

Tripole-like Antarctic Sea Ice Pattern Linked to Remote Forcing from the Indian Ocean and Maritime Continent

Corresponding Author: Professor Li Zhang

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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 Professor Zhang,

Your manuscript titled "Tripole-like Sea Ice Pattern around Antarctica Induced by Remote Forcing from Indian Ocean and Maritime Continent" 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.

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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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

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,

Prof Seung-Ki Min
Editorial Board Member
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Nicola Colombo, PhD
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

General comments

This well-written manuscript tells a good story, moving away from the Pacific-centric view of sea ice variability to encompass a more hemispheric scale. The motivation and approach are clearly laid out but there's a tendency to labour some points, such as the complex nature of atmospheric teleconnections, and the various paths of Rossby waves and their seasonal

changes. Hence, I feel the text could be trimmed in places, perhaps by ten percent or so.

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Using a combination of observational analyses and model simulations, this manuscript gives a nice summary of aspects of Antarctic sea ice variability and its connection to atmospheric forcing. It clearly demonstrates the separate effects of Indian Ocean-derived vs Pacific Ocean-derived circulation anomalies, and the seasonality of those effects, and it raises the prominence of the role of the Indian Ocean. Hence, I feel it deserves publication. However I feel this manuscript is a smaller advance than the authors claim, given previous work on the effects of ZW3.

Specific comments

1. Line 20: I think the word “seasonal” would be better replaced with “regional” as you’re talking about sea ice variations outside the Pacific dipole.
2. Lines 112-113: Replace “in” with “over”.
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4. Figure 2: Plotting the “transitional belts” for SIC in relation to the circulation anomalies is illuminating, nicely done, and the associated discussion makes sense.
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References

Goyal, R., Jucker, M., Sen Gupta, A., Hendon, H. H., & England, M. H. (2021). Zonal wave 3 pattern in the Southern Hemisphere generated by tropical convection. *Nature Geoscience*, 14(10), 732-738. <https://doi.org/10.1038/s41561-021-00811-3>

Raphael, M. N. (2007). The influence of atmospheric zonal wave three on Antarctic sea ice variability. *Journal of Geophysical Research: Atmospheres*, 112(D12), D12112. <https://doi.org/10.1029/2006jd007852>

Renwick, J. A., Kohout, A., & Dean, S. (2012). Atmospheric forcing of Antarctic sea ice on intraseasonal time scales. *Journal of Climate*, 25(17), 5962-5975. <https://doi.org/10.1175/jcli-d-11-00423.1>

Reviewer #2 (Remarks to the Author):

Ma et al. is a well-written, compelling paper that provides interesting insights into the pattern of Antarctic sea ice variability and its distinct seasonality. Antarctic sea ice variability has usually been described as a dipole pattern between the Ross-Amundsen Seas and the Bellingshausen-Weddell Seas. This paper illustrates that during certain seasons of the year, Antarctic sea ice variability exhibits a tripole pattern. This tripole pattern is present during the austral winter and spring seasons, with the exact shape of the pattern differing between the two seasons. Ma et al. show that this tripole pattern is correlated with SST variability in the Indo-Pacific basins. They use partial regression analysis to isolate the individual contributions from each particular basin, and use this to explain the differing tripole pattern between the winter and spring seasons. They find that the central Pacific Ocean dominates the formation of the tripole pattern during the winter season, while the Indian Ocean and Maritime Continent regions dominate the formation of the tripole pattern during the spring season.

Overall, I think the results are novel, offer an advancement in our understanding of the pattern of Antarctic sea ice variability, and will be of interest to others in the community. They provide important insights into the nuances of Antarctic sea ice variability and highlight the importance of investigating sea ice variability as a function of season. The methods are sound and the combination of observational analysis and modeling experiments builds confidence in the results. I have a few major comments and suggestions that I think will help clarify the analysis and figures for future readers, but I recommend that this paper for publication after minor revisions.

Major comments:

1. It would be helpful if the authors added a few short descriptive sentences about the methodology throughout the results. It was sometimes unclear whether the results were based on observations or model output. Additionally, a short description of the pacemaker experiments and the atmospheric transient experiments within the main text would be very helpful. While I agree that the majority of the details should remain in the Methods section, a brief overview of the experiments within the

main text would help the reader follow the arguments more clearly.

2. One general question I had was whether this tripole pattern is also present in model output? Since model experiments were heavily used in the results via the Pacemaker experiments and Atmospheric transient experiments, it might be helpful to see what the pattern of variability looked like in CESM to compare with the observational results.

3. Consider labeling box III differently between the AWT and AST patterns. Since the box is in a substantially different location for each season, having the third sector labeled as III in both seasons can be confusing. For example, adding a subscript of AWT or AST to make the label III_{AWT} or III_{AST} could make this more clear.

4. Do the authors have a sense of why the tripole pattern is only apparent during the winter/spring seasons? I think it would be useful to include some discussion on why the pattern is so different during the summer/fall seasons.

Minor comments:

L27-28: Consider including a reference to Holland et al. 2018 “The Regional, Seasonal, and Lagged Influence of the Amundsen Sea Low on Antarctic Sea Ice” in this section. They find a distinct seasonality to the impact of the ASL on Antarctic Sea Ice which is related to the importance of seasonality that the authors here focus on.

L47-56 : Consider moving this paragraph describing the tropical-polar teleconnections to before the previous paragraph (L39-46). That way the reader would be provided with a description of how these teleconnections work before citing the specific teleconnections relevant to this particular work.

L54: Reword “further seasonally impacting on the Antarctic sea ice variability” to “further seasonally impacting Antarctic sea ice variability”.

L56: Consider adding additional background about the current state of the research, i.e. where prior research has left off or what is still unknown about this variability. This would add additional helpful motivation to the reader and provide some context for why the authors are investigating the seasonal differences of Antarctic sea ice variability.

L62: It would be helpful to have a short definition of “circulation pairs”. I found this term unclear at this stage in the paper.

Fig 1: I recommend rotating the labels of the different regions in 1a so that they are all facing right-side up (i.e. so none of the labels are upside down). The upside-down labels make them hard to read.

Figure captions: While I do not personally mind having a descriptive sentence about the key points of the figure as part of the caption, it is a bit untraditional, and such sentences might be better suited to be in the main text instead.

L101: It would be helpful to have boxes labeled I-III on Supplementary Figure 1. I found it challenging to see how the anomaly centers of the tripole aligned with the transitional belts in Supplementary Fig 1 due to the differing map projections. Adding the boxes from Fig 1 denoting the anomaly centers to Supplementary Fig 1 would help make this more clear.

L105-106: Reword “patterns or the seasonal displacement” to “patterns and the seasonal displacement”

L110: It would be helpful to have a general description of how the regression analysis was performed. Such as: were the regressions performed on a grid point level or were any spatial averages performed? It would make the main text clearer to have a few more details about what regression analysis is performed.

L113-114: I did not find that the alignment of the “circulation pairs” with the transitional belts as clear as the authors suggested. I would recommend some additional discussion about what features are present in Fig 2a,b that indicate this clear alignment.

L115: Reword this phrase to something like “atmospheric forcing is correlated with sea ice dynamics” to highlight that this regression analysis cannot prove causality or the direction of the relationship.

Figure 2: The spacing and units of the contours in panels a and b are not defined. Additionally, it is unclear what the red/blue contours in panels c and d are, this should be more clearly defined.

Figures 2,4,5: I found the green arrows hard to see, especially the directionality. I would suggest plotting fewer arrows or increasing their size to make the directionality clearer.

L164: JJA boxes I and III and SON box III appear to be shifted in Supplementary Fig 2 compared to Fig 1, do the authors have any ideas as to why this shift is apparent?

