this may indicate that the shift is primarily internally driven. If this is the case, the authors should emphasize that the recent pattern reflects internal or natural variability of the climate system (eg., in the abstract).

Response:

We thank the reviewer for this helpful suggestion. We agree that the PNA has strong internal variability and can also be influenced by tropical forcing, and that its canonical wave-train structure is most clearly expressed in winter. In summer, the PNA-related circulation pattern is generally less canonical and more strongly affected by regional Pacific–Arctic circulation variability.

In our analysis, because the recent poleward-shifted Pacific–Arctic cyclonic anomaly lacks a dominant tropical driver, and given the complex, multi-modal interactions characteristic of summer high-latitude circulation, we believe it is most scientifically rigorous to frame this event as a manifestation of the climate system's natural atmospheric variability rather than attributing it to a single isolated internal mode or a persistent structural shift.

Following the reviewer's suggestion, we have carefully revised the Abstract and Discussion to emphasize this interpretation. The final sentence of the Abstract has been updated to explicitly highlight the role of natural regional variability, while also correcting a minor phrasing structure for better clarity:

L28-L35:

“... Furthermore, we demonstrate that the Pacific–North American (PNA) mode was linked to summer Chukchi Sea ice concentration, with its influence expressed through the regional position of the associated Pacific–Arctic cyclonic anomaly. These findings identify the Chukchi Sea as a sensitive Pacific Arctic sector where natural regional circulation variability can generate abrupt, localized reversals in summer sea-ice loss, thereby offering a fresh perspective on the role of summer PNA-related circulation variability in Pacific-sector Arctic sea ice.”

We have also clarified the role of the PNA in the revised manuscript in relation to existing atmospheric modes and possible atmospheric co-variability. The 2020–2024 recovery is not interpreted as being directly triggered by a structurally shifted PNA; rather, the REOF-based PNA provides an established large-scale framework that remains linked to Chukchi Sea SIC and to the meridional displacement of the Pacific–Arctic cyclonic anomaly center.

L479-L488:

“...In this context, the REOF-based PNA index serves as a valuable framework for describing this large-scale background. However, available evidence is currently

insufficient to conclude whether the 2020–2024 recovery stems from a structural shift in the PNA mode; rather, our findings demonstrate that the influence of PNA-related circulation on Chukchi Sea SIC remains contingent upon the regional configuration of the associated Pacific–Arctic cyclonic anomaly. Given the rarity of the 2020–2024 multi-year recovery and late-summer ice-retention event, its recurrence and predictability will require longer records and targeted model experiments, including large-ensemble simulations.”

2. The study is based on only one observational sample. This limitation makes me feel that the conclusions require stronger support. I wonder whether it is possible to use model results to identify additional cases of this type of 4-year reversal and to test whether a similar PNA-shift mechanism can be found in the model world. Otherwise, for a single case study, there is considerable flexibility in framing the idea, and the physical and statistical robustness of the proposed mechanism becomes less clear.

Response:

Following the reviewer’s suggestion, we examined the CESM Large Ensemble (CESM-LE) simulations. As shown in Response Fig. R1a, the ensemble mean exhibits a continuous long-term decline in summer Chukchi Sea ice, contrasting with the observed 2020–2024 recovery, although the ensemble spread (standard deviation) indicates strong internal variability in sea ice area. Simulating this localized, multi-year event poses a substantial challenge for current climate models, largely because Arctic atmospheric circulation during summer has a notably low signal-to-noise ratio dominated by chaotic internal noise. Because the simulated spatial ensemble mean anomalies fail to reproduce the key regional circulation and temperature features identified in our observations (Response Fig. R1b, c), this event represents an exceptional short-term fluctuation that stands far outside the model's average response. Therefore, we cannot use these simulation results as a direct mechanistic test. Accordingly, we have updated the Discussion section of the manuscript to emphasize

that evaluating the recurrence and predictability of this rare event requires targeted, long-term model simulations:

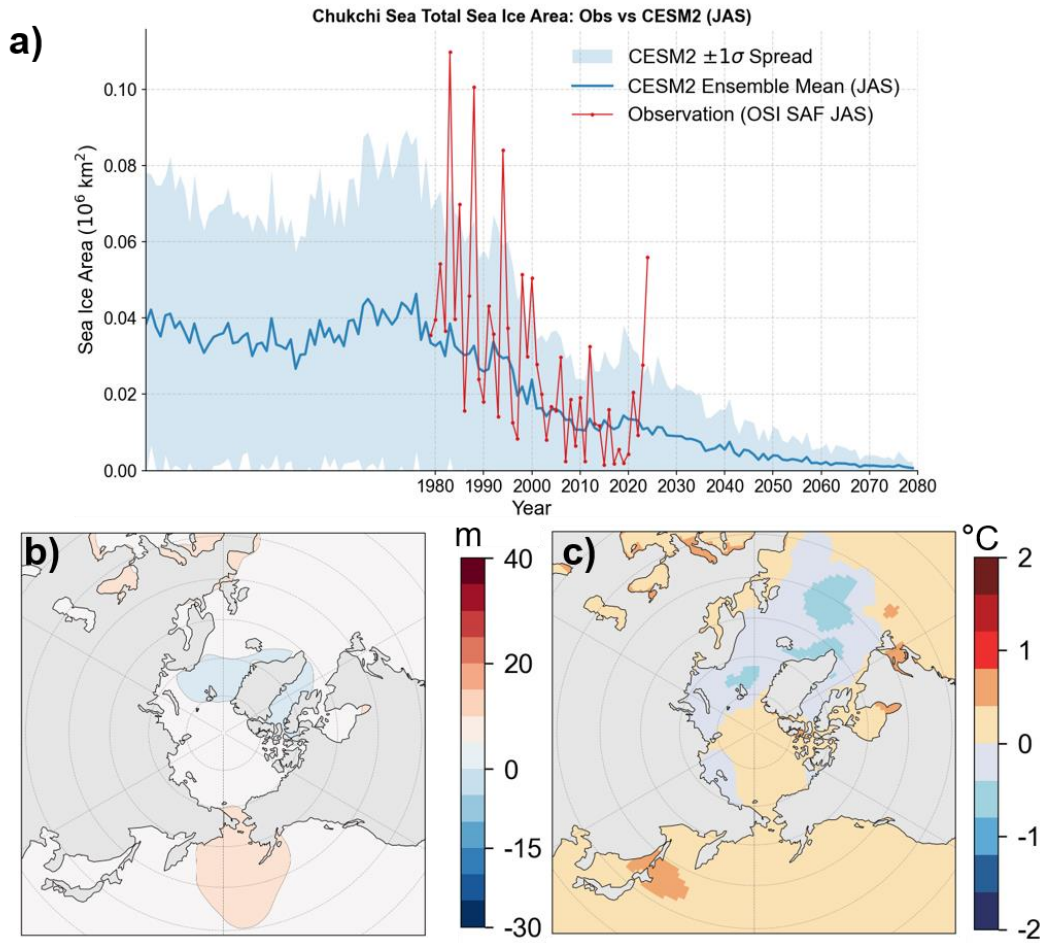
L485-L488:

“...Given the rarity of the 2020–2024 multi-year recovery and late-summer ice-retention event, its recurrence and predictability will require longer records and targeted model experiments, including large-ensemble simulations.”

We acknowledge the reviewer's concern regarding the single case study. However, the robustness of our proposed mechanism relies on the strong physical consistency among multiple independent observational datasets (cloud cover, radiation, and ocean heat feedbacks), rather than a large statistical sample size. These tightly coupled variables form a self-consistent causal chain where the physical fields validate one another. We have revised the manuscript to clarify that our conclusions are anchored in this solid observational framework, while explicitly noting that future model simulations are required to fully assess the event's predictability. To reinforce this process-based perspective and clearly state the regional significance of our empirical findings, the summary paragraph of the manuscript has been refined as follows:

L514-L521:

“In summary, the 2020–2024 Chukchi Sea recovery represents an extreme regional manifestation of recent Pacific Arctic sea-ice variability. Its development was sustained by the concurrence of Pacific-sector atmospheric, oceanic, and ice-dynamic processes that favored regional cooling, delayed melt, and late-season ice retention. By showing that a poleward-shifted Pacific–Arctic cyclonic anomaly can produce a local Chukchi Sea response distinct from the canonical PNA-related melt pathway, our results refine the existing PNA–sea ice framework and highlight the importance of regional circulation configuration in shaping Arctic sea-ice extremes.”



Response Fig. R1 | CESM-LE comparison of Chukchi Sea ice recovery and atmospheric anomalies. a) Observed and CESM-LE-simulated JAS Chukchi Sea total sea-ice area. The CESM-LE ensemble mean and ± 1 standard deviation spread are shown in blue, and the observed OSI SAF sea-ice area is shown in red. b) Ensemble mean Z500 anomalies and c) surface air temperature anomalies in CESM-LE for the 2020–2024 period, calculated relative to the 2002–2019 climatology. The model does not reproduce a coherent analogue of the observed 2020–2024 Chukchi Sea ice recovery or its associated poleward-shifted Pacific–Arctic cyclonic anomaly.

3. I have also recently read quite a few papers that make similar arguments, linking regional sea ice recovery to tropical-extratropical SST variability or related processes. It would be helpful for the authors to clarify the key implication of this study. If a PNA-like pattern can favor sea ice recovery, why could it not also favor rapid sea ice decline

during earlier periods? I feel that the current study still focuses too much on interpreting the results at a relatively surface level. A deeper discussion would help the community better understand the role of large-scale circulation in shaping summer Arctic sea ice changes.

Response:

We thank the reviewer for this insightful comment. We agree that the key implication of this study should be clarified more explicitly, particularly regarding how the same large-scale atmospheric framework can favor rapid sea-ice decline during some periods but regional recovery during others.

Our results show that PNA-related circulation can influence Chukchi Sea summer sea ice in different directions depending on the latitude and regional configuration of the associated anomaly center. In 2007, the PNA-related circulation anomaly was configured in a way that favored warm advection, less low cloud, and rapid summer ice loss over the Chukchi Sea. By contrast, during 2020–2024, the low-pressure anomaly shifted poleward and was located closer to the Bering Strait–Chukchi Sea sector, producing regional wind and thermodynamic conditions that favored summer ice retention. To explicitly highlight this bidirectional mechanism, we have reorganized the sequence of the Results sections. In the revised manuscript, we positioned this comparative diagnosis of the 2007 and 2020–2024 extremes immediately following the introduction of the 2020–2024 recovery event, allowing us to first establish how the regional positioning of the cyclonic anomaly shapes opposing localized sea-ice extremes before introducing the large-scale PNA framework analysis.

L203-L217:

“The MZD anomalies identified above highlight pronounced changes in the regional position of the Pacific–Arctic cyclonic anomaly. Since the Chukchi Sea lies close to the pathway of the Pacific–Arctic cyclonic anomaly between the Aleutian–North Pacific sector and the Bering–Chukchi region (Fig. 2a), its local circulation and thermodynamic conditions are likely sensitive to regional shifts in the cyclonic

anomaly center. We therefore compare the 2007 extreme ice-retreat year with the 2020–2024 recovery period to examine how different anomaly-center locations were associated with different local sea-ice conditions.

The year 2007 provides a representative low-ice case for this comparison. It marked the then-record minimum in Arctic sea-ice extent^{Error! Reference source not found.} and also corresponded to the lowest summer Chukchi Sea SIC within our analysis period (Fig. 2c). In this extreme retreat year, the Pacific–Arctic cyclonic anomaly was centered farther south over the Aleutian–North Pacific sector, forming a circulation configuration that favored Chukchi Sea ice loss (Fig. 4a) ...”

