

Pacific Sub-Decadal Sea Surface Temperature Variations Contributed to Recent Antarctic Sea Ice Decline Trend

Corresponding Author: Professor Qigang Wu

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 is a timely and interesting study that addresses some of the questions raised recently in the literature concerning the decline in Antarctic sea ice extent over the last few years. The study provides insights into the role of different ocean basins as the source of teleconnections that modify atmospheric circulation and ultimately sea ice extent around Antarctica. The authors follow a standard modelling method for assessing the role of teleconnections and conclude that sea surface temperature variability in the Pacific Ocean, with a smaller contribution from the Atlantic Ocean have forced changes to sea level pressure and therefore the wind regime that have ultimately tended towards less sea ice in recent years. The pattern of changes in the tropical ocean reflects the negative phase of the IPO and a typical La Niña condition. The major influence of the teleconnection on the Antarctic atmosphere over the last decade is a deepening of the ASL and increased pressure over the Weddell Sea and West Pacific region.

The introduction gives a concise but well-researched description of Antarctic sea ice variability. I didn't notice any missing studies and have discovered a couple of studies that I wasn't aware of. Overall, I find this to be an interesting piece of work that adds to the ongoing discussions regarding the drivers of Antarctic sea ice variability. The suggestion that the negative IPO is a driver of Antarctic sea ice change is not new, but this study applies a modelling study to demonstrate how the trends in Pacific SSTs link to the patterns in Antarctic sea ice extent change, which gives some extra weight to the suggestion that the IPO is a major drive of sea ice variability when this is a climate mode of decadal variability that is challenging to compare to the short Antarctic sea ice record. I outline a couple of major concerns below but would be interested to see this article published if the authors address these. I also list some minor comments below.

Major Concerns

Other recent work has highlighted the potential role of the ocean in driving recent sea ice change, e.g. Hobbs et al., 2024 and Purich and Doddridge, 2023 (see references listed below), but so far there is a lack of evidence as to how and why. This study concludes that that teleconnections from the Pacific and Atlantic have increased subsurface warming (lines 206-208). However, the only evidence I see for this link is that these mechanisms have decreased sea ice and the inference is that therefore there would be ocean warming as there is less sea ice. I do not see how this definitively shows why the ocean has warmed. During spring, an early retreat, or more extensive retreat allows more solar energy to warm the ocean mixed layer. But, subsequent sea ice melt forms a well-stratified surface layer, which does would have to be overcome to lead to increased melting of sea ice. This study does not give evidence of any mechanism for overcoming the increased stratification. Either the statement should be revised or more evidence provided for the role of the teleconnections in driving the ocean warming.

I don't know much about the CESM1.2 model. The authors do not show the modelled sea ice extent, perhaps because the model does not adequately reproduce the sea ice extent. This may not be important as all models struggle to reproduce Antarctic sea ice extent. However, it would be helpful to show that the atmosphere is well represented, either through a direct comparison with ERA5 or with reference to articles that support the use of the model in this way.

Is there a particular reason that you chose 2013-2023 for your analysis. It may be perfectly reasonable to pick any time

period you like, but I ask because Purich and Doddridge, 2023 found a transition in Antarctic sea ice state in 2007, which could be an interesting break point.

Minor comments

Line 40: suggest replacing "middle" with "mid"

Line 155: refers to "divergence" but on line 152, the text talks about anomalous convergence, not divergence.

Line 173: suggest to add "activity" after "anticyclonic"

Line 174: Why does the fact that the GLTrend experiment is similar to the PACTrend experiment mean that the model captures the observed atmospheric circulation trend features remarkably well?

Line 189: suggest adding Hobbs et al., 2024 to the references 27 and 28.

Line 194: The similarities are broad scale, It is interesting that the Amundsen-Bellingshausen Seas have an overall decreasing trend while showing such hotspots of warming during 2006, 2016 and 2020. The decadal trend masks a large amount of interannual variability. How much data is there for each ocean basin? I.e., are there many data point between 50 and 65 S in the Amundsen Sea?

References

Hobbs, W., Spence, P., Meyer, A., Schroeter, S., Fraser, A. D., Reid, P., Tian, T. R., Wang, Z., Liniger, G., Doddridge, E. W., & Boyd, P. W. (2024). Observational evidence for a regime shift in summer Antarctic sea ice. *Journal of Climate* 37, 2263–2275. <https://doi.org/10.1175/JCLI-D-23-0479.1>

Purich, A., and E. W. Doddridge, 2023: Record low Antarctic sea ice coverage indicates a new sea ice state. *Communications Earth & Environment*, 4, 314, 10.1038/s43247-023-00961-9.