L175: Why do the authors neglect to look at the Maritime continent for the JJA season? If it is because there is little to no correlation between Maritime continent SSTs and the Antarctic sea ice pattern during this season, it would be helpful to show that, at least as a supplementary figure.

L190: I was a little bit confused about what the results of the Atmospheric transient experiments are adding to the analysis? I think some more clarification on how the atmospheric transient experiments are adding to the analysis would be helpful.

L191-192: The magnitude of regression coefficients in Fig 4c,d and the simulated forcing (panels e and f) are quite different.

What does this indicate about the observational regression analysis or the modeled results? Is this difference in magnitude expected?

Figure 6: Why are some of the red/blue contours solid or dashed lines? Clarification of this in the main text and caption would be helpful.

L322-323: Is this monthly data detrended prior to analysis? I would imagine that removing the long term trend of the data would be important prior to analysis.

L325: Why is the 30% SIC definition for sea ice edge used? Since the traditional definition of sea ice extent is 15% SIC, it would be helpful to provide some discussion on why the 30% SIC definition was used.

L404-414: I suggest providing some additional information as to how the forcing for the atmospheric transient experiments was designed. From my understanding, the SSTs outside of the regions of interest were held fixed at the climatological seasonal cycle, while SSTs inside the regions of interest were perturbed. If this is correct, how were the SSTs inside the regions of interest perturbed?

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Decision Letter:

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Dear Professor Zhang,

Your manuscript titled "Tripole-like Sea Ice Pattern around Antarctica Induced by Remote Forcing from Indian Ocean and Maritime Continent" 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 therefore 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,

Prof Seung-Ki Min
Editorial Board Member
Communications Earth & Environment
0000-0002-6749-010X

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

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I thank the authors for their comprehensive responses to my review. The addition of the ZW3 discussion is well done and adds nicely to the discussion. The text has also been shortened by about the amount I suggested. I am happy with the manuscript now.

Reviewer #2 (Remarks to the Author):

I thank the authors for their thorough response to my comments and the comments from the other reviewer. I am satisfied with the author's responses and changes made pertaining to my comments. I have no further comments, and would recommend this study for publication.

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Review of manuscript *Tripole-like Sea Ice Pattern around Antarctica Induced by Remote Forcing from Indian Ocean and Maritime Continent*, by Ma et al, submitted to Communications Earth & Environment.

General comments

This well-written manuscript tells a good story, moving away from the Pacific-centric view of sea ice variability to encompass a more hemispheric scale. The motivation and approach are clearly laid out but there's a tendency to labour some points, such as the complex nature of atmospheric teleconnections, and the various paths of Rossby waves and their seasonal changes. Hence, I feel the text could be trimmed in places, perhaps by ten percent or so.

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References

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Response to Reviewers

Reviewer #1

General comments

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We appreciate the reviewer's positive assessment of the manuscript and thank you for the candid comment regarding the length of the discussion on teleconnection pathways and Rossby wave dynamics. Our initial intention was to clearly describe the distinct Rossby wave trajectories originating from different ocean basins in austral winter and spring, along with the associated dynamical mechanisms. However, we agree that several explanations were overly detailed and could affect the reading experience.

In response, we trimmed the relevant paragraphs in the section "*Teleconnections linking tropical Indo-Pacific variability and the Antarctic sea ice tripole*." To further reduce redundancy, Figs. 4 and 5 now display only the observational sea-ice anomalies and associated Rossby wave trains, while the corresponding atmospheric transient experiments results have been moved to the Supplementary Materials. We believe these revisions sharpen the focus on the key mechanisms highlighted in the paper while still providing model-based support without duplicating information in the main text.

At least some of the variability documented here could be accounted for by the action of Zonal Wave 3 (ZW3, Raphael 2007) which is most prominent over the winter, where the AWT is prominent. That pattern has recently been shown to be driven by Rossby waves emanating from the Tropical Pacific (Goyal et al 2021). It would be good to bring these ideas into the discussion.

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We thank the reviewer for raising the connection to ZW3, and we agree that ZW3 represents a major component of Southern Hemisphere atmospheric variability and have an impact on sea ice variability. This is an important context, and we now

acknowledge this in the Discussion.

At the same time, we find that the tripole pattern examined here cannot be fully interpreted as a direct manifestation of ZW3. Although both patterns contain three primary centers in West Antarctica, the spatial expression of the tripole differs in several fundamental ways. In ZW3-related analyses (Goyal et al., 2022; Raphael, 2007), the associated sea-ice anomalies display six distinct centers around the continent, with the three West Antarctic centers typically showing the strongest amplitude. This structure reflects the canonical ZW3 wave packet, which is strongest over the West Antarctic sector and produces pronounced meridional wind and heat flux anomalies there.

By contrast, the tripole mode identified in this study shows three strong centers and one markedly weaker anomaly (Fig. 1d, e) rather than a symmetric six-center pattern. Moreover, in both winter and spring, the tripole spans a much larger longitudinal extent (roughly 220° - 240°), substantially exceeding the West Antarctic sea ice anomalies (roughly 180° - 200°) seen in ZW3-related composites (Goyal et al., 2022). The differences are even clearer over East Antarctica: ZW3-based sea-ice anomalies exhibit three relatively distinct centers around the sector, whereas the tripole pattern shows only a very weak and spatially confined center in this region. This West-East asymmetry is not characteristic of ZW3 and distinguishes the tripole from known ZW3-associated sea ice patterns. These structural differences, especially the asymmetry between the West and East Antarctic sectors and the much broader longitudinal span, indicating that the tripole cannot be viewed as a simple seasonal projection or phase expression of ZW3.

Moreover, the seasonal evolution of the tripole does not resemble the continuous, equidistant longitudinal phase progression typically associated with ZW3. ZW3 is characterized by a zonal shift in its phase (Renwick, 2005), which peaks in austral winter and exhibits a mean longitudinal difference of about 20° - 40° relative to other seasons (Goyal et al., 2022). By contrast, the tripole is defined by the interannual variability of sea ice within each season, rather than by a seasonally rotating wave pattern. In particular, the two dominant centers associated with the classical Antarctic dipole remain nearly stationary from winter to spring, while only the third center shifts longitudinally, from the King Hakon VII region in winter to the Dumont d'Urville sector in spring. This displacement is closely linked to the seasonal difference in the meridional position of the “circulation pair” over this region. Taken together, these features indicate that the tripole reflects season-specific atmospheric responses to basin-scale SST anomalies, rather than a seasonal phase progression of a quasi-stationary wave. These distinctions suggest that the tripole represents a seasonally dependent response mode linked to basin-scale SST forcing, rather than an expression of a rotating planetary wave.

For these reasons, while ZW3 offers an important and valuable context, the tripole-like SIC variability examined here reflects a different perspective, one based on the interannual variability of sea ice itself. Our analysis highlights the contrasting

influences of Indo-Pacific SST anomalies in shaping the winter and spring patterns. These seasonally dependent SST-forced pathways enable the tripole to capture a band of sea-ice variability over East Antarctica that is comparable in strength to that in West Antarctica, underscoring its tight linkage to tropical SST forcing. To situate our findings within this broader context, we have added a paragraph in the Discussion clarifying how the tripole relates to, yet remains distinct from, the ZW3 perspective.