Crucially, the insight that meridional cyclonic displacement drives these sea-ice extremes directly inspired our PNA framework evaluation. We focus on using detailed observational diagnostics (including cloud cover, radiation, and ocean feedbacks) to uncover the exact physical mechanisms behind this event. Through these comprehensive diagnostics, we have recontextualized the physical meaning of the summer PNA mode. Our results demonstrate that variations in the summer PNA index reflect not just changes in background intensity but the specific meridional shifts of the Pacific–Arctic cyclonic anomaly center that drive regional thermodynamic pathways. To explicitly highlight this refined understanding and present the event's mechanisms accurately, we have revised the text in the Results section as follows:

L391-L405:

“Together, these findings clarify how Summer PNA-related circulation controls Chukchi Sea SIC through regional thermodynamic processes. Building on the established moisture-intrusion and longwave-warming pathway, our results show that the latitude and configuration of the Pacific–Arctic cyclonic anomaly further regulate Chukchi Sea SIC by modulating cloud cover, shortwave radiation, and ocean feedbacks. Variations in the REOF-based PNA index should therefore not be interpreted solely as changes in the intensity of the positive PNA background but also as reflecting the influence of meridional shifts in the Pacific–Arctic low-pressure

anomaly and the associated thermodynamic processes controlling local sea-ice variability. Because the Chukchi Sea is highly sensitive to the latitude and configuration of Pacific–Arctic circulation anomalies, this regional pathway helps explain how large-scale PNA-related circulation is translated into locally distinct sea-ice responses. These results refine the existing understanding of PNA-driven western Arctic sea-ice variability by highlighting the regional processes through which this large-scale circulation signal affects the Chukchi Sea.”

Based on this framing, we have significantly expanded the Discussion to provide a deeper interpretation of the event, explicitly linking the 2020–2024 recovery to tropical–extratropical SST variability and the recent slowdown in Arctic sea-ice loss. Beyond the previously examined potential influences of PDO and ENSO, we added recent literature on Arctic sea-ice loss slowdown, North Pacific wave-train influences, summer atmospheric circulation changes, and Pacific-sector variability to place the 2020–2024 recovery in a broader climate context. We also emphasize that the Chukchi Sea response cannot be explained solely by the sign or amplitude of PNA-related circulation, but depends critically on the regional position and structure of the Pacific–Arctic circulation anomaly. This revision clarifies why PNA-related circulation can favor rapid sea-ice decline during some periods but temporary regional recovery during others, depending on how the anomaly pattern modifies regional winds, heat and moisture transport, cloud–radiative effects, and ice–ocean processes.

L408-L430:

“The rapid decline of Arctic sea ice has transformed the Arctic into a “New Arctic” characterized by thinner, younger, and more atmosphere-sensitive sea ice^{Error! Reference source not found.}. In this new background state, Arctic sea ice no longer responds only as a slowly declining ice cover, but increasingly as a highly variable system that can amplify atmospheric perturbations into pronounced regional anomalies^{Error! Reference source not found.}. Recent studies have drawn attention to a broader slowdown in Arctic sea-ice loss over the past one to two decades, linking it to internal

variability, summer atmospheric circulation changes, North Pacific wave-train influences, and sea-ice volume processes^{Error! Reference source not found.}^{Error! Reference source not found.}^{Error! Reference source not found.}. Within this slowdown-era “New Arctic”, the 2020–2024 summer Chukchi Sea recovery stands out as an extreme regional manifestation, with anomalous ice retention persisting into September 2024 at low Arctic latitudes. Such events are important to be investigated because they represent extreme regional expressions of the recent slowdown-era variability and complicate seasonal sea-ice outlooks, Arctic navigation planning, and regional risk assessment^{Error! Reference source not found.}.

North Pacific oceanic warming and associated atmospheric circulation changes have been linked to recent sea-ice recovery in the central Arctic^{Error! Reference source not found.}. The 2020–2024 Chukchi Sea recovery examined here represents a sharper Pacific Arctic expression of this variability. Located immediately north of the Bering Strait, the Chukchi Sea is a low-latitude marginal sea highly sensitive to Pacific-sector atmospheric and oceanic anomalies. During 2020–2024, the poleward-shifted cyclonic anomaly placed this region under sustained coupled circulation-cloud-ocean–ice forcing, allowing regional cooling. This convergence of processes helps explain why the Chukchi Sea became the site of a pronounced low-latitude sea-ice reversal.”

Reference

Yu, L., Bi, H., Zhong, S., Zhang, P., & Sui, C. Decelerated Arctic Sea ice loss triggered by accelerated North Pacific warming over the past decade. *Communications Earth & Environment*, 6(1), 922(2025). <https://doi.org/10.1038/s43247-025-02882-1>

Wang, C., Su, H., Zhai, C., Zheng, J., Yu, S., Mo, H., ... & Jiang, L. (2025). Recent slowing of Arctic sea ice melt tied to multidecadal NAO variability. *Nature Communications*, 16(1), 8504. <https://doi.org/10.1038/s41467-025-63520-0>

Zhang, J. (2021). Recent slowdown in the decline of Arctic sea ice volume under increasingly warm atmospheric and oceanic conditions. *Geophysical Research Letters*, 48(18), e2021GL094780. <https://doi.org/10.1029/2021GL094780>

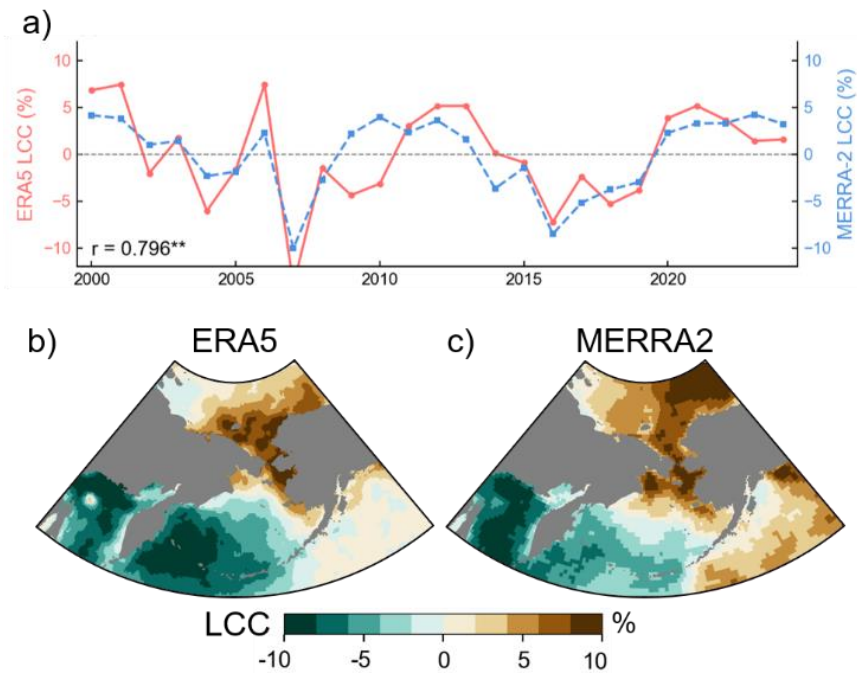
England, M. R., Polvani, L. M., Screen, J., & Chan, A. C. (2025). Minimal Arctic sea ice loss in the last 20 years, consistent with internal climate variability. *Geophysical Research Letters*, 52(15), e2025GL116175. <https://doi.org/10.1029/2025GL116175>

4. Cloud variations during these 4 years can be quite sensitive to the choice of reanalysis product. If MERRA-2 or CALIPSO is used, does the low level cloud change signal still hold?

Response:

We thank the reviewer for this valuable comment. To assess this uncertainty, we obtained monthly MERRA-2 low-level cloud fraction from the NASA Global Modeling and Assimilation Office. Specifically, we used the low-level cloud fraction variable (CLDLow) from the MERRA-2 M2TMNXRAD/tavgM_2d_rad_Nx radiation diagnostics product, and averaged the monthly data to the seasonal timescale used in this study.

The MERRA-2 results are broadly consistent with ERA5. The regional low-level cloud fraction from MERRA-2 is strongly correlated with that from ERA5 during the analysis period (Response Fig. R2a). In addition, the 2020–2024 low-level cloud anomalies show a similar spatial pattern and sign over the Chukchi Sea and adjacent Pacific Arctic sector in both datasets (Response Figs. R2b, c). These results suggest that the enhanced low-level cloud signal is not specific to ERA5.



Response Fig. R2 | Consistency of low-level cloud-cover anomalies between ERA5 and MERRA-2. a) Time series of JAS low-level cloud-cover (LCC) anomalies over the Chukchi Sea from ERA5 and MERRA-2 during 2000–2024. The two datasets show a strong positive correlation ($r = 0.796$, $p < 0.01$). b), c) Spatial patterns of JAS LCC anomalies from ERA5 and MERRA-2, respectively, showing broadly consistent enhanced low-level cloud cover over the Chukchi Sea during the recent recovery period.

Reviewer #2

General Comments: This paper discusses a recent recovery in sea ice extent in the Pacific Arctic, which the authors propose was triggered by a poleward shift in the Pacific North American (PNA) teleconnection pattern. The authors present a detailed argument that supports this hypothesis. I found the work compelling, but several stylistic and technical issues will require revision before publication.

Response:

We sincerely thank the reviewer for the constructive comments. We have revised the manuscript to improve both presentation and technical clarity, including reorganizing figures, adopting more consistent map projections, recalculating the EOF analysis using a consistent spatial domain, streamlining the Supplementary Information, and revising the Introduction and relevant figure captions.

Specific comments:

Major Issues

1. Presentation of Results: I found many of the figures to have issues with the way there were presented. There were inconsistencies in the map projections used, which detracted from readers' ability to assess the results. Mercator, Lambert Conformal, Polar Stereographic projections and some sort of 'birds-eye view (Fig 1b) are all used, often mixing projections within a single figure. I found this mixing disconcerting and made it a challenge to understand what is being presented. The Mercator projection is especially problematic at high latitudes as it distorts the area. The authors have chosen to include labels in the colorbars. This was confusing and detracted from the important role that the colorbars play in allowing readers to understand the results presented. Many figures contain multiple subpanels that end up being quite small and difficult to read. Figure 1b is especially problematic as the authors present 2 fields (sea ice concentration and SST. The way the fields are presented makes it difficult to interpret

what is going on.

Response:

Thank you very much for pointing these out. We fully agree and feel sorry for the inconsistencies. We have revised the figures substantially to improve clarity and consistency. We revised all the maps by adopting a consistent polar stereographic projection, except for Fig. 1a, which is retained as a 3D schematic overview. Secondly, we simplified Fig. 1b to emphasize the sea-ice edge and schematic shipping-route information, while removing SIC and SST background fields that distracted from the main message.

Furthermore, we revised the colorbars with clear tick marks and units throughout the main and supplementary figures. We also enlarged fonts and adjusted the layout of several multi-panel figures to improve readability within the available page format.