(Remarks on code availability)

The climate model code is a standard code so anyone who wanted to run this model would be able to do so. The modifications made by the authors are available on request, but someone could reproduce these experiments by using the forcing data as described by the authors.

Reviewer #2

(Remarks to the Author)

This study focuses on the observed decline in Antarctic sea ice extent (SIE) in the recent decade (2013-2023). The authors propose that the recent SIE decline has been significantly influenced by atmospheric circulation changes near Antarctica. Using a set of prescribed SST simulations with CESM1, the authors further conclude that the observed circulation changes, including a deepening of the Amundsen Sea Low and associated northerly winds that are conducive to reducing SIE, were mainly forced by the sub-decadal Pacific SST changes (notably the negative phase of IPO), with additional contributions from Atlantic SST changes. The atmospheric circulation impact on SIE has enhanced the Southern Ocean subsurface warming effect, altogether contributing to the total observed Antarctic climate changes.

Overall, I find the paper to be interesting and the topic to be important. However, I have several major concerns about the foundation of the main argument and the experiments used to support the story, which I will elaborate on below. These concerns led me to worry that the current version of the manuscript is not suitable for publication.

Major concern 1.

Regarding the recent decline of Antarctic SIE, previous studies have proposed the role of Southern Ocean subsurface warming (e.g., Zhang et al. 2022). Here the authors propose that the decadal-long SIE decline can be additionally caused by atmospheric circulation changes, which are forced mainly by Pacific SST variations. The authors have done a great job establishing the link between Antarctic circulation changes and their corresponding SST forcing. Although I appreciate the thorough discussion in the paper, I don't think this atmospheric bridge mechanism is a new piece. There have been many papers showing how tropical Pacific SST anomalies remotely modulate Antarctic circulation (e.g., Ding et al. 2011, Meehl et al. 2016 for the early SIE expansion period). On the contrary, the other part of the proposed causal connection - atmospheric circulation changes drive SIE changes – is not well discussed and validated. The authors put forward the hypothesis that "the forcings of atmospheric circulation changes have played a key role in driving the rapid decline of Antarctic SIE in the recent decades" (line 71). However, this main argument seems built simply on a qualitative speculation that the SLP-associated wind anomalies induce anomalous advection, resulting in SIE changes (Fig. 1). The simulations and analysis in the rest of the paper, awkwardly, fail to verify this hypothesis. That is, the prescribed SST (presumably also fixed SIE) simulations are unable to provide the actual SIE response to the SST-driven circulation forcing by construction. Thus, I find that the inconsistency between the modeling evidence and the conclusion makes the paper less convincing.

Furthermore, the conclusion that atmospheric circulation plays a significant role in driving SIE changes is weakened by the

finding that the SIE decline appears to be indeed associated with Southern Ocean subsurface warming, most pronounced in the Weddell Sea (Fig. 4), as previously proposed. This raises a key question for this paper: to what extent does the proposed atmospheric circulation effect contribute to the recent SIE decline? Is it a major contributor or only a secondary player compared to the subsurface warming effect? In my opinion, the argument would have been more novel and impactful if the authors had quantified the relative roles of atmospheric circulation and ocean subsurface warming effects on the recent SIE decline.

Major concern 2.

Related to the above, the limitation of this work seems to in part arise from the caveat that the prescribed-SST simulations do not allow one to estimate the SIE response. The authors also invoke results from a set of fully-coupled pacemaker simulations with PDV-associated SST anomalies in the Pacific, although the SIE decline response in the Weddell Sea appears to be much weaker and the SIE increase in the Amundsen Sea and Ross Sea appears to be too strong than those observed. I wonder why the authors don't use more realistic pacemaker simulations, with SSTs in the Pacific/Atlantic sectors nudged towards observed transient anomalies over the targeted period (2013-2023). This way, the authors could isolate and quantify the impacts of realistic SST variations on Antarctic SIE in the coupled system. These are likely to be better than the AGCM runs (which don't allow dynamic SIE response) and the idealized PDV-SST pacemaker runs (which only provide the SIE response to PDV phase transitions rather than the realistic full SST variations).

Minor comments:

Line 111: when introducing the “pacemaker” simulations, it would be helpful to highlight that these are “coupled” simulations, distinct from the above AGCM simulations.

Line 117: I would suggest adding pattern correlation here to quantify the level of resemblance between the observed circulation pattern and the SST-driven circulation pattern.

Line 184: northwesterly -> southerly?