Line 319-333:

“The tripole-like pattern identified here emerges from the perspective of sea ice–dominated variability. Although it shares some similarities with the circulation-based zonal wave-3 (ZW3) pattern^{49,50}, the two differ fundamentally in their wavenumber characteristics and seasonal behavior. ZW3 is a well-established circulation mode that peaks in austral winter and exhibits a mean longitudinal phase shift of about 20°–40° between seasons^{51,52}. It is characterized by six sea-ice anomaly centers around Antarctica, with the strongest three located in West Antarctica, reflecting the enhanced wave-packet amplitude in this region⁵¹. This circulation-based framework has been highly valuable for understanding how planetary-wave variability imprints on Antarctic sea ice⁵³. In contrast, when sea-ice internal variability is used as the organizing perspective, the leading interannual SIC mode neither displays the six-center structure nor shows the seasonally rotating phase that typifies ZW3. Instead, during JJA and SON it appears as a tripole, with the dipole centers remaining nearly stationary and only the third center shifting between seasons. This behavior indicates that the seasonal differences of the tripole do not arise from a rotating phase but reflect internal sea-ice variability together with seasonally shifting Rossby-wave pathways originating from the Indo-Pacific basins.”

Reference:

- Goyal, R., Jucker, M., Gupta, A. S., & England, M. H. (2022). A New Zonal Wave-3 Index for the Southern Hemisphere. *JOURNAL OF CLIMATE*, 35(15), 5137–5149. <https://doi.org/10.1175/JCLI-D-21-0927.1>
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- Renwick, J. A. (2005). Persistent Positive Anomalies in the Southern Hemisphere Circulation. *Monthly Weather Review*, 133(4), 977–988. <https://doi.org/10.1175/MWR2900.1>

Specific comments

1. Line 20: I think the word “seasonal” would be better replaced with “regional” as you’re talking about sea ice variations outside the Pacific dipole.

We thank the reviewer for the helpful suggestion. We agree that “regional” more accurately describes the broader spatial scope. We have therefore replaced “seasonal” with “regional” in the revised manuscript.

Line 19-23:

“Despite this, the inter-annual variability of Antarctic sea ice exhibits pronounced regional differences, and emerging evidence suggests that variability in East Antarctic sea ice, particularly in regions west of the Ross Sea and east of Weddell Sea, may rival the variability observed in the West Antarctic^{3,4}.”

2. Lines 112-113: Replace “in” with “over”.

We thank the reviewer for the suggestion. The preposition has been corrected from “in” to “over”.

Line 126-127:

“Specifically, two low-pressure centers are located over the western Ross Sea and Weddell Sea, while a high-pressure center is situated in the Amundsen Sea.”

3. Lines 116-117: You may also wish to reference Renwick et al (2012) which discusses thermal vs mechanical forcing of the SIC field and shows “tripole-like” EOF patterns at some times of year.

We thank the reviewer for pointing us to this relevant study. Renwick et al. (2012) indeed provides an insightful discussion of the roles of atmospheric wave activity on Antarctic sea ice during both the growth and maximum ice periods. We have now added this reference in the revised manuscript.

Line 131-133:

“The local circulation regulates sea ice redistribution primarily through thermal advection^{8,13,14} and mechanical forcing^{7,15}, particularly during the growth and maximum ice periods⁴¹. ”

4. Figure 2: Plotting the “transitional belts” for SIC in relation to the circulation anomalies is illuminating, nicely done, and the associated discussion makes sense.

We thank the reviewer for the positive feedback. We also find the “transitional belt” concept to be a useful way to illustrate how regional circulation patterns organize the SIC response, and we are glad that the figure and discussion were clear.

5. Line 168: Change the word “confirm” to “support”.

We thank the reviewer and agree that “support” is more appropriate in this context. The sentence has been revised accordingly.

Line 185-187:

“Although the pacemaker experiments support the combined influence of tropical Indo-Pacific SST variability on Antarctic sea ice tripole patterns, the individual contributions of each basin remain unclear.”

6. Figure 5: Very nice results, but very small panels. Could this Figure be rotated and blown up?

We thank the reviewer for the suggestion. To create the necessary space and further reduce redundancy, Figures 4 and 5 now present only the observational sea-ice anomalies and the associated Rossby wave trains, while the corresponding atmospheric transient-experiment results have been moved to the Supplementary Materials.

In addition, the panel layout has been reorganized (left column: SIC anomalies; right column: Rossby wave trains), and the scaling of the Plumb wave-activity flux vectors has been adjusted for better visual clarity, with the underlying data remaining unchanged

7. Lines 228-229: This is the first time I have read that the Southern Hemisphere subtropical jet forms “a broad imaginary wave number region”, but quite so.

We thank the reviewer for this remark. The region where the refractive index becomes imaginary is indeed quite extensive during JJA, in clear contrast to SON, and this distinction highlights the strong influence of the background subtropical jet on the propagation of Rossby wave trains.

Reviewer #2

Ma et al. is a well-written, compelling paper that provides interesting insights into the pattern of Antarctic sea ice variability and its distinct seasonality. Antarctic sea ice variability has usually been described as a dipole pattern between the Ross-Amundsen Seas and the Bellingshausen-Weddell Seas. This paper illustrates that during certain seasons of the year, Antarctic sea ice variability exhibits a tripole pattern. This tripole pattern is present during the austral winter and spring seasons, with the exact shape of the pattern differing between the two seasons. Ma et al. show that this tripole pattern is correlated with SST variability in the Indo-Pacific basins. They use partial regression analysis to isolate the individual contributions from each particular basin, and use this to explain the differing tripole pattern between the winter and spring seasons. They find that the central Pacific Ocean dominates the formation of the tripole pattern during the winter season, while the Indian Ocean and Maritime Continent regions dominate the formation of the tripole pattern during the spring season.

Overall, I think the results are novel, offer an advancement in our understanding of the pattern of Antarctic sea ice variability, and will be of interest to others in the community. They provide important insights into the nuances of Antarctic sea ice variability and highlight the importance of investigating sea ice variability as a function of season. The methods are sound and the combination of observational analysis and modeling experiments builds confidence in the results. I have a few major comments and suggestions that I think will help clarify the analysis and figures for future readers, but I recommend that this paper for publication after minor revisions.

We sincerely thank Reviewer #2 for taking the time to review our manuscript. We greatly appreciate the care and effort devoted to the review process. The comments are constructive and insightful, and they have been very helpful for improving the clarity and presentation of the manuscript. We are also grateful for the positive evaluation of the novelty and significance of our results.

In response to the major comments, we have made several targeted revisions to the manuscript. These include clarifying throughout the Results section whether each analysis is based on observational data or model output, restructuring the figures to more clearly distinguish observational diagnostics from simulation-based results, and providing additional explanation of the roles of the pacemaker and atmospheric transient experiments. We have also revised figures and captions to improve readability, and expanded the Discussion to better address the physical mechanism of the seasonal dependence of the Antarctic sea-ice tripole.

Below, we respond to each comment in detail. All reviewer comments are followed by our point-by-point responses and descriptions of the corresponding revisions in the manuscript, shown in italics.

Major comments:

1. It would be helpful if the authors added a few short descriptive sentences about the methodology throughout the results. It was sometimes unclear whether the results were based on observations or model output. Additionally, a short description of the pacemaker experiments and the atmospheric transient experiments within the main text would be very helpful. While I agree that the majority of the details should remain in the Methods section, a brief overview of the experiments within the main text would help the reader follow the arguments more clearly.

We thank the reviewer for this constructive suggestion. To clarify the data source behind each result, we revised Figs. 4 and 5 so that the main text now presents only observation-based diagnostics. In each figure, the left panels show sea ice anomalies and the right panels show the associated Rossby wave trains. The Plumb wave-flux vectors were adjusted to improve visual clarity, but the underlying data remain unchanged. The model-based diagnostics that previously appeared in the main figures have been moved to the Supplementary Material (now Supplementary Figs. 4 and 5), where they are clearly labeled as simulation results in both the captions and the text. This restructuring makes the distinction between observational evidence and model experiments more transparent to readers.