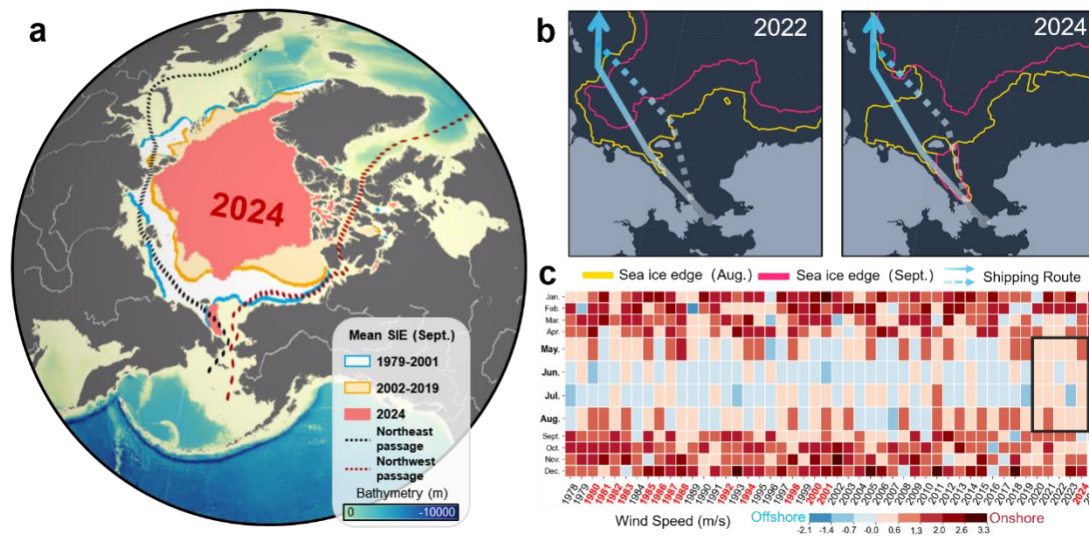


Fig. 1 | Observed anomalous summer sea-ice retention in the Chukchi Sea during 2020-2024 and its association with summer wind anomalies. a) September sea-ice-extent (SIE) during 1979–2024, highlighting anomalous sea-ice retention between the East Siberian coast and Wrangel Island in September 2024. Blue and orange contours show the mean September SIE for 1979–2001 and 2002–2019, respectively; red shading denotes 2024. Dashed lines indicate the Northeast and Northwest Passage

routes. **b)** August and September sea-ice edge positions in 2022 and 2024, defined by the 15% SIC contour. The solid blue lines denote the more direct near-coastal route along the Siberia, whereas the dashed blue lines indicate the offshore route passing north of Wrangel Island. **c)** Monthly onshore and offshore wind variability over the Chukchi Sea (66°N – 73°N , 180° – 160°W) from 1979 to 2025. The box with a black outline highlights persistent anomalous onshore winds in the melt season during the 2020–2024 sea-ice recovery; red-marked years indicate documented sea-ice retention events.

2. Calculation of EOFs: EOFs are a function of the domain used to calculate them. The authors do not provide information on the domain used. Based on Fig. 2 and Fig. 3, it appears (though I could be wrong) that different domains are used for EOF1 and EOF3. If true, it is problematic and needs to be corrected. I assume that the same domain was used, and the authors chose different domains. In this case, I don't see the reason why different domains were used. The Mercator projection is also an issue.

Response:

We thank the reviewer for pointing out this critical issue. We recognize that using inconsistent spatial domains for parts of the EOF analysis in the original submission lacked sufficient rigor, even though it was initially intended to highlight the regional North Pacific–North America wave-train structure. To rectify this and ensure full comparability between modes, we have thoroughly revised the analysis by recalculating all EOF modes using a single, consistent spatial domain of 35° – 75°N , 130°E – 130°W throughout the manuscript. Importantly, the recalculated EOF structures remain robust and fully support our original conclusions regarding the wave-train configuration and its impact on sea ice. Accordingly, we have updated the relevant figure captions to explicitly specify this unified EOF domain. Furthermore, in line with the reviewer's recommendation, all corresponding maps have been replotted using a Polar Stereographic projection, completely removing the Mercator projection from these

high-latitude figures to eliminate any spatial distortion.

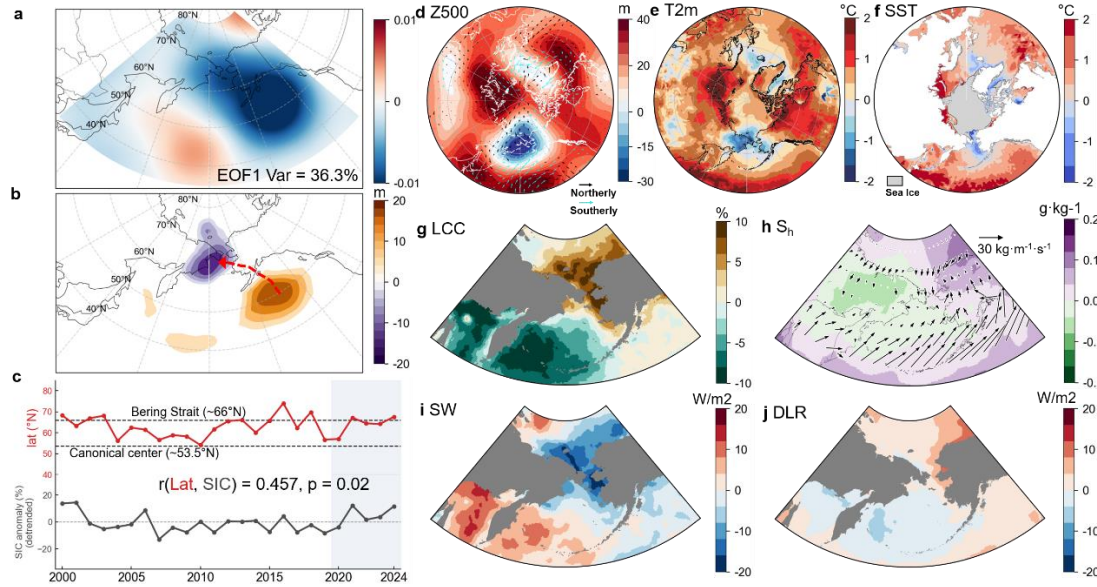


Fig. 2 | Summer (JAS) mean circulation anomalies over the Chukchi Sea during 2020–2024 and associated atmospheric thermodynamic anomalies. *a)* First empirical orthogonal function (EOF1) mode of JAS 500-hPa geopotential height (Z500) anomalies during 2002–2019, calculated over the North Pacific–Pacific Arctic sector (35°–75°N, 130°E–130°W). *b)* Difference between the 2020-2024 mean negative Z500 anomalies and those during 2002-2019; the dashed red arrow illustrates the pronounced northwestward migration of the cyclonic center toward the Bering Strait. *c)* Time series of the latitude of the anomalous low-pressure center and the detrended SIC anomalies during 2020-2024. *d)* Z500 anomalies and arrows denote anomalous meridional 10-m wind (V10) vectors, with black and light-blue colors distinguishing northerly and southerly components, respectively. *e)* 2-m air temperature (T2m), *f)* sea surface temperature (SST) with contemporaneous sea-ice extent (SIC > 15%) superimposed, *g)* low-level cloud cover (LCC), *h)* vertically integrated low-troposphere (1000-850 hPa) specific humidity (S_h), overlaid with black arrows representing vertically integrated water vapor flux vectors, *i)* net surface shortwave radiation (SW), and *j)* downward longwave radiation (DLR) anomalies. All anomalies are calculated relative to the 2002-2019 climatology.

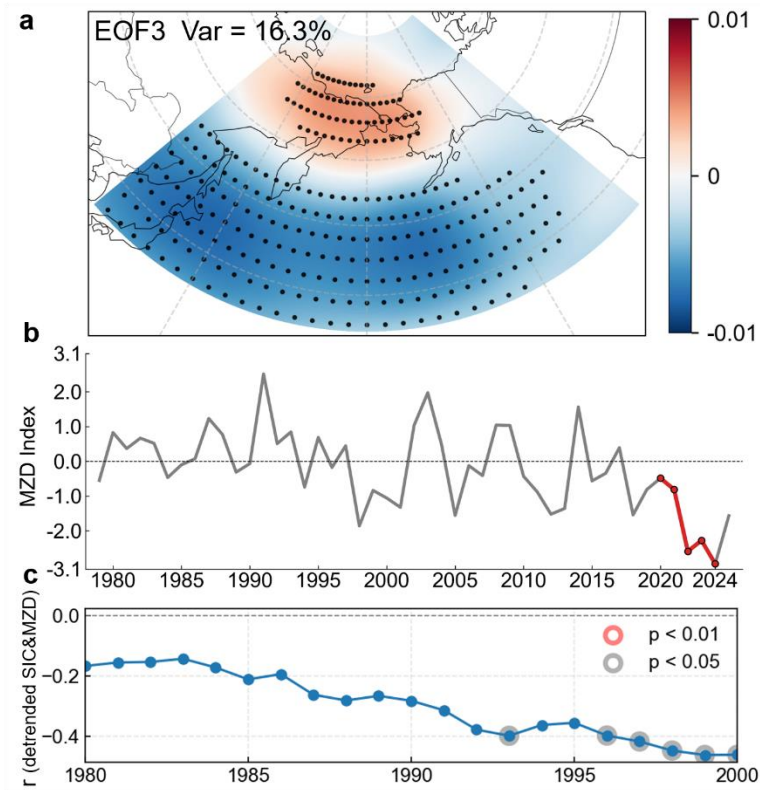


Fig. 3 | Relationship between the meridional Z500 dipole (MZD) mode and Chukchi sea-ice concentration during summer (JAS). *a)* Third empirical orthogonal function (EOF3) mode of summer (JAS) Z500 anomalies during 1979–2025, computed over the North Pacific–Pacific Arctic sector (35°–75°N, 130°E–130°W) and defined here as the MZD pattern. Stippling in *a)* indicates regions where the Z500 anomalies are statistically significant at the 95% confidence level. *b)* Standardized MZD index, highlighting its pronounced amplification during the 2020–2024 sea-ice recovery period and its historical low in 2024. *c)* A 26-year running correlation between detrended JAS Chukchi Sea SIC and detrended MZD index. Each data point is plotted at the beginning year of its 26-year window (e.g., the value at 2000 corresponds to the 2000–2025 period).

3. Excessive Supplementary Figures

There are 15 SFs. I assume that journal constraints forced the authors to have so many SFs. In my opinion, SFs should be used sparingly and curated to maximize impact.

Given the number of SFs, it appears the authors did not follow this approach. I think it is asking a lot of readers to look at so many SFs and one is left with the opinion that many of the important results are delegated to SFs that many readers will not consider. This detracts from the paper's impact.

Response:

We thank the reviewer for this constructive critique. The original inclusion of 15 Supplementary Figures stemmed from our attempt to transparently document the wide range of diagnostics supporting the atmosphere–ocean–sea-ice pathway—such as sea-ice thickness, ocean temperature, and atmospheric indices—while avoiding overly dense, multi-panel layouts. We completely agree that a more curated selection maximizes the manuscript's impact and prevents important results from being diluted. Following the reviewer's suggestion, we have thoroughly streamlined the supplementary materials by removing non-essential plots, consolidating overlapping panels, and replacing figures of well-established regional patterns with appropriate literature citations. Consequently, the number of Supplementary Figures has been successfully reduced from **15 to 8**. This substantial reduction simplifies the supporting material for better readability while fully preserving the core physical arguments of the study. All in-text citations have also been updated to ensure correct sequential ordering.