Line 225 – 226: I do not follow why this suggests the SIE decline results from internal variability. The IPO pacemaker simulations show a weaker SIE response compared to observations and the PACTtrend simulation. Doesn't this suggest the observed SST forcing on SIE may have involved some forced response beyond just the IPO SST forcing?

Line 288: how is SIE handled in these AGCM runs? Is it fixed to the observed climatology?

Line 291-292: I would suggest adding a plot to show the regions of the SST forcing specified in AGCM runs (if the authors were to continue using these simulations).

Reference:

Ding, Q., Steig, E. J., Battisti, D. S., & Küttel, M. (2011). Winter warming in West Antarctica caused by central tropical Pacific warming. *Nature Geoscience*, 4(6), 398-403.

Meehl, G. A., Arblaster, J. M., Bitz, C. M., Chung, C. T., & Teng, H. (2016). Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. *Nature Geoscience*, 9(8), 590-595.

Zhang, L., Delworth, T. L., Yang, X., Zeng, F., Lu, F., Morioka, Y., & Bushuk, M. (2022). The relative role of the subsurface Southern Ocean in driving negative Antarctic Sea ice extent anomalies in 2016–2021. *Communications Earth & Environment*, 3(1), 302.

(Remarks on code availability)

The code used in this paper is not provided in the current version of the paper (it is available only upon request).

Reviewer #3

(Remarks to the Author)

Review Qigang Wu et al : *Nature Communications*

Contributions of Sub-Decadal Pacific Sea Surface Temperature Variations to Rapid Antarctic Sea Ice Decline in the Recent Decade

There have been several papers written on the 2023 sea ice anomaly, which have come into press after the writing of this paper, but now cannot be ignored. However, there is still a requirement for a paper on the remote drivers of the changes. Unfortunately, such drivers can be quite complicated (similar to what the drivers are of PDO). Attempting to do this through a trend analysis is, I feel, not the correct method for the reasons given below.

39 & 44: The low of 2016 does not persist but recovers such that the ice is back at the climatic mean by 2021 (Fig 1). This confirms a subsurface ocean heat source being depleted. Why do the authors now plot a trend line through the 2013-2023 when clearly this is not a sustained trend? To do so is an oversimplification. The decadal trend theme, rather than intermittent events, as most other papers on the subject describe, possibly associated with different mechanisms, is a weakness of this paper. It requires a complex sequence of drivers, as evidenced by the number of supplementary plots, none of which is convincing. As a consequence, the paper is confusingly written, attempting to describe too much in words when a schematic diagram such as Fig3 in Scott Power's paper *Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects* | *Science* would greatly simplify and clarify the process. The

intermittency of the events would also make the use of causal networks (were they to be used) to solve the remote forcing very difficult.

Breaking up the description into smaller paragraphs and making a distinct connection in each paragraph would help clarify the argument. As it stands the argument is a mess, and very hard to follow.

51-69: Monica Ionita (Frontiers | Large-scale drivers of the exceptionally low winter Antarctic sea ice extent in 2023 (frontiersin.org)) makes a compelling case that the event of 2023 was associated with a wave mode 3 pattern. It is possible that a deepening and shift of the Bellingshausen Sea Low is associated with this pattern, but this would need to be demonstrated. Your description here is rather messy and would be better summarized by the wave mode 3 analogy. Of course, the driver of the wave mode 3 is not discussed in Ionita's paper and needs investigation.

Another characteristic of the sea ice changes, as discussed by Hobbs et al (2024) Observational Evidence for a Regime Shift in Summer Antarctic Sea Ice in: Journal of Climate Volume 37 Issue 7 (2024) (ametsoc.org) is that the Antarctic sea ice has recently become predictable season by season. This would need to be explained within a remote forcing context.

(Remarks on code availability)

The code has not been made available and although this is reasonable for climate model data which care very large datasets, the analysis code should be made available

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I have reviewed the revised manuscript, which has been substantially improved to address the concerns raised in my initial review. The manuscript investigates the causes of the significant decline in Antarctic sea ice extent from June 2013 to May 2023, focusing on the roles of Pacific sub-decadal sea surface temperature trends, atmospheric circulation changes, and the influence of tropical polar teleconnections. This is an interesting manuscript, and the topic is important given the need to understand the drivers of the recent low sea ice cover around Antarctica.