In addition, we have added brief descriptions of the CESM pacemaker experiments and the CAM5 atmospheric transient experiments in the Result section *“Teleconnections linking tropical Indo-Pacific variability and the Antarctic sea ice tripole.”* These short summaries provide context for how the experiments are used, while the full technical details remain in the Methods. We believe these revisions improve the readability of the Results and help guide the reader through the development of our arguments.

Line 175-179:

“To assess the atmospheric response of Antarctic sea ice to Indo-Pacific SST anomalies, we conducted a set of pacemaker experiments forced by observed SST anomalies in Fig. 3 (see “Pacemaker experiments” in Methods). By imposing basin-wide Indo-Pacific SST anomalies on the coupled air-ocean-ice system, these experiments evaluate the integrated remote influence of SST forcing.”

Line 191-196:

“We then examined how each index influences sea ice and its associated Rossby-wave pathways using observational data (Fig. 4, 5), and subsequently evaluated these pathways using atmospheric transient experiments (Supplementary Fig. 4, 5) (see “Atmospheric transient experiments” in Methods). In these simulations, SST anomalies associated with each tropical basin are prescribed separately, allowing us to isolate the basin-specific atmospheric forcing responsible for generating distinct Rossby wave trains.”

2. One general question I had was whether this tripole pattern is also present in model output? Since model experiments were heavily used in the results via the Pacemaker

experiments and Atmospheric transient experiments, it might be helpful to see what the pattern of variability looked like in CESM to compare with the observational results.

We appreciate the reviewer's important and thoughtful question. CESM is used in this study not to evaluate intrinsic sea-ice variability, but as a dynamical framework to examine teleconnection mechanisms. Consistent with previous assessments, coupled climate models, including CESM and large-ensemble simulations from CMIP5/6, exhibit notable biases in Antarctic sea-ice annual cycle, regional distribution, interannual variability, and long-term trends (Roach et al., 2018, 2020; Singh et al., 2021; Sun & Eisenman, 2021; Turner et al., 2013). These biases have been linked to uncertainties in sea-ice thickness, drift, and ice–ocean coupling processes (Danabasoglu et al., 2020; Hurrell et al., 2013; Singh et al., 2021), which complicate the interpretation of internal sea-ice variability modes in models.

Accordingly, the primary goal of this study is not to assess whether a numerical model reproduces the observed tripole as an internal mode of variability, but to determine whether tropical Indo-Pacific SST forcing can dynamically induce a tripole-like Antarctic sea-ice response. To address this question, we employ CESM pacemaker experiments and atmospheric transient simulations, which has been widely used as a dynamical framework for investigating Southern Hemisphere teleconnection processes (Gillett et al., 2022; X. Li et al., 2014; Man et al., 2025; L. Zhang et al., 2024). In these experiments, SST forcing is applied within specific tropical regions to suppress internal variability and isolate the forced atmospheric response. Within this controlled framework, CESM produces a tripole-like sea-ice pattern during austral winter and spring (Supplementary Figure 2). We have clarified this methodological choice in the revised manuscript.

Line 191-196:

“ We then examined how each index influences sea ice and its associated Rossby-wave pathways using observational data (Fig. 4, 5), and subsequently evaluated these pathways using atmospheric transient experiments (Supplementary Fig. 4, 5) (see “Atmospheric transient experiments ” in Methods). In these simulations, SST anomalies associated with each tropical basin are prescribed separately, allowing us to isolate the basin-specific atmospheric forcing responsible for generating distinct Rossby wave trains.”

Line 419-421:

“Here CESM is employed as a dynamical framework to examine teleconnection processes, with the pacemaker approach used to isolate the forced response to tropical SST anomalies.”

Reference:

Danabasoglu, G., Lamarque, J.-F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C.,

- Holland, M. M., Large, W. G., Lauritzen, P. H., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., ... Strand, W. G. (2020). The community earth system model version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, 12(2), e2019MS001916. <https://doi.org/10.1029/2019MS001916>
- Gillett, Z. E., Hendon, H. H., Arblaster, J. M., Lin, H., & Fuchs, D. (2022). On the Dynamics of Indian Ocean Teleconnections into the Southern Hemisphere during Austral Winter. *Journal of the Atmospheric Sciences*, 79(9), 2453–2469. <https://doi.org/10.1175/JAS-D-21-0206.1>
- Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J.-F., Large, W. G., Lawrence, D., Lindsay, K., Lipscomb, W. H., Long, M. C., Mahowald, N., Marsh, D. R., Neale, R. B., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., ... Marshall, S. (2013). The Community Earth System Model: A Framework for Collaborative Research. *Bulletin of the American Meteorological Society*, 94(9), 1339–1360. <https://doi.org/10.1175/BAMS-D-12-00121.1>
- Li, X., Holland, D. M., Gerber, E. P., & Yoo, C. (2014). Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice. *Nature*, 505(7484), Article 7484. <https://doi.org/10.1038/nature12945>
- Man, K., Luterbacher, J., Holland, D. M., Yuan, N., Geng, L., Wang, Y., Liu, Y., Shi, G., Hou, Y., Cai, W., & Li, X. (2025). Century-long West Antarctic snow accumulation changes induced by tropical teleconnections. *Science Advances*, 11(5), eadr2821. <https://doi.org/10.1126/sciadv.adr2821>
- Roach, L. A., Dean, S. M., & Renwick, J. A. (2018). Consistent biases in Antarctic sea ice concentration simulated by climate models. *CRYOSPHERE*, 12(1), 365–383. <https://doi.org/10.5194/tc-12-365-2018>
- Roach, L. A., Dörr, J., Holmes, C. R., Massonnet, F., Blockley, E. W., Notz, D., Rackow, T., Raphael, M. N., O’Farrell, S. P., Bailey, D. A., & Bitz, C. M. (2020). Antarctic sea ice area in CMIP6. *Geophysical Research Letters*, 47(9), e2019GL086729. <https://doi.org/10.1029/2019GL086729>
- Singh, H. K. A., Landrum, L., Holland, M. M., Bailey, D. A., & DuVivier, A. K. (2021). An overview of antarctic sea ice in the community earth system model version 2, part I: Analysis of the seasonal cycle in the context of sea ice thermodynamics and coupled atmosphere-ocean-ice processes. *Journal of Advances in Modeling Earth Systems*, 13(3), e2020MS002143. <https://doi.org/10.1029/2020MS002143>
- Sun, S., & Eisenman, I. (2021). Observed Antarctic sea ice expansion reproduced in a climate model after correcting biases in sea ice drift velocity. *Nature Communications*, 12(1), 1060. <https://doi.org/10.1038/s41467-021-21412-z>
- Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., & Hosking, J. S. (2013). An Initial Assessment of Antarctic Sea Ice Extent in the CMIP5 Models. *JOURNAL OF CLIMATE*, 26(5), 1473–1484. <https://doi.org/10.1175/JCLI-D-12-00068.1>
- Zhang, L., Ren, X., Cai, W., Li, X., & Wu, L. (2024). Weakened western Indian Ocean dominance on Antarctic sea ice variability in a changing climate. *Nature*

3. Consider labeling box III differently between the AWT and AST patterns. Since the box is in a substantially different location for each season, having the third sector labeled as III in both seasons can be confusing. For example, adding a subscript of AWT or AST to make the label III_{AWT} or III_{AST} could make this more clear.

We thank the reviewer for this clear and helpful suggestion. We fully agree that distinguishing the third sector between the AWT and AST patterns improves clarity. Following the reviewer's recommendation, we have revised the labels in Fig. 1d, e by adding seasonal subscripts (III_{AWT} and III_{AST}). We have also updated the corresponding descriptions in the main text and applied the same convention consistently across all subsequent figures where these sectors appear (Figs. 4 and 5). This modification improves readability and avoids confusion regarding the distinct locations of the third anomaly center in different seasons.