Minor Issues

4. Abstract. The 2007 sea ice extent minimum is not fully explained, which may confuse readers unfamiliar with Arctic sea ice variability.

Response:

We thank the reviewer for this insightful suggestion. We agree that introducing the 2007 sea-ice minimum in the Abstract without sufficient background could distract or confuse readers unfamiliar with the region's history. To sharpen the logical flow and enhance clarity, we have removed the mention of 2007 from the Abstract. The revised

segment of the Abstract reads as follows:

L28-L35:

“... Furthermore, we demonstrate that the Pacific–North American (PNA) mode was linked to summer Chukchi Sea ice concentration, with its influence expressed through the regional position of the associated Pacific–Arctic cyclonic anomaly. These findings identify the Chukchi Sea as a sensitive Pacific Arctic sector where natural regional circulation variability can generate abrupt, localized reversals in summer sea-ice loss, thereby offering a fresh perspective on the role of summer PNA-related circulation variability in Pacific-sector Arctic sea ice.”

5. The Introduction includes some results related to Fig. 2. I found this non-standard as I am a firm believer that the Introduction should summarize previous work and provide context for the results that follow.

Response:

Thanks for the comment. We fully agree and have addressed this by moving the Fig. 2-related results and corresponding text to the first Results subsection. The Introduction has been revised to focus on previous work, research context, and study motivation.

L988-L112:

“This sustained recovery raises a key question: what atmospheric conditions favored enhanced late-summer sea-ice persistence in a region that has experienced some of the most rapid ice loss in the Arctic? Previous studies have linked Pacific Arctic sea-ice variability to a range of large-scale circulation modes, including Arctic-centered variability^{Error! Reference source not found..Error! Reference source not found..Error! Reference source not found.} and midlatitude–Arctic teleconnections^{Error! Reference source not found..Error! Reference source not found..Error! Reference source not found.}. However, it remains unclear whether these established frameworks can adequately explain the recent recovery episode. To address this

question, we combine satellite observations, modeled sea-ice thickness, and atmospheric and oceanic reanalysis datasets to characterize the dynamical and thermodynamic conditions associated with the recovery period. We further examine whether the circulation anomalies can be interpreted within existing teleconnection frameworks or instead reflect a previously unrecognized mode of variability. By identifying the mechanisms responsible for this anomalous sea-ice state, our study provides new insight into the Arctic sea-ice extremes and their implications for environmental change and operational risks along increasingly important Arctic shipping routes.”

6. Line 78: Moore et al (2025) emphasized the role that a large-scale convergence event in Feb 2024 played in the persistence of sea ice in the southern Chukchi Sea through the following summer.

Response:

Thanks for providing a more complete background for the 2024 ice-retention event by acknowledging the role of wintertime ice accumulation and thickening prior to the following summer. We have revised the Introduction to include the February 2024 sea-ice transport and convergence event discussed by Moore et al. (2025).

L75-L79:

“Anomalous onshore winds in 2024 persisted through nearly the entire freezing and melting seasons^{Error! Reference source not found.}, favoring substantial sea-ice accumulation in the Chukchi Sea. In particular, a severe ice transport and convergence event in February led to pronounced clustering and thickening of the winter sea ice^{Error! Reference source not found.}, followed by sustained onshore ice advection during June and July^{Error! Reference source not found.}.”

Reviewer #3

General Comments: The paper documents an unusual five-year reappearance of summer sea ice in the Chukchi Sea during 2020–2024, culminating in the September 2024 congestion of the Northeast Passage. The authors argue that this recovery was driven by a poleward-shifted summer PNA pattern, which produced persistent northerly winds, enhanced cloud cover, reduced shortwave absorption, colder ocean and air temperatures, and a self-reinforcing cooling feedback. They further argue that the PNA index provides a unified framework for understanding both the 2007 extreme sea-ice retreat and the 2020–2024 recovery.

The observation is interesting and the paper brings together a useful set of atmospheric, oceanic, and sea-ice diagnostics. However, the manuscript repeatedly makes claims that are stronger than the evidence supports. In particular, it treats a short regional anomaly as evidence for a structural shift in a hemispheric teleconnection pattern, relies heavily on correlations and EOF-based arguments, and does not sufficiently establish causality or future predictive value. I think the paper could be much stronger if reframed as a diagnostic case study of a recent regional anomaly, rather than as evidence for a robust new PNA-driven sea-ice recovery mechanism. Below are some major comments.

Response:

We sincerely thank the reviewer for this profound and constructive assessment. We completely agree that our original phrasing overextended the evidence by implying a structural shift in a hemispheric teleconnection. Taking your guidance, we have comprehensively reframed the manuscript as a diagnostic case study centered on this remarkable regional anomaly, avoiding any claims of a persistent structural change in the PNA mode or a demonstrated predictive mechanism. To ensure a more balanced and cautious presentation, we have thoroughly revised the title, abstract, section headings, and main text to eliminate overly causal or predictive language.

In the revised manuscript, **Result Section 1** first presents the 2020–2024 Arctic sea-ice recovery and its corresponding atmospheric circulation anomalies. This immediately leads into **Result Section 2** with a direct comparative diagnosis of the 2007 extreme sea-ice retreat and the 2020–2024 recovery periods. This comparison clearly demonstrates that these sea-ice extremes depend not just on the intensity of the cyclonic anomaly, but crucially on its regional position.

This diagnostic finding naturally motivates **Result Section 3: REOF-based PNA** index exhibits a strong correlation with Chukchi Sea SIC precisely because it captures the meridional shifts of the cyclonic anomaly center. Compared to the broader western Arctic, the Chukchi Sea occupies a unique geographic position directly along this specific anomaly pathway. This unique positioning allows the PNA framework to successfully reconcile two opposing sea-ice extremes—the 2007 extreme retreat and the 2020–2024 recovery. In both cases, the large-scale circulation signal is translated into locally distinct, yet physically consistent, thermodynamic responses (modulating cloud cover, shortwave radiation, and ocean feedbacks) depending on the cyclonic anomaly's latitude. Therefore, rather than framing the event as a structural change in the large-scale PNA pattern, the revised manuscript highlights how large-scale atmospheric forcing exerts a refined, sector-specific control on Arctic sea ice. It demonstrates that the REOF-based PNA index serves as an effective metric under existing climate modes to bridge large-scale circulation variability with localized thermodynamic processes.

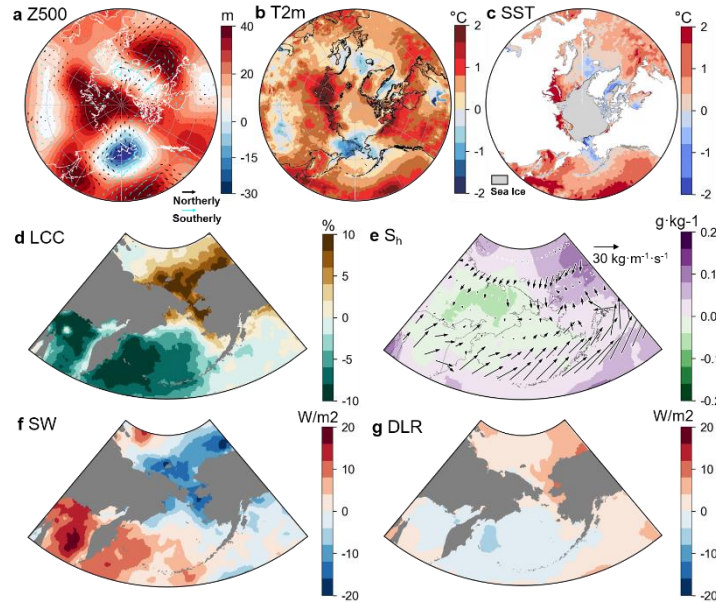
Specific comments:

1. The period of interest is very short. The main result is based on only five summers, and much of the signal appears to be dominated by 2024. The authors should test whether the results hold if 2024 is removed, or through a leave-one-year-out analysis across 2020–2024.

Response:

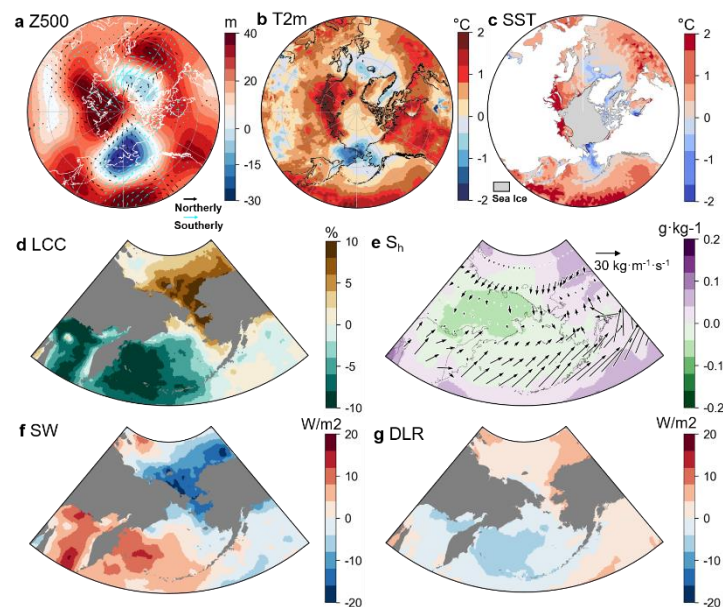
We appreciate this suggestion. According to the comment, we performed a leave-one-year-out sensitivity analysis for the 2020–2024 period: repeated the composite analysis five times, each time excluding one year from 2020 to 2024, and examined the same circulation, thermodynamic, cloud, moisture, and radiation variables used in the main analysis.

The results in Response Figs. R3–R7 show that the key anomaly patterns are not solely controlled by 2024. Even when 2024 is excluded, the main circulation feature remains evident: a poleward-shifted cyclonic/Z500 anomaly center near the Bering Strait–Chukchi Sea sector, accompanied by regional wind and thermodynamic anomalies favorable for summer sea-ice retention. Similar patterns are also obtained when each of the other years is excluded. Although the magnitude of individual anomalies varies among the leave-one-year-out composites, the spatial structure of the mechanism remains broadly consistent across the tests.

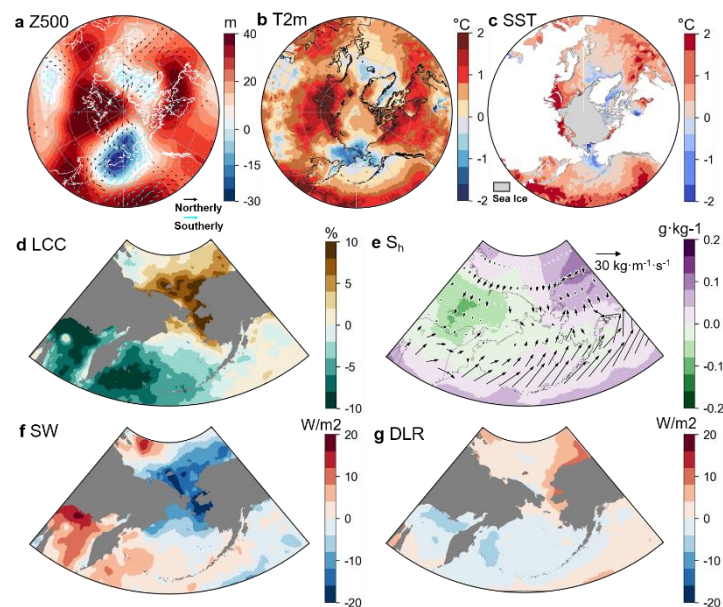


Response Fig. R3 | Leave-one-year-out composite excluding 2024. Panels (a–g) show, respectively, Z500 and meridional 10-m wind anomalies, T2m anomalies, SST anomalies with the contemporaneous sea-ice extent ($SIC > 15\%$) superimposed, LCC anomalies, vertically integrated 1000–850 hPa specific humidity and water vapor flux

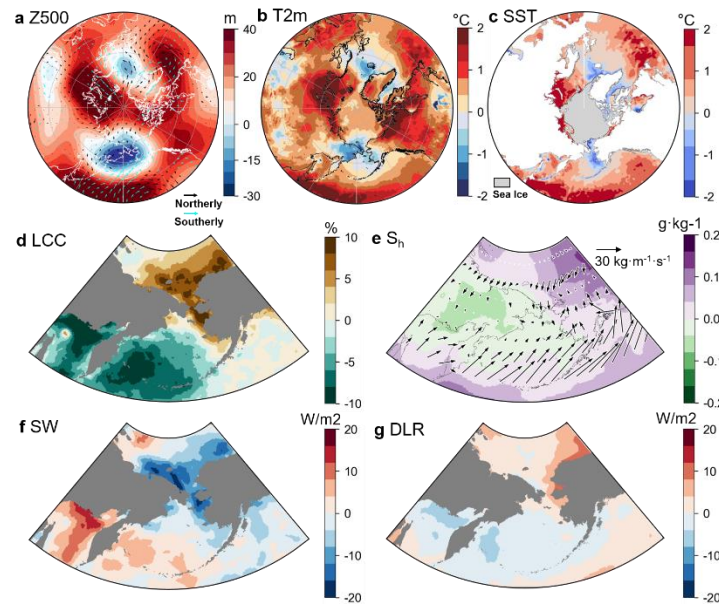
anomalies, net surface shortwave radiation anomalies, and downward longwave radiation anomalies. All anomalies are relative to the 2002–2019 climatology.



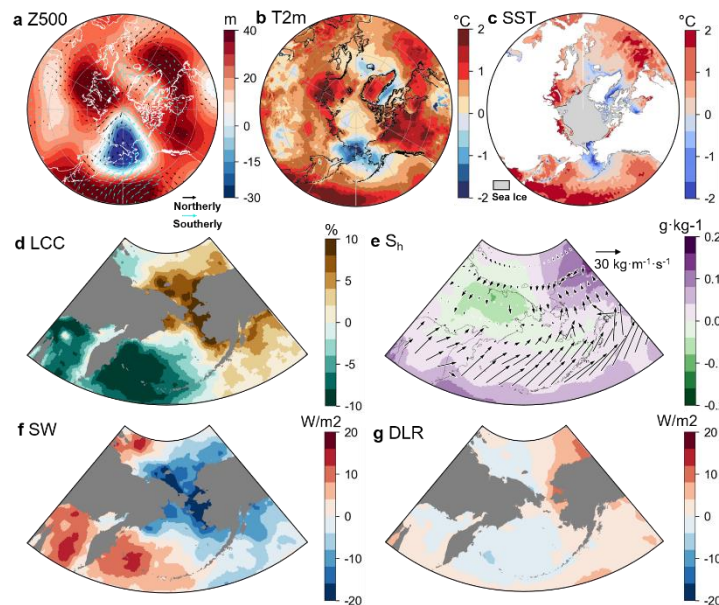
Response Fig. R4 | Leave-one-year-out composite excluding 2023. Same as Fig. R3, but excluding 2023 from the 2020–2024 composite.



Response Fig. R5 | Leave-one-year-out composite excluding 2022. Same as Fig. R3, but excluding 2022 from the 2020–2024 composite.



Response Fig. R6 | Leave-one-year-out composite excluding 2021. Same as Fig. R3, but excluding 2021 from the 2020–2024 composite.



Response Fig. R7 | Leave-one-year-out composite excluding 2021. Same as Fig. R3, but excluding 2020 from the 2020–2024 composite.

2. The causal language is too strong. Terms such as “triggered,” “drove,” and “self-reinforcing feedback” require more than contemporaneous composites and correlations.

Response:

We thank the reviewer for this important comment. We have revised the manuscript throughout to avoid overstating causality while preserving the mechanistic interpretation supported by our analyses.

Specifically, we revised the manuscript title from “*A poleward shift in the Pacific–North American pattern triggered summer sea-ice recovery in the Pacific Arctic*” to “*Unexpected return of late-summer sea ice in the Pacific Arctic under persistent poleward-shifted cyclonic circulation.*” This revision avoids implying that the recovery was directly triggered by a structural change in the PNA itself. Instead, it emphasizes the observed regional circulation change most relevant to the recovery: the persistent poleward displacement of the Pacific–Arctic cyclonic anomaly center. Our analyses show that this displacement is most closely related to the REOF-based PNA among the established large-scale atmospheric modes examined here, but we do not interpret it as being caused solely by changes in the PNA. To further align the manuscript with this diagnostic perspective, we have reorganized the Results section by moving the comparative analysis of the 2007 and 2020–2024 extremes forward to the second section, allowing the empirical observations to guide the narrative before introducing the large-scale index analysis in the third section.

The subsequent heading of result-section 2 “*Contrasting sea-ice extremes under canonical and noncanonical positive PNA conditions*” was revised to “*Contrasting Chukchi Sea ice extremes linked to the regional position of Pacific–Arctic cyclonic anomalies*” Similarly, the heading of result-section 3 “*Summer sea-ice variability in the Chukchi Sea captured by the PNA index*” was changed to “*Chukchi Sea summer sea-ice variability within the PNA-related circulation framework*” which better reflects that the PNA index provides a large-scale diagnostic framework rather than fully explaining all causal aspects of local SIC variability.

In addition to these structural adjustments, we have thoroughly refined the text across the Abstract, Results, and Discussion sections to ensure that the scientific

language precisely reflects the observational and diagnostic nature of our analysis. To strictly separate process-based empirical evidence from formal causal attribution, deterministic verbs (such as "triggered," "drove," or "caused") have been carefully replaced with more precise, description-oriented terms (including "coincided with," "linked to," and "consistent with") where appropriate.

Importantly, while we removed the phrase "self-reinforcing feedback" from the Abstract to maintain a conservative presentation, the full physical chain of the coupled dynamic–thermodynamic mechanism remains completely intact and robustly supported by our multi-source diagnostics. The relevant part of the revised Abstract now reads:

L24-L35:

“...Here we show that this recovery coincided with a persistent poleward-shifted Pacific–Arctic cyclonic anomaly near the Bering Strait. This shifted circulation produced a coupled dynamic–thermodynamic response, with Arctic cold advection, enhanced low-cloud cooling, reduced oceanic heat, and delayed seasonal thinning acting together to sustain late-summer ice retention. Furthermore, we demonstrate that the Pacific–North American (PNA) mode was linked to summer Chukchi Sea ice concentration, with its influence expressed through the regional position of the associated Pacific–Arctic cyclonic anomaly. These findings identify the Chukchi Sea as a sensitive Pacific Arctic sector where natural regional circulation variability can generate abrupt, localized reversals in summer sea-ice loss, thereby offering a fresh perspective on the role of summer PNA-related circulation variability in Pacific-sector Arctic sea ice.”

3. The PNA argument is conceptually unclear. The canonical positive PNA is described as promoting Chukchi sea-ice loss, but the 2020–2024 recovery is also attributed to the PNA because its structure shifted poleward. It is unclear whether the PNA index is measuring canonical PNA amplitude, anomaly latitude, or simply covarying with another regional circulation pattern.

Response:

First, we have explicitly clarified in the revised text that this study employs a Rotated Empirical Orthogonal Function (REOF)-based PNA index rather than a traditional fixed pointwise definition, which inherently accounts for spatial and seasonal variations. Unlike the classic pointwise approach (Wallace and Gutzler, 1981) that relies on rigid geographic centers of action, the REOF-based index is derived from the full Northern Hemisphere 500-hPa geopotential height anomaly field. This mathematical approach allows the index to robustly represent the amplitude and phase of the coherent wave-train mode as a whole, even when its centers of action experience seasonal or regional shifts. This is particularly crucial for the summer months, when the PNA-related circulation is less canonical and often exhibits regional displacements, a methodology aligned with recent studies on western Arctic summer sea ice (Liu et al., 2021; L'Heureux et al., 2008; Zhang et al., 2020). We have now explicitly detailed this methodological basis in [L295-L300](#) and [L530-L534](#).

[L295-L300:](#)

“...The PNA index used here follows an established REOF-based definition of Northern Hemisphere 500-hPa circulation variability^{Error! Reference source not found.}, rather than a fixed pointwise definition based on height anomalies at several prescribed centers of action⁰. It was commonly used to provide a large-scale measure of the amplitude and phase of the coherent North Pacific–North American wave-train mode identified from the full Z500 field^{Error! Reference source not found..Error! Reference source not found..Error!}Reference source not found.”

[L530-L534:](#)

“...Compared with pointwise indices based on a linear combination of height anomalies at several fixed centers of action⁰, the REOF-based approach identifies the PNA as a coherent circulation mode from the full hemispheric Z500 field and has been used in previous studies of summer PNA-like wave trains and Arctic sea-ice variability^{Error! Reference source not found..Error! Reference source not found..Error! Reference source not found.}”

Second, we clarified why the REOF-based PNA index remains useful for analyzing the 2020–2024 Chukchi Sea recovery. The index is more appropriate for examining how large-scale PNA-related circulation is connected to regional Pacific–Arctic circulation changes. Our analysis shows that the 2020–2024 recovery occurred under a weakened positive PNA state accompanied by a poleward-shifted Pacific–Arctic cyclonic anomaly center. Importantly, the REOF-based PNA index is significantly correlated with the latitude of this cyclonic anomaly center ($r = -0.64$, $p < 0.01$), indicating that this regional circulation displacement is closely linked to the REOF-based PNA framework. This clarification has been added in [L315-L328](#) and [L391-L405](#).

[L315-L328](#):

“...The 2020–2024 recovery occurred under a weakened positive PNA phase, allowing these years to remain statistically consistent with the negative SIC–PNA relationship and helping preserve the recent-window correlation. Rather than showing the reduced ice-loss tendency under a weakened positive PNA phase, the 2020–2024 period exhibited even more pronounced sea-ice recovery, suggesting that the Chukchi Sea response involves additional regional processes beyond the conventional western Arctic positive-PNA ice-loss pathway. As suggested by the contrasting circulation configurations associated with the 2007 extreme retreat and the 2020–2024 recovery, the latitudinal displacement of the Pacific–Arctic cyclonic anomaly is relevant to Chukchi Sea SIC not only through the previously emphasized moisture-intrusion pathway but also through local cloud-cover and radiation effects. The significant correlation between the REOF-based PNA index and the latitude of the Pacific–Arctic low-pressure center during 2000–2024 ($r = -0.64$, $p < 0.01$; Fig. 5d) further links the PNA index to this regional circulation displacement...”