Line 101-106:

“The AWT, explaining 23.8% of wintertime sea ice variance, is characterized by the classic Antarctic Dipole pattern (box I - II in Fig. 1d), alongside a newly identified negative sea ice anomaly center in the King Hakon Sea (box III_{AWT} in Fig. 1d). Similarly, the AST, accounting for 19.9% of the interannual variance in SON, features dipole-like anomalies (box I - II in Fig. 1e) and a pronounced positive anomaly center over the Dumont d'Urville Sea (III_{AST} in Fig. 1e).”

4. Do the authors have a sense of why the tripole pattern is only apparent during the winter/spring seasons? I think it would be useful to include some discussion on why the pattern is so different during the summer/fall seasons.

We appreciate the reviewer's insightful question. The seasonality of the Antarctic tripole can be understood from two complementary perspectives: internal sea-ice variability and external tropical forcing.

On the sea ice side, sea ice undergoes a pronounced seasonal cycle in both areal extent and sensitivity to atmospheric forcing. JJA and SON correspond to the growth and maximum ice seasons (Renwick, 2005). During these seasons, the climatological mean sea-ice cover is much larger than during DJF and MAM. The classic Antarctic Dipole spans the Ross, Amundsen, Bellingshausen, and Weddell Seas. These sectors maintain persistently high ice cover. As a result, the dipole remains detectable in MAM, JJA, and SON. It weakens markedly during DJF. In contrast, the sea ice over King Hakon VII Sea and Dumont d'Urville Sea exhibit large seasonal amplitude. Their winter mean sea ice fraction (June–November) becomes comparable to that of West Antarctica. Their summer and autumn ice cover is substantially lower (Raphael & Hobbs, 2014). A sufficiently large ice fraction is needed for a robust anomaly center to form. The poleward-extending winter and spring ice margins respond strongly to meridional wind anomalies (Matear et al., 2015). These features explain

why additional centers in the King Hakon VII and Dumont d'Urville sectors emerge only during JJA and SON.

From a dynamical perspective, JJA and SON are also the seasons in which tropical–Antarctic teleconnections are strongest. ENSO undergoes its growth phase in JJA, while the Indian Ocean Basin mode matures in JJA and the Indian Ocean Dipole peaks in SON (Du et al., 2009; Saji et al., 1999). These SST anomalies, together with Indo-Pacific interactions, generate strong Rossby wave sources that can influence high-latitude circulation (Nuncio & Yuan, 2015; Scott Yiu & Maycock, 2019; L. Zhang et al., 2024; P. Zhang & Duan, 2023). The Southern Hemisphere background flow is also critical: the subtropical jet is strongest and most coherent in JJA and remains sufficiently organized in SON, forming an effective waveguide that allows Rossby waves to reach Antarctica (Hoskins & Ambrizzi, 1993; X. Li et al., 2015). During DJF, although ENSO peaks, the weakened subtropical jet reduces meridional wind shear and inhibits Rossby-wave propagation into polar latitudes, preventing the dynamical pathway required to excite the tripole.

Taken together, these internal and external factors help explain why the tripole-like sea-ice pattern is most apparent in winter and spring but diminishes during summer and autumn. Following the reviewer's suggestion, we have added a paragraph in the Discussion section to examine the physical basis of this seasonality.

Line 306-318:

“The classic Antarctic Dipole pattern has been recognized for more than two decades^{1,2}, with a primary focus on sea ice variability around West Antarctica. However, sea ice variability over King Hakon Sea and Dumont d'Urville Sea exhibits a similar magnitude to that in West Antarctica³, yet its structure and driving forces have not received adequate investigation. One reason this broader tripole-like pattern has not been identified previously is that these East Antarctic centers emerge only during specific seasons. Their sea-ice cover becomes sufficiently extensive in winter and spring to support large, coherent anomaly centers, whereas during summer and autumn the reduced ice extent masks this variability³. At the same time, the subtropical jet is also strongest and most coherent during JJA and remains organized in SON⁴⁶, forming an efficient waveguide that allows wave activity from tropical ocean to reach Antarctica³⁰. In contrast, the weakened summer jet limits Rossby-wave penetration into polar latitudes, and the reduced sea-ice extent limits the surface expression of anomalies, suppressing the tripole during DJF and MAM.”

Reference:

- Du, Y., Xie, S.-P., Huang, G., & Hu, K. (2009). Role of Air–Sea Interaction in the Long Persistence of El Niño–Induced North Indian Ocean Warming*. *Journal of Climate*, 22(8), 2023–2038. <https://doi.org/10.1175/2008JCLI2590.1>
- Hoskins, B. J., & Ambrizzi, T. (1993). Rossby Wave Propagation on a Realistic Longitudinally Varying Flow. *Journal of the Atmospheric Sciences*, 50(12), 1661–1671. [https://doi.org/10.1175/1520-0469\(1993\)050%253C1661:RWPOAR%253E2.0.C](https://doi.org/10.1175/1520-0469(1993)050%253C1661:RWPOAR%253E2.0.C)

- Li, X., Holland, D. M., Gerber, E. P., & Yoo, C. (2015). Rossby Waves Mediate Impacts of Tropical Oceans on West Antarctic Atmospheric Circulation in Austral Winter. *Journal of Climate*, 28(20), 8151–8164. <https://doi.org/10.1175/JCLI-D-15-0113.1>
- Matear, R. J., O’Kane, T. J., Risbey, J. S., & Chamberlain, M. (2015). Sources of heterogeneous variability and trends in Antarctic sea-ice. *Nature Communications*, 6(1), 8656. <https://doi.org/10.1038/ncomms9656>
- Nuncio, M., & Yuan, X. (2015). The Influence of the Indian Ocean Dipole on Antarctic Sea Ice*. *Journal of Climate*, 28(7), 2682–2690. <https://doi.org/10.1175/JCLI-D-14-00390.1>
- Raphael, M. N., & Hobbs, W. (2014). The influence of the large-scale atmospheric circulation on Antarctic sea ice during ice advance and retreat seasons. *Geophysical Research Letters*, 41(14), 5037–5045. <https://doi.org/10.1002/2014GL060365>
- Renwick, J. A. (2005). Persistent positive anomalies in the southern hemisphere circulation. *Monthly Weather Review*, 133(4), 977–988. <https://doi.org/10.1175/MWR2900.1>
- Saji, N. H., Goswami, B. N., Vinayachandran, P. N., & Yamagata, T. (1999). A dipole mode in the tropical Indian ocean. *Nature*, 401(6751), 360–363. <https://doi.org/10.1038/43854>
- Scott Yiu, Y. Y., & Maycock, A. C. (2019). On the Seasonality of the El Niño Teleconnection to the Amundsen Sea Region. *Journal of Climate*, 32(15), 4829–4845. <https://doi.org/10.1175/JCLI-D-18-0813.1>
- Zhang, L., Ren, X., Cai, W., Li, X., & Wu, L. (2024). Weakened western Indian Ocean dominance on Antarctic sea ice variability in a changing climate. *Nature Communications*, 15(1), 3261. <https://doi.org/10.1038/s41467-024-47655-0>
- Zhang, P., & Duan, A. (2023). Connection between the Tropical Pacific and Indian Ocean and Temperature Anomaly across West Antarctic. *Npj Climate and Atmospheric Science*, 6(1), 49. <https://doi.org/10.1038/s41612-023-00381-8>

Minor comments:

L27-28: Consider including a reference to Holland et al. 2018 “The Regional, Seasonal, and Lagged Influence of the Amundsen Sea Low on Antarctic Sea Ice” in this section.