[L391-L405](#):

“Together, these findings clarify how Summer PNA-related circulation controls

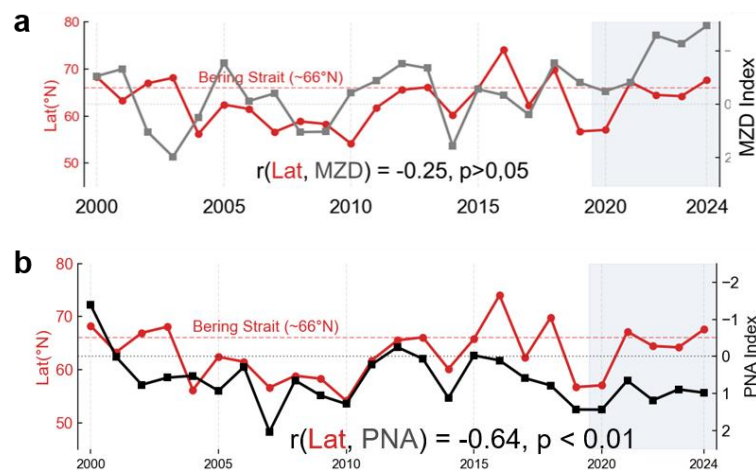
Chukchi Sea SIC through regional thermodynamic processes. Building on the established moisture-intrusion and longwave-warming pathway, our results show that the latitude and configuration of the Pacific–Arctic cyclonic anomaly further regulate Chukchi Sea SIC by modulating cloud cover, shortwave radiation, and ocean feedbacks. Variations in the REOF-based PNA index should therefore not be interpreted solely as changes in the intensity of the positive PNA background but also as reflecting the influence of meridional shifts in the Pacific–Arctic low-pressure anomaly and the associated thermodynamic processes controlling local sea-ice variability. Because the Chukchi Sea is highly sensitive to the latitude and configuration of Pacific–Arctic circulation anomalies, this regional pathway helps explain how large-scale PNA-related circulation is translated into locally distinct sea-ice responses. These results refine the existing understanding of PNA-driven western Arctic sea-ice variability by highlighting the regional processes through which this large-scale circulation signal affects the Chukchi Sea.”

Finally, we have systematically evaluated alternative atmospheric patterns and confirmed that neither climate modes nor regional indices provide a more appropriate long-term framework than the REOF-based PNA. During our study period, neither the Arctic Oscillation (AO) nor the Arctic Dipole (AD) showed a significant correlation with Chukchi Sea SIC, allowing us to exclude them as primary drivers. Furthermore, while the regional MZD captures the localized circulation contrast during the 2020–2024 recovery, it explains a limited variance of 16.3% and does not significantly correlate with the long-term latitude shifts of the cyclonic center $r = -0.25$, $p > 0.05$, Response Fig. R8a). In contrast, the REOF-based PNA index demonstrates a far superior capability in capturing this meridional displacement ($r = -0.64$, $p < 0.01$, Response Fig. R8b), establishing it as a much more effective framework for tracking the key circulation features linked to sea-ice variability. We do not exclude the potential influence of other regional circulation processes or ocean–ice feedbacks on the 2020–2024 recovery; rather, our comparison indicates that, among the indices examined here,

the REOF-based PNA provides the most relevant established large-scale framework for linking Chukchi Sea SIC variability with the meridional displacement of the Pacific–Arctic cyclonic anomaly center. This corresponding explanation has now been integrated into the Discussion section in [L470-L488](#).

[L470-L488](#):

“...At the same time, we cannot fully exclude the possibility that other modes of atmospheric variability also contributed to the recent circulation configuration. However, the AO and AD show no significant correlation with Chukchi Sea SIC during the period including the recent recovery years, suggesting that they do not provide a primary explanation for the 2020–2024 recovery. The MZD, in contrast, is better interpreted as a regional diagnostic of the meridional displacement of the Pacific–Arctic cyclonic anomaly rather than as an independent climate mode. The poleward displacement of the Pacific–Arctic cyclonic anomaly therefore represents a regional circulation configuration superimposed on the broader Pacific–Arctic wave-train background. In this context, the REOF-based PNA index serves as a valuable framework for describing this large-scale background. However, available evidence is currently insufficient to conclude whether the 2020–2024 recovery stems from a structural shift in the PNA mode; rather, our findings demonstrate that the influence of PNA-related circulation on Chukchi Sea SIC remains contingent upon the regional configuration of the associated Pacific–Arctic cyclonic anomaly. Given the rarity of the 2020–2024 multi-year recovery and late-summer ice-retention event, its recurrence and predictability will require longer records and targeted model experiments, including large-ensemble simulations.”



Response Fig. R8 | Comparison of circulation indices and the low-pressure center latitude (2000–2024). **a)** Correlation with the regional MZD index ($r = -0.25, p > 0.05$), which fails to quantitatively track the long-term meridional displacement. **b)** Correlation with the REOF-based PNA index ($r = -0.64, p < 0.01$; corresponding to Fig. 5c in the main text). The strong coupling indicates that the PNA index effectively captures the poleward shift of the cyclonic center toward the Bering Strait (dashed line), thereby regulating the thermodynamic forcing on Chukchi Sea SIC. Light blue shading denotes the 2020–2024 recovery period

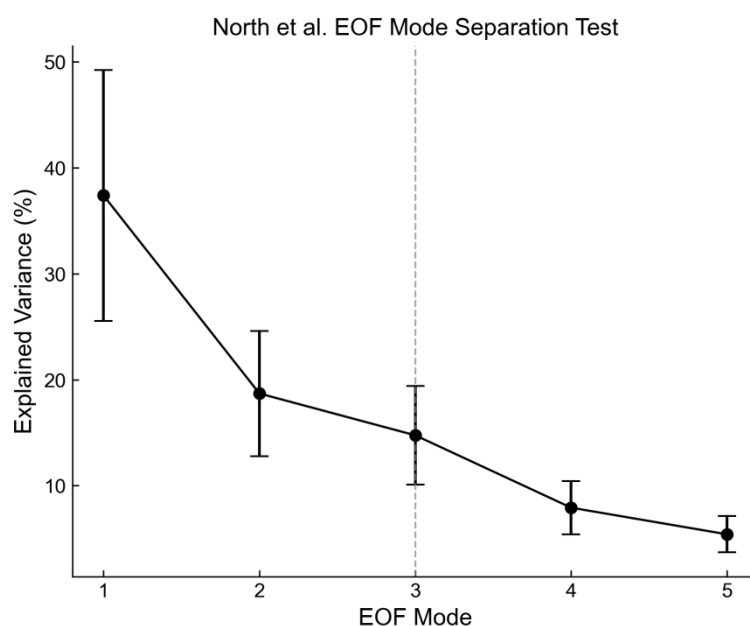
Reference:

Wallace, J. M., & Gutzler, D. S. Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly weather review*, 109(4), 784-812 (1981). [https://doi.org/10.1175/1520-0493\(1981\)109<0784:TITGHF>2.0.CO;2](https://doi.org/10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2)

4. The MZD argument is weak as currently presented. EOF3 explains only 16.3 percent of Z500 variance, and the authors acknowledge that the MZD has only a weak relationship with SIC over the full record. They should test EOF mode separation, for example using a North et al. eigenvalue separation test, and clarify whether this mode is statistically robust.

Response:

We thank the reviewer for this helpful suggestion. Following the reviewer's recommendation, we have now added a North et al (1982) eigenvalue separation test to further assess the robustness of the EOF modes (Response Fig. R9). The test indicates that EOF3 is not fully separated from neighboring modes within sampling uncertainty. We therefore further clarified in the revised manuscript that the MZD is not interpreted as a statistically independent or dominant mode controlling Chukchi Sea SIC. Instead, it is retained only as a diagnostic pattern that helps identify the Z500 anomaly structure associated with the recent recovery period. In particular, EOF3 highlights a meridional dipole-like Z500 anomaly that is temporally consistent with the poleward displacement of the Pacific–Arctic cyclonic anomaly during 2020–2024.



Response Fig. R9 | North et al. eigenvalue separation test for the leading Z500 EOF modes. Explained variance of the first five EOF modes of Z500 anomalies. Error bars indicate sampling uncertainty estimated following North et al (1982). The dashed vertical line marks EOF3, which corresponds to the meridional Z500 dipole pattern discussed in the manuscript.

Accordingly, we have revised the text to make this limited role explicit. The main interpretation is now placed more clearly on the REOF-based PNA index and the associated Z500 anomaly fields, while the MZD is presented only as supporting diagnostic evidence for the source and structure of the recent circulation anomaly.

L167-L174:

“The higher-order EOF modes reveal an additional circulation structure associated with the recent poleward-shifted anomalies. In particular, the third EOF mode (EOF3) explains 16.3% of the total summer Z500 variance and captures a distinct meridional pressure dipole over the North Pacific–Pacific Arctic sector, with its northern center extending over the Chukchi Sea (Fig. 3a). We define this mode as the Meridional Z500 Dipole (MZD) in this study. Despite not being the leading mode, the MZD provides a meaningful representation of the meridional displacement of Pacific–Arctic cyclonic anomalies associated with the recent recovery period.”

L462-L470:

“These local dynamic–thermodynamic processes were embedded within a broader Pacific–Arctic circulation framework. The REOF-based PNA index describes the large-scale North Pacific–Arctic wave-train background and its connection to Chukchi Sea summer SIC, whereas the MZD more directly diagnoses the regional meridional displacement of the cyclonic anomaly associated with the 2020–2024 recovery. The enhanced MZD-like pattern during 2020–2024 indicates that the recovery was associated with a northwestward displacement of summer Pacific–Arctic circulation anomalies. This displacement may be related to broader North Pacific atmospheric variability, including the observed poleward shift of the North Pacific storm track^{Error! Reference source not found.}.”

L475-L477:

“...The MZD, in contrast, is better interpreted as a regional diagnostic of the meridional displacement of the Pacific–Arctic cyclonic anomaly rather than as an

independent climate mode...

Reference:

North, G. R., Bell, T. L., Cahalan, R. F., & Moeng, F. J. (1982). Sampling errors in the estimation of empirical orthogonal functions. *Monthly weather review*, 110(7), 699-706.

5. The 26-year running correlation needs much more justification. The window length appears arbitrary, adjacent windows share 25 years of data, and significance is likely overstated without accounting for autocorrelation and overlapping samples. Sensitivity to 15-, 20-, and 30-year windows would help.

Response:

We thank the reviewer for this important comment. We agree that the 26-year window requires clearer justification and that adjacent running windows are not statistically independent. We have therefore revised the *L308-L312* and clarified that the running-correlation analysis is used as a diagnostic tool to examine multidecadal changes in the SIC–PNA relationship, rather than as a formal test based on independent temporal samples.