They find a distinct seasonality to the impact of the ASL on Antarctic Sea Ice which is related to the importance of seasonality that the authors here focus on.

We thank the reviewer for this helpful suggestion. We have added a citation to Holland et al. (2018) in the revised manuscript.

Line 26-28:

“The inter-annual variability of the Antarctic sea ice, in particular the sea ice dipole pattern, is considered to be driven by the local atmospheric dynamics, such as the Amundsen Sea Low (ASL)7 – 10.”

L47-56 : Consider moving this paragraph describing the tropical-polar teleconnections to before the previous paragraph (L39-46). That way the reader would be provided with a description of how these teleconnections work before citing the specific teleconnections relevant to this particular work.

We appreciate the reviewer’s suggestion. To improve the logical flow of the Introduction, we have reordered the relevant paragraphs so that the general dynamical processes underlying tropical–polar teleconnections appear before the discussion of the specific ENSO-related pathways examined in this study. This restructuring provides a clearer conceptual lead-in for readers before introducing the particular Indo-Pacific teleconnections relevant to our work.

Line 39-59:

“These teleconnections, triggered by tropical variability, propagate to the high-latitude Southern Hemisphere through Rossby wave dynamics. The propagation pathway depends strongly on the atmospheric mean flow19 – 21. In particular, the subtropical jet serves as a waveguide and barrier to these wave trains: the intensified anticyclonic curvature on its poleward flank creates a channel of stationary wave trains toward Antarctica29,34. Seasonal variations in the subtropical jet alter the pathway of these wave trains by changing their strength and phase22. This seasonality becomes especially pronounced during austral winter and spring when the jet is stronger24. The enhanced jet structure allows Rossby wave activity from the tropics to propagate more efficiently into high latitudes, further impacting Antarctic sea ice variability.

Building on this general framework, previous studies have identified several specific teleconnection pathways linking individual tropical basins to Antarctica. The Pacific-Antarctic teleconnections, driven by El Niño/Southern Oscillation (ENSO)-related tropical atmospheric deep convection25,26, have been the most extensively investigated27 – 30. The ENSO-induced stationary Rossby wave train, referred to as the Pacific South America (PSA) pattern31,32, propagates southeastward to Antarctica33, interacting with the ASL to amplify the Antarctic Dipole around West Antarctica34,35. Similarly, warm SST anomalies in the tropical Atlantic can deepen the ASL through poleward-propagating Rossby wave trains22,36.

While these Pacific and Atlantic influences predominantly affect West Antarctic sea ice, emerging evidence shows that the Indian Ocean can modulate not only West Antarctica but also East Antarctica^{4,37,38}, with its impacts strengthening during austral winter and spring. ”

L54: Reword “further seasonally impacting on the Antarctic sea ice variability” to “further seasonally impacting Antarctic sea ice variability”.

We thank the reviewer for the suggestion. The sentence has been revised accordingly.

Line 46-48:

“The enhanced jet structure allows Rossby wave activity from the tropics to propagate more efficiently into high latitudes, further seasonally impacting Antarctic sea ice variability. ”

L56: Consider adding additional background about the current state of the research, i.e. where prior research has left off or what is still unknown about this variability. This would add additional helpful motivation to the reader and provide some context for why the authors are investigating the seasonal differences of Antarctic sea ice variability.

We thank the reviewer for this constructive suggestion. In response, we have expanded the Introduction to better situate our work within the current research landscape. Recent studies indicate that teleconnection influences on Antarctic sea ice extend beyond the well-studied West Antarctic sector, with emerging evidence that the Indian Ocean can also modulate East Antarctic conditions during specific seasons. We have incorporated this context into the Introduction to clarify the existing research gap and to better motivate our focus on the seasonal behavior of Antarctic sea ice variability.

Line 57-70:

“While these Pacific and Atlantic influences predominantly affect West Antarctic sea ice, emerging evidence shows that the Indian Ocean can modulate not only West Antarctica but also East Antarctica^{4,37,38}, with its impacts strengthening during austral winter and spring.

Despite recent progress, our understanding of Antarctic sea-ice variability remains incomplete. While the Antarctic Dipole is widely recognized as the leading mode of interannual variability driven primarily by ENSO, the pronounced seasonality of tropical – Antarctic teleconnections, together with growing evidence for Indian Ocean influence, raises the prospect that East Antarctic sectors may host variability centers of comparable magnitude during specific seasons. This has not yet been systematically explored. Moreover, even if such seasonally dependent centers exist, it remains unclear how concurrent forcing from multiple tropical basins

combines to shape Antarctic sea-ice variability, and how individual basins contribute to the resulting patterns. These unresolved questions motivate our examination of the dominant sea-ice variability mode in each season and the basin-specific tropical – Antarctic pathways that generate these patterns.”

L62: It would be helpful to have a short definition of “circulation pairs”. I found this term unclear at this stage in the paper.

We thank the reviewer for pointing this out. We have added a brief definition to clarify the term at its first appearance.

Line 76-78:

“This circulation pattern consists of three pressure centers that regulate surface winds near the sea ice edge and generate pronounced sea ice anomalies in each season.”

Fig 1: I recommend rotating the labels of the different regions in 1a so that they are all facing right-side up (i.e. so none of the labels are upside down). The upside-down labels make them hard to read.

Figure captions: While I do not personally mind having a descriptive sentence about the key points of the figure as part of the caption, it is a bit untraditional, and such sentences might be better suited to be in the main text instead.

We appreciate the reviewer’s comments on the figure labels and captions. Following the suggestion, we standardized the orientation of the regional labels in Fig. 1a so that all text faces upward and is easier to read. We also added dashed lines to mark the boundaries between the sectors. In addition, we removed most of the descriptive sentences from the captions of Figs. 1-6 and incorporated the essential information into the main text.

L101: It would be helpful to have boxes labeled I-III on Supplementary Figure 1. I found it challenging to see how the anomaly centers of the tripole aligned with the transitional belts in Supplementary Fig 1 due to the differing map projections. Adding the boxes from Fig 1 denoting the anomaly centers to Supplementary Fig 1 would help make this more clear.

We thank the reviewer for this very helpful suggestion. To improve the readability and facilitate comparison with Fig. 1d, e, we have added the boxes labeled I–III to Supplementary Fig. 1c, d.

L105-106: Reword “patterns or the seasonal displacement” to “patterns and the seasonal displacement”

We appreciate the reviewer's suggestion. The sentence has been revised accordingly.

Line 115-117:

“Given that the transitional belts are highly sensitive to atmospheric forcing^{39,40}, it is essential to examine the role of local atmospheric circulation in shaping the tripole-like sea ice patterns and the seasonal displacement of the third anomaly center (box III in Fig. 1d, e).”

L110: It would be helpful to have a general description of how the regression analysis was performed. Such as: were the regressions performed on a grid point level or were any spatial averages performed? It would make the main text clearer to have a few more details about what regression analysis is performed.

We thank the reviewer for raising this point. The AWT and AST indices are the principal component (PC) time series of the seasonal leading EOF mode of sea ice anomalies. All regression fields are computed by regressing each atmospheric variable at every grid point onto these PC time series. To improve clarity, we have added a brief description in the main text.

Line 121-123:

“We define the principal component time series of the JJA and SON leading EOF modes as the AWT and AST indices, respectively (see “EOF analysis ” in Methods). The regression fields are obtained by regressing each atmospheric variable at every grid point onto these indices.”

L113-114: I did not find that the alignment of the “circulation pairs” with the transitional belts as clear as the authors suggested. I would recommend some additional discussion about what features are present in Fig 2a,b that indicate this clear alignment. L115: Reword this phrase to something like “atmospheric forcing is correlated with sea ice dynamics” to highlight that this regression analysis cannot prove causality or the direction of the relationship.