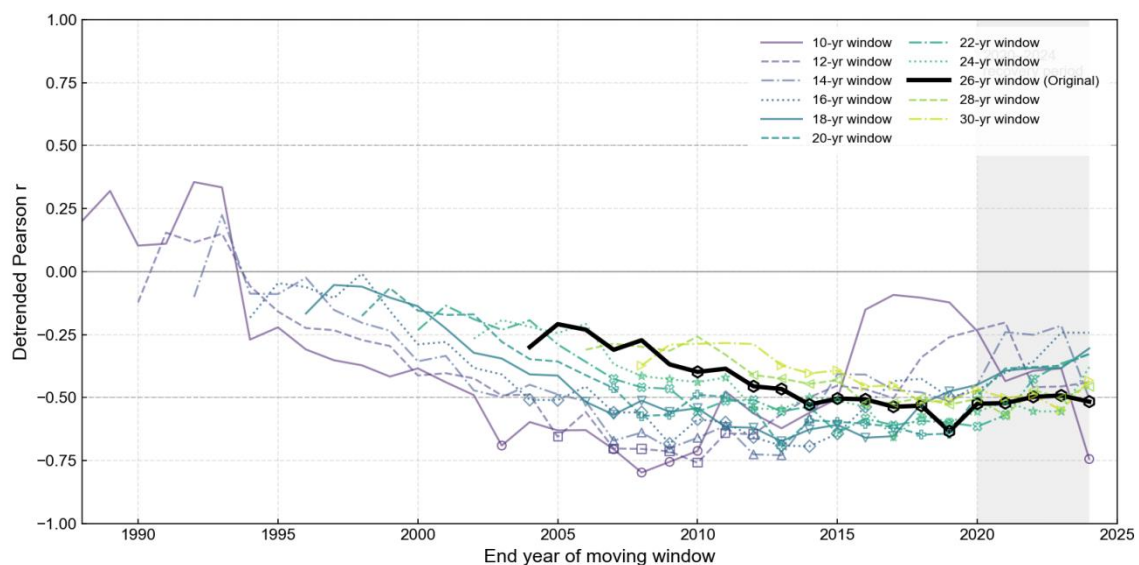
L308-L312:

“The running correlation suggests a strengthening of the detrended SIC–PNA relationship from the 1990s onward (red circle in Fig. 5c). This strengthening broadly coincided with the transition of the PNA toward a predominantly positive multidecadal background phase, consistent with previous understanding that positive PNA conditions are associated with reduced sea ice over the western Arctic

not found.”

The 26-year window was retained because it spans the post-2000 period to the end of the record, thereby including both the long-term Chukchi Sea ice decline and the

recent 2020–2024 recovery. This window length is also close to the 25-year interval used in previous work to examine the relationship between western Arctic sea ice and the PNA index (Liu et al., 2021). However, we agree that the interpretation should not rely on this single window length. To address this concern, we performed a window-length sensitivity test using multiple moving windows from 10 to 30 years, with the original 26-year window highlighted for reference (Response Fig. R10). The results show that the negative SIC–PNA relationship is generally preserved for medium-to-long windows, suggesting that the 26-year result is not an artifact of a single arbitrary window choice. Shorter windows exhibit larger variability, with the 10-year window showing particularly pronounced fluctuations (purple line in Response Fig. R10), reflecting the greater sensitivity of short-window correlations to endpoint years and recent circulation changes.



Response Fig. R10 | Window-length sensitivity of SIC–PNA running correlations.

Running correlations between detrended JAS Chukchi Sea SIC anomalies and detrended JAS PNA anomalies were recalculated using multiple moving-window lengths from 10 to 30 years. The original 26-year window used in the main analysis is highlighted in black. Open symbols indicate correlations with $p < 0.05$ and are shown only as a visual guide because adjacent moving windows are not statistically

independent. The grey shading marks the final years of the record.

In addition, we clarified why the 2000–2025 window still shows a significant negative SIC–PNA correlation despite the different local mechanisms during 2020–2024. The recovery occurred under a weakened positive PNA state, which is consistent with the overall negative SIC–PNA relationship. However, the poleward-shifted Pacific–Arctic cyclonic anomaly indicates that the local circulation pathway differed from the earlier positive-PNA ice-loss pathway. Thus, the long-window correlation is useful for identifying the statistical relevance of the PNA to Chukchi Sea SIC variability, but it cannot by itself distinguish changes in the local mechanism.

L315-L331:

“The 2020–2024 recovery occurred under a weakened positive PNA phase, allowing these years to remain statistically consistent with the negative SIC–PNA relationship and helping preserve the recent-window correlation. Rather than showing the reduced ice-loss tendency under a weakened positive PNA phase, the 2020–2024 period exhibited even more pronounced sea-ice recovery, suggesting that the Chukchi Sea response involves additional regional processes beyond the conventional western Arctic positive-PNA ice-loss pathway. As suggested by the contrasting circulation configurations associated with the 2007 extreme retreat and the 2020–2024 recovery, the latitudinal displacement of the Pacific–Arctic cyclonic anomaly is relevant to Chukchi Sea SIC not only through the previously emphasized moisture-intrusion pathway, but also through local cloud-cover and radiation effects. The significant correlation between the REOF-based PNA index and the latitude of the Pacific–Arctic low-pressure center during 2000–2024 ($r = -0.64$, $p < 0.01$; Fig. 5c) further links the PNA index to this regional circulation displacement. This linkage may help explain why the PNA remains closely related to Chukchi Sea SIC, but the specific physical processes through which PNA-related circulation affects this region require further examination.”

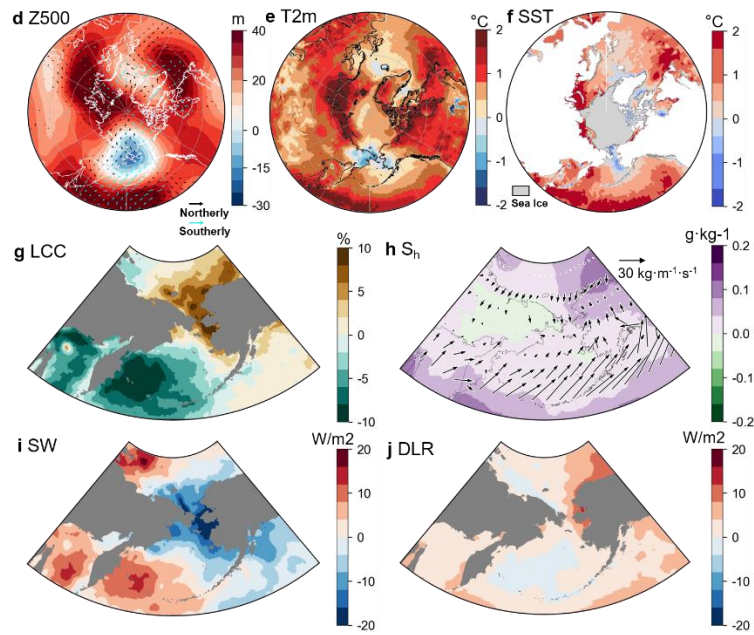
Reference:

Liu, Z. et al. Acceleration of western Arctic sea ice loss linked to the Pacific North American pattern. *Nature Communications*, 12(1), 1519(2021).
<https://doi.org/10.1038/s41467-021-21830-z>

6. The 2002–2019 baseline may exaggerate the apparent recovery because it is the period of rapid sea-ice decline. Key figures should be repeated using a standard climatology such as 1991–2020 to test whether the recovery framing survives.

Response:

We thank the reviewer for this helpful suggestion. We agree that the choice of baseline can affect the apparent magnitude of anomalies. To test whether this interpretation depends on the baseline choice, we repeated the key anomaly analysis using the standard 1991–2020 climatology. The main anomaly patterns remain evident, including the poleward-shifted Pacific–Arctic cyclonic anomaly, anomalous northerly winds, cold conditions over the Chukchi Sea, reduced surface shortwave absorption, cooler SSTs, and enhanced late-summer sea-ice persistence (Response Fig. R11). Therefore, although the anomaly magnitude is sensitive to the baseline period, the recovery signal and the associated circulation–ice mechanism are not artifacts of the 2002–2019 baseline.



Response Fig. R11 | Atmospheric, oceanic, and sea-ice anomalies during 2020–2024 relative to the 1991–2020 climatology. The key circulation, thermodynamic, radiation, SST, and sea-ice anomaly patterns remain broadly consistent with those obtained using the 2002–2019 baseline, indicating that the main recovery signal and associated circulation–ice mechanism are robust to the choice of climatological reference period.

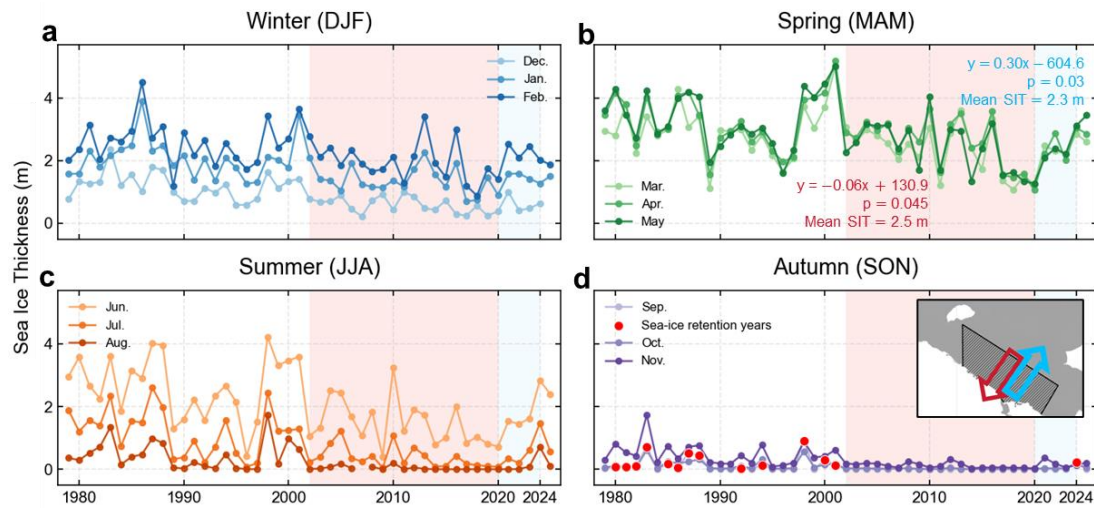
The original choice of the 2002–2019 baseline was deliberate and physically motivated: it delineates the modern "low-ice regime" or "new normal" of the Chukchi Sea, a period during which late-summer coastal ice retention had virtually disappeared. By benchmarking against this recent period, our study highlights an abrupt and unexpected interruption of the ongoing rapid sea-ice decline. Importantly, this 2020–2024 event is characterized not merely by statistical anomalies, but by a substantial physical return of sea ice, as evidenced by the absolute increases in both sea-ice concentration (SIC) and thickness (SIT; Supplementary Fig. 2) during spring and summer.

Furthermore, defining this event as a recovery relative to the recent low-ice state

is conceptually aligned with the latest literature. For instance, Moore et al. (2025, *npj CAS*) similarly contrasted the remarkable 2024 ice return with the preceding decades of drastically reduced summer sea ice. We have added a clarifying discussion in the revised manuscript to explicitly state that while the 2020–2024 anomaly does not represent a permanent return to the heavy-ice conditions of the early satellite era, it constitutes a physically robust, regime-specific recovery relative to the post-2000 low-ice background.

Reference:

Moore, G. W. K. et al. Summer sea ice in the Northwestern Chukchi Sea observed in 2024 for the first time in 25 years. *npj Climate and Atmospheric Science*, 8(1), 324(2025). <https://doi.org/10.1038/s41612-025-01099-5>



Supplementary Fig. 2 | Interannual variability of Chukchi Sea coastal sea-ice thickness and its recovery during 2020–2024. Seasonal-mean SIT time series are shown for **a)** winter (DJF), **b)** spring (MAM), **c)** summer (JJA), and **d)** autumn (SON), averaged over the analysis region (black box in the map). In **b)**, shaded regions highlight the shift from an accelerated decline period (2002–2019; red) to a recent SIT recovery (2020–2024; blue). In **d)**, red markers denote years with documented September ice retention along the western Chukchi coast. The map also defines the onshore (red) and offshore (blue) wind components referenced to the East Siberian coastal orientation.

7. The paper does not sufficiently engage with the broader slowdown in Arctic sea-ice loss literature. Recent work is directly relevant, including England et al. 2025 on the post-2005 pause in September sea-ice area decline, doi:10.1029/2025GL116175; Wang et al. 2025 on the post-2012 slowdown and summer NAO phase shift, doi:10.1038/s41467-025-63520-0; Yu et al. 2025 on decelerated Arctic sea-ice loss linked to North Pacific warming, doi:10.1038/s43247-025-02882-1; and Zhang 2021 on the slowdown in Arctic sea-ice volume decline during 2007–2020, doi:10.1029/2021GL094780. The authors should clarify whether the Chukchi anomaly is part of a broader Arctic or Pacific-sector slowdown, distinct from it, or simply internal variability.

Response:

We thank the reviewer for this insightful suggestion. In this broader context, we interpret the Chukchi Sea anomaly as a localized and amplified Pacific-sector expression of the recent slowdown in Arctic sea-ice loss. The key distinction is that the Chukchi response was not merely a weaker rate of decline but a pronounced regional rebound in summer sea ice, culminating in exceptional September ice retention in 2024 at relatively low Arctic latitudes. This interpretation is particularly consistent with recent work linking decelerated Arctic sea-ice loss to North Pacific warming and associated atmospheric wave-train changes, while our study further identifies how the Chukchi Sea responded strongly because it was located close to the poleward-shifted Pacific–Arctic cyclonic anomaly. We have revised the Discussion to put our work in a broader context.

L408-L430:

“The rapid decline of Arctic sea ice has transformed the Arctic into a “New Arctic” characterized by thinner, younger, and more atmosphere-sensitive sea ice^{Error! Reference source not found.}*. In this new background state, Arctic sea ice no longer responds only as a slowly declining ice cover, but increasingly as a highly*

variable system that can amplify atmospheric perturbations into pronounced regional anomalies^{Error! Reference source not found.}. Recent studies have drawn attention to a broader slowdown in Arctic sea-ice loss over the past one to two decades, linking it to internal variability, summer atmospheric circulation changes, North Pacific wave-train influences, and sea-ice volume processes^{Error! Reference source not found..Error! Reference source not found..Error! Reference source not found.}. Within this slowdown-era “New Arctic”, the 2020–2024 summer Chukchi Sea recovery stands out as an extreme regional manifestation, with anomalous ice retention persisting into September 2024 at low Arctic latitudes. Such events are important to be investigated because they represent extreme regional expressions of the recent slowdown-era variability and complicate seasonal sea-ice outlooks, Arctic navigation planning, and regional risk assessment^{Error! Reference source not found.}.

North Pacific oceanic warming and associated atmospheric circulation changes have been linked to recent sea-ice recovery in the central Arctic^{Error! Reference source not found.}. The 2020–2024 Chukchi Sea recovery examined here represents a sharper Pacific Arctic expression of this variability. Located immediately north of the Bering Strait, the Chukchi Sea is a low-latitude marginal sea highly sensitive to Pacific-sector atmospheric and oceanic anomalies. During 2020–2024, the poleward-shifted cyclonic anomaly placed this region under sustained coupled circulation-cloud-ocean-ice forcing, allowing regional cooling. This convergence of processes helps explain why the Chukchi Sea became the site of a pronounced low-latitude sea-ice reversal.”

Reference

Yu, L., Bi, H., Zhong, S., Zhang, P., & Sui, C. Decelerated Arctic Sea ice loss triggered by accelerated North Pacific warming over the past decade. *Communications Earth & Environment*, 6(1), 922(2025). <https://doi.org/10.1038/s43247-025-02882-1>

Wang, C., Su, H., Zhai, C., Zheng, J., Yu, S., Mo, H., ... & Jiang, L. (2025). Recent

slowing of Arctic sea ice melt tied to multidecadal NAO variability. *Nature Communications*, 16(1), 8504. <https://doi.org/10.1038/s41467-025-63520-0>

Zhang, J. (2021). Recent slowdown in the decline of Arctic sea ice volume under increasingly warm atmospheric and oceanic conditions. *Geophysical Research Letters*, 48(18), e2021GL094780. <https://doi.org/10.1029/2021GL094780>

England, M. R., Polvani, L. M., Screen, J., & Chan, A. C. (2025). Minimal Arctic sea ice loss in the last 20 years, consistent with internal climate variability. *Geophysical Research Letters*, 52(15), e2025GL116175. <https://doi.org/10.1029/2025GL116175>

8. The broader significance is unclear. The manuscript gestures toward improved prediction and future shipping risks, but it does not show that this mechanism has predictive skill. If this is short-lived internal variability, its future relevance may be limited. If it reflects a structural PNA change, the authors need much stronger evidence.

Response:

We thank the reviewer for this important comment. We agree that our analysis does not directly demonstrate predictive skill, and have revised the Discussion L479-L488 of the manuscript. We have tempered the wording regarding PNA structural change, and no longer interpret the recent recovery as evidence for a persistent structural shift in the background PNA. Rather, we describe it as a short-term but persistent poleward displacement of the Pacific–Arctic cyclonic anomaly during 2020–2024, which is statistically linked to the REOF-based PNA index but is not treated as a permanent change in the PNA mode itself. In addition, we framed the broader significance of the study as identifying a physically interpretable circulation–ice pathway that may lead to localized, shipping-relevant sea-ice retention in the Pacific Arctic. We also clarify that this study does not demonstrate predictive skill directly; rather, it identifies a testable circulation anomaly feature that future initialized prediction systems and targeted model experiments can evaluate for its potential value in anticipating localized late-

summer sea-ice retention events.

L479-L488:

“.... In this context, the REOF-based PNA index serves as a valuable framework for describing this large-scale background. However, available evidence is currently insufficient to conclude whether the 2020–2024 recovery stems from a structural shift in the PNA mode; rather, our findings demonstrate that the influence of PNA-related circulation on Chukchi Sea SIC remains contingent upon the regional configuration of the associated Pacific–Arctic cyclonic anomaly. Given the rarity of the 2020–2024 multi-year recovery and late-summer ice-retention event, its recurrence and predictability will require longer records and targeted model experiments, including large-ensemble simulations.”

9. Overall, the paper would be more convincing if the central claim were softened and the statistics more robust. The authors can reasonably argue that the 2020–2024 Chukchi sea-ice retention was associated with unusual circulation, northerly winds, and cloud-radiative cooling. They have not yet shown that a structurally shifted PNA triggered a robust sea-ice recovery or provides a reliable framework for future prediction.

Response:

We thank the reviewer for this constructive overall assessment. As also noted in our response to **Comment 2**, we have revised the manuscript to soften overly causal language. In response to this overall comment, we further reviewed the manuscript as a whole to ensure that the central claim is framed more cautiously, the role of the PNA is described more precisely, and the statistical support for the SIC–PNA relationship is strengthened. The main revisions are as follows.

First, we revised the manuscript title:

From: *A poleward shift in the Pacific–North American pattern triggered summer sea-*

ice recovery in the Pacific Arctic

To: *Unexpected return of late-summer sea ice in the Pacific Arctic under persistent poleward-shifted cyclonic circulation*

Second, we fundamentally reorganized the structural sequence of the Results sections to structurally weaken any implication that a persistent change in the PNA pattern directly caused the recovery. In the revised manuscript, we moved the comparative diagnosis of the 2007 and 2020–2024 extremes forward to Result Section 2. This structural modification allows us to first establish how the position of the regional cyclonic anomaly center shapes localized sea-ice extremes before introducing any large-scale statistical index analysis (which has now been shifted to Result Section 3). Crucially, this structural rearrangement directly refines our final synthesis by clarifying the mechanism behind the PNA's relationship with Chukchi sea ice. In the summary stages of the manuscript, we have updated our text to highlight how this regional pathway clarifies the interpretation of the REOF-based PNA index.

Third, we revised the Results section headings to both reflect this rearranged sequence and explicitly soften our conclusions by removing deterministic language.

From: *Poleward-shifting cyclonic anomalies: Key driver for 2020–2024 summer sea-ice recovery*

To: *Poleward-shifting cyclonic anomalies: A key circulation feature linked to the 2020–2024 summer sea-ice recovery*

From: “*Contrasting sea-ice extremes under canonical and noncanonical positive PNA conditions*” (formerly Section 3)

To: “*Contrasting Chukchi Sea ice extremes linked to the regional position of Pacific–Arctic cyclonic anomalies*” (now Section 2)

From: *Summer sea-ice variability in the Chukchi Sea captured by the PNA index*

To: *Chukchi Sea summer sea-ice variability within the PNA-related circulation framework.* (now Section 3).

Fourth, we clarified the role of the REOF-based PNA index in Results Section 3 and the Discussion, and demonstrated how this regional pathway refines the understanding of PNA-driven sea-ice variability across the western Arctic.

L391-L405:

“Together, these findings clarify how Summer PNA-related circulation controls Chukchi Sea SIC through regional thermodynamic processes. Building on the established moisture-intrusion and longwave-warming pathway, our results show that the latitude and configuration of the Pacific–Arctic cyclonic anomaly further regulate Chukchi Sea SIC by modulating cloud cover, shortwave radiation, and ocean feedbacks. Variations in the REOF-based PNA index should therefore not be interpreted solely as changes in the intensity of the positive PNA background but also as reflecting the influence of meridional shifts in the Pacific–Arctic low-pressure anomaly and the associated thermodynamic processes controlling local sea-ice variability. Because the Chukchi Sea is highly sensitive to the latitude and configuration of Pacific–Arctic circulation anomalies, this regional pathway helps explain how large-scale PNA-related circulation is translated into locally distinct sea-ice responses. These results refine the existing understanding of PNA-driven western Arctic sea-ice variability by highlighting the regional processes through which this large-scale circulation signal affects the Chukchi Sea.”

Finally, we explicitly clarified in the Discussion that available evidence is currently insufficient to confirm a structural shift in the PNA mode and noted that demonstrating predictive skill remains a task for future modeling research. The relevant passage in the Discussion reads as follows:

L481-L488:

“... However, available evidence is currently insufficient to conclude whether the 2020–2024 recovery stems from a structural shift in the PNA mode; rather, our findings demonstrate that the influence of PNA-related circulation on Chukchi Sea SIC remains contingent upon the regional configuration of the associated Pacific–Arctic

cyclonic anomaly. Given the rarity of the 2020–2024 multi-year recovery and late-summer ice-retention event, its recurrence and predictability will require longer records and targeted model experiments, including large-ensemble simulations.”

Together, these structural and textual revisions reframe the central claim more cautiously while significantly deepening our conceptual understanding of the PNA's role. The 2020–2024 Chukchi Sea ice retention was associated with unusual regional circulation and thermodynamic conditions, while the predictability, recurrence, and long-term relevance of such events remain topics for future initialized prediction experiments and targeted model-based attribution studies.

We sincerely thank the reviewer for prompting this re-examination. These structural and textual adjustments have significantly improved the balance and clarity of our manuscript.

Reviewer #1

Comments: The paper has been greatly improved and is ready for publication.

Response: We sincerely thank the reviewer for the positive evaluation and are pleased that the revised manuscript has addressed the reviewer's concerns.

Reviewer #2

Comments: The authors have addressed all the issues I have. I thank them for their diligence.

Response: We sincerely thank the reviewer for the thoughtful comments, which have helped improve the presentation of the manuscript.

Reviewer #3

Comments: The authors have sufficiently addressed my main concerns.

Response: We sincerely thank the reviewer for the insightful and constructive comments. The revised manuscript has been improved accordingly, particularly in its structure, discussion, and conclusions.