We thank the reviewer for this helpful suggestion. We have revised the text to more clearly describe what aspects of Fig. 2a, b indicate the proximity between the “circulation pair” centers and the transitional sea ice belts. Specifically, we now explain that the pressure centers overlap with, or are located immediately adjacent to, the regions of strongest sea-ice transitions, and that the associated meridional wind anomalies cross these transitional belts. This clarification improves the transparency of our interpretation of the spatial alignment.

As recommended, we have also modified the phrasing to avoid implying causality.

Line 127-130:

“The centers of these “circulation pairs” lie on, or are situated close to, the

transitional belts (color shading in Fig. 2a, b), where the associated wind anomalies cut across these sensitive transition zones, indicating that atmospheric circulation is strongly correlated with regional sea-ice anomalies.”

Figure 2: The spacing and units of the contours in panels a and b are not defined. Additionally, it is unclear what the red/blue contours in panels c and d are, this should be more clearly defined.

We appreciate the reviewer’s careful reading of Fig. 2. In response, we have clarified the contour information in the figure caption. For Fig. 2a, b, we now specify that the geopotential-height contours are plotted at 6-gpm intervals. For Fig. 2c, d, we explicitly state that the red and blue contours indicate positive and negative SIC anomalies of +5% and –5% in Fig. 1d, e, respectively. These clarifications have been added to the revised caption of Fig. 2.

Figure 2 caption:

“Fig.2 | Local circulation pairs controlling the Antarctic sea ice tripole. a-b Regressions of 500 hPa geopotential height (H500; contours at 6 gpm intervals) against the AWT index during JJA (a), and against the AST index during SON (b). Black contours denote the 10% and 80% seasonal-mean SIC, and shading indicates regions where the SIC standard deviation exceeds 22%. **c-d** Regressions of 2m-temperature (T2m; shading) and wind stress (green arrows) against the AWT during JJA (c), and against the AST index during SON (d). Red (blue) contours indicate positive (negative) SIC anomalies of +5% (–5%) in Fig. 1d, e. Stippling in c-d represents the areas with statistically significant regression coefficients at a level of <5% based on Student’s t test.”

Figures 2,4,5: I found the green arrows hard to see, especially the directionality. I would suggest plotting fewer arrows or increasing their size to make the directionality clearer.

We thank the reviewer for this helpful suggestion. In the revised figures, we have improved the visibility of the vectors by increasing the arrow size and reducing their density, which makes the direction much clearer. These adjustments have been applied consistently across Figs. 2, 4, and 5.

L164: JJA boxes I and III and SON box III appear to be shifted in Supplementary Fig 2 compared to Fig 1, do the authors have any ideas as to why this shift is apparent?

We thank the reviewer for noticing this detail. The slight positional shifts of the sea-ice anomaly centers in Supplementary Fig. 2 are expected in coupled model simulations. These displacements can arise from mean-state biases in sea-ice variability and extent (Hurrell et al., 2023). Importantly, despite these positional shifts, the relative phase relationship among the three anomaly centers and the overall tripole-like structure are well preserved in the model results, which is the key aspect relevant to the

teleconnection mechanism examined here. We have clarified this point in the revised manuscript to avoid potential confusion.

Line 175-184:

“To assess the atmospheric response of Antarctic sea ice to Indo-Pacific SST anomalies, we conducted a set of pacemaker experiments forced by observed SST anomalies in Fig. 3 (see “Pacemaker experiments” in Methods). By imposing basin-wide Indo-Pacific SST anomalies on the coupled air-ocean-ice system, these experiments evaluate the integrated remote influence of SST forcing. The simulations (Supplementary Fig. 2) reasonably reproduce the observed Antarctic sea-ice tripole patterns in both seasons. Minor regional differences are mainly confined to the systematic model bias in sea ice extent and variability⁴⁵. For example, the simulated third center exhibits modest longitudinal shifts, moving westward in both seasons (box IIIAWT and IIIAST in Supplementary Fig. 2) relative to the observed locations (box IIIAWT and IIIAST in Fig. 1d, e).”

Reference:

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J.-F., Large, W. G., Lawrence, D., Lindsay, K., Lipscomb, W. H., Long, M. C., Mahowald, N., Marsh, D. R., Neale, R. B., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., ... Marshall, S. (2013). The Community Earth System Model: A Framework for Collaborative Research. *Bulletin of the American Meteorological Society*, 94(9), 1339–1360. <https://doi.org/10.1175/BAMS-D-12-00121.1>

L175: Why do the authors neglect to look at the Maritime continent for the JJA season? If it is because there is little to no correlation between Maritime continent SSTs and the Antarctic sea ice pattern during this season, it would be helpful to show that, at least as a supplementary figure.

We thank the reviewer for raising this point. The Maritime Continent (MC) is not emphasized for the JJA season because its SST variability shows little association with the Antarctic sea-ice tripole during winter. To make this clear, we conducted an additional analysis showing that MC-related SST variability does not produce a statistically significant tripole-like sea ice pattern during this season. We now refer to this result in the revised manuscript and include it as Supplementary Fig. 3, which explains why MC forcing is not discussed further for JJA.

Line 202-206:

“In contrast, MC-related SST variability during JJA does not generate statistically significant Antarctic sea-ice anomalies or a tripole-like pattern (Supplementary Fig. 3a), consistent with its weak relationship with AWT (Fig. 3a). Accordingly, the following analysis focuses on the PO- and IO-related atmospheric

responses.”

L190: I was a little bit confused about what the results of the Atmospheric transient experiments are adding to the analysis? I think some more clarification on how the atmospheric transient experiments are adding to the analysis would be helpful.

We appreciate the reviewer’s request for clarification. The atmospheric transient experiments are included to provide a dynamical verification of the statistical results. While the responses derived from independent SST indices represent statistically significant correlations, they do not establish causality. The transient atmospheric experiments address this limitation by isolating the atmospheric response to SST variability in individual ocean basins. By prescribing basin-specific, time-evolving SST anomalies, these experiments directly test whether SST forcing from each basin can generate the Rossby wave pathways inferred from observations and help confirm the contrasting wave trains associated with different ocean basins. We have clarified this role in the revised manuscript.

Line 191-196:

“We then examined how each index influences sea ice and its associated Rossby-wave pathways using observational data (Fig. 4, 5), and subsequently evaluated these pathways using atmospheric transient experiments (Supplementary Fig. 4, 5) (see “Atmospheric transient experiments” in Methods). In these simulations, SST anomalies associated with each tropical basin are prescribed separately, allowing us to isolate the basin-specific atmospheric forcing responsible for generating distinct Rossby wave trains.”

L191-192: The magnitude of regression coefficients in Fig 4c,d and the simulated forcing (panels e and f) are quite different. What does this indicate about the observational regression analysis or the modeled results? Is this difference in magnitude expected?

We appreciate the reviewer’s insightful question. As noted above, following the revision the original Fig. 4 has been separated into observational diagnostics (Fig. 4b, d) and model-based transient experiment results (Supplementary Fig. 4a, b). The simulated Rossby-wave response is indeed weaker, with an amplitude roughly half of that inferred from observations. This reduced magnitude is expected for AGCM-based transient experiments, which typically underrepresent wave–subtropical jet interactions and wave reflection processes due to limited horizontal resolution (Danabasoglu et al., 2020). Nevertheless, the simulated wave trains capture the key propagation pathways and phasing seen in the observational regressions, indicating that the underlying physical mechanism of the Indo-Pacific Ocean–Antarctic teleconnection is robust. We have added this explanation to the main text.

Line 218-222:

“Additionally, the intensity of the simulated response is approximately half of that seen in observations. This discrepancy in strength could stem from limitations in model resolution, which may affect the model's ability to accurately capture interactions within the subtropical jet and complex wave reflection processes. ”

Reference:

Danabasoglu, G., Lamarque, J.-F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lauritzen, P. H., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., ... Strand, W. G. (2020). The community earth system model version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, 12(2), e2019MS001916. <https://doi.org/10.1029/2019MS001916>

Figure 6: Why are some of the red/blue contours solid or dashed lines? Clarification of this in the main text and caption would be helpful.

Thank you for pointing out this ambiguity. Solid contours in Fig. 6 indicate circulation anomalies located close enough to the sea-ice edge to influence the tripole pattern in each season, whereas dashed contours denote weaker or more distant anomalies that have limited impact. We have added a concise explanation to both the main text and the revised caption of Fig. 6.

Line 246-263:

“Therefore, partial regression and transient experiments confirm that Rossby wave trains from different basins display contrasting seasonal behavior. To investigate the origin of this contrast, we further analyze the moderating role of the Southern Hemisphere mean flow in shaping Rossby wave trajectories. The subtropical jet (black contours in Fig. 6) forms a broad imaginary wave number region (white zone in Fig. 6) south of the jet core, which acts as a barrier to the wave propagation (see “Rossby wave number” in Methods). This barrier strengthens in JJA and weakens in SON. In both seasons, wave activity originating from the central Pacific (red arrows) crosses the barrier-free region and produces the eastern high – low “circulation pair” (red and blue solid circles), thereby contributing efficiently to the winter tripole.

In contrast, the pathways of wave trains originating from the Indian Ocean and Maritime Continent depend strongly on the seasonal configuration of the subtropical jet. During JJA (Fig. 6a), the strengthened barrier deflects Indian Ocean wave activity (blue arrows) past the Ross Sea, allowing it to reach the King Hakon VII Sea, supporting the winter tripole. During SON (Fig. 6b), the barrier contracts westward, allowing wave trains from both the Indian Ocean (blue arrows) and the Maritime Continent (purple arrows) to penetrate the westerlies and reach the western Ross Sea, where they amplify the western low – high “circulation pair” (blue and red solid circles) that characterizes the spring tripole.”

Figure 6 caption:

“Fig.6 | Southern Hemisphere mean flow related to Rossby wave dynamics. a-b Rossby wave number (K) during JJA (a) and SON (b). The black contour represents the mean state of 200-hPa zonal wind speed, which indicates the strength of the subtropical jet. South of the jet, strong zonal wind shear generates regions of negative zonal wind velocity, resulting in areas of imaginary K (white shading) that act as reflective barriers to wave propagation (see “Rossby wave number” in Methods). Colored arrows indicate stationary Rossby wave trains triggered by tropical forcing from the IO (blue), PO (red), and MC (purple). Red (blue) circles denote the anomalous high (low) circulation centers in the “circulation pair.” Solid contours denote circulation anomalies located sufficiently close to the sea ice edge to influence the tripole pattern, whereas dashed contours indicate weaker or more distant anomalies with limited impact.”

L322-323: Is this monthly data detrended prior to analysis? I would imagine that removing the long term trend of the data would be important prior to analysis.

We thank the reviewer for raising this important point. All monthly variables used in the EOF and regression analyses were detrended at each grid point prior to computing anomalies. We have now added this information to the Methods section to clarify the procedure.

Line 369-371:

“Anomalies are computed relative to the 1979-2023 climatological annual cycle, and all fields are detrended at each grid point over the same period.”

L325: Why is the 30% SIC definition for sea ice edge used? Since the traditional definition of sea ice extent is 15% SIC, it would be helpful to provide some discussion on why the 30% SIC definition was used.

We thank the reviewer for raising this point. Yuan & Martinson (2001) used the 15% SIC contour as the sea-ice edge (SIE), which effectively describes a one-dimensional longitudinal character of the Antarctic Dipole (ADP). However, our objective is to characterize the two-dimensional spatial pattern of sea-ice anomalies associated with the ADP and the tripole. To more clearly represent the full spatial structure of these modes, we follow S. Li et al., (2021), who used the 30% SIC contour in EOF analyses to derive the ADP index and then regressed SIC onto this index to obtain its full two-dimensional expression. This approach more clearly represents the spatial characteristics of ADP-like variability.

Importantly, the choice between 15% and 30% does not materially affect the results. As noted by Yuan & Martinson (2000), “the SIE is not overly sensitive to the isopleth chosen, because sea-ice concentration increases rapidly near the ice edge during most of the ice-covered season.” Consistent with this, Supplementary Fig. 1 shows that the

10% and 80% SIC isolines are tightly packed, indicating a steep ice gradient in the transitional belt; therefore, the 15% and 30% contours differ only slightly in position. The 30% contour more robustly captures the mean characteristics of this transitional belt and thus provides a clearer representation of the spatial patterns examined here.

Reference:

- Li, S., Cai, W., & Wu, L. (2021). Weakened Antarctic Dipole Under Global Warming in CMIP6 Models. *GEOPHYSICAL RESEARCH LETTERS*, 48(16), e2021GL094863. <https://doi.org/10.1029/2021GL094863>
- Yuan, X., & Martinson, D. G. (2000). Antarctic Sea Ice Extent Variability and Its Global Connectivity*. *Journal of Climate*, 13(10), 1697–1717. [https://doi.org/10.1175/1520-0442\(2000\)013%3C1697:ASIEVA%3E2.0.CO;2](https://doi.org/10.1175/1520-0442(2000)013%3C1697:ASIEVA%3E2.0.CO;2)
- Yuan, X., & Martinson, D. G. (2001). The Antarctic dipole and its predictability. *Geophysical Research Letters*, 28(18), 3609–3612. <https://doi.org/10.1029/2001GL012969>

L404-414: I suggest providing some additional information as to how the forcing for the atmospheric transient experiments was designed. From my understanding, the SSTs outside of the regions of interest were held fixed at the climatological seasonal cycle, while SSTs inside the regions of interest were perturbed. If this is correct, how were the SSTs inside the regions of interest perturbed?

We appreciate the reviewer’s request for clarification. In the atmospheric transient experiments, SSTs outside the target basin are fixed to the seasonally varying climatological mean (1981–2010), while SSTs inside the target basin follow the observed monthly HadISST fields from 1979–2023, effectively prescribing realistic interannual SST perturbations. This design isolates the atmospheric response to SST variability originating from each basin. We have added this explanation to the Methods section.

Line 453-467:

“A 100-year control simulation is first performed using the seasonally varying climatological mean SST and SIC from 1981 – 2010. Twelve years from this control run are randomly selected to initialize 12 ensemble members.

To isolate the atmospheric response to SST variability originating from different parts of the Indo-Pacific, we design three basin-specific experiments targeting the tropical Pacific (20 ° S – 20 ° N), Indian Ocean (20 ° S to its northern boundary), and Maritime Continent (20 ° S – 20 ° N). These non-overlapping domains collectively span the tropical Indo-Pacific, and 5 ° buffer zones are applied along the adjacent boundaries to ensure smooth dynamical transitions.

Within each experiment, SSTs inside the target basin are replaced by the observed monthly HadISST fields from 1979 – 2023, thereby retaining their full interannual variability. Outside the target basin, SSTs are fixed to the seasonally varying climatological mean (1981 – 2010) with no interannual variability. This configuration

isolates the atmospheric response to SST variability originating solely from the selected basin.

Each ensemble member is integrated from 1979 to 2023, and the 12-member ensemble mean is used to suppress internal atmospheric noise and highlight the forced atmospheric response.”