In particular, the methodology has been strengthened by switching from AGCM simulations to coupled pacemaker experiments, providing more robust evidence for the proposed mechanisms. The authors employ a multi-method approach. They analysed satellite-derived sea ice concentrations and atmospheric variables (ERA5 reanalysis) to demonstrate that the decline in Antarctic sea ice is closely linked to a strengthened ASL and associated wind anomalies. They use a heat budget analysis to evaluate the mixed layer temperature in the Southern Ocean and demonstrate the role of subsurface ocean heat flux in driving the decline of Antarctic sea ice, with wind-driven upwelling and Ekman transport as key mechanisms. The revised manuscript now includes coupled ensemble pacemaker simulations to impose Pacific and global SST anomalies over the 10-year study period (June 2013 to May 2023). The PACTrend experiments impose observed SST from the Pacific Ocean, while the GLTrend experiment imposes global SST anomalies. The pacemaker experiments provide robust evidence of the link between Pacific SST trends and Antarctic sea ice variability by demonstrating a clear mechanistic connection between tropical SST anomalies and the decline of Antarctic sea ice through tropical-polar teleconnections. By controlling these external forcing patterns, the experiment can simulate the atmospheric and oceanic responses and isolate regional contributions. They subsequently examine the responses to radiative forcing under historical and SSP370 scenarios from 17 CMIP6 models to independently validate their findings by confirming that natural variability, particularly driven by Pacific SST anomalies, is the dominant factor behind the recent decline in Antarctic sea ice.

Their key findings reveal that Pacific sub-decadal sea surface temperature (SST) trends were the primary driver of changes in Southern Ocean atmospheric circulation and subsurface ocean warming and that these SSTs, through tropical-polar teleconnections, significantly contributed to the decline of Antarctic sea ice. Approximately 40% of the observed decline in Antarctic sea ice extent (SIE) is attributed to variations in Pacific and Atlantic SSTs. Radiative forcing contributed about 12% to the overall reduction in SIE, emphasising the dominant influence of teleconnections.

My main concern with the previous version of the manuscript was the lack of robust evidence for the teleconnection in driving ocean warming. The revised (and strengthened) approach to using pacemaker experiments has addressed this concern with the PACTrend simulation reproducing warming in the Southern Ocean subsurface layers (100-500 m depth) in response to tropical Pacific SST anomalies. The authors acknowledge my point about stratification, and I accept that these effects may be small at the timescales this work is looking at (sub-decadal). The model agreement with observations strengthens the evidence for this mechanism. Warmer Pacific SSTs strengthen the IPO in its negative phase, creating a La Nina-like state. These anomalies intensify the ASL, enhancing cyclonic wind patterns over the Southern Ocean. Strengthened winds drive Ekman transport, upwelling warm subsurface water that melts sea ice.

I also queried how well the model represented the atmosphere, and the revised manuscript demonstrates that the atmospheric and sea ice responses in the new coupled pacemaker experiments align well with the reanalysis data and satellite observations. The coupled experiments capture the spatial and seasonal patterns of Antarctic sea ice concentration decline, particularly the significant ice loss in the Amundsen-Bellingshausen Sea and the Weddell Sea, especially in austral spring and summer when tropical-polar teleconnections are strongest. The simulations also reproduce the strengthening of the ASL in all seasons, positive sea-level pressure anomalies over the Weddell Sea and the western South Pacific, and

PSA-like Rossby wave patterns. The model reproduces the spatial and seasonal patterns of subsurface warming seen in the Argo observations with high fidelity but underestimates the magnitude of warming in certain regions. The agreement between observed and simulated warming trends provides strong support for the proposed mechanisms linking tropical Pacific SST anomalies, Southern Ocean circulation changes, and Antarctic sea ice decline.

The choice of study period has been justified with clear reasoning related to ENSO evolution and IPO phase shifts.

I recommend this manuscript for publication. The authors have successfully addressed all major concerns and significantly improved the scientific quality of their work. The revised analysis presents a comprehensive and well-supported understanding of ocean-atmosphere-sea ice interactions in Antarctica.

(Remarks on code availability)

This is a well-laid out repository with clear instructions. It contains NCL programs and datasets to reproduce the figures in the manuscript.

Reviewer #2

(Remarks to the Author)

I appreciate that the authors considered my suggestion and added the new set of fully-coupled pacemaker runs. These new simulations have greatly strengthened the paper and provided valuable modeling evidence. Overall, I find the paper in much better shape.

Regarding the results of these new simulations, I have some additional concerns. As listed below, some of them may be critical for interpreting the modeling results. I may have some misunderstandings here, in which case, clarifications would be helpful (potentially also for the broader audience).

Line 473 – 483: The method section describing the coupled pacemaker runs would benefit from further clarification. For example, what SSTs are exactly restored in the model? The SST climatology + linearly ramping anomalies that amount to the observed trend at each grid box? If so, why are the simulations 100-years long while the targeted observational SST trends span only 10 year (2013-2023)? In other words, do the pacemaker runs maintain the same trend (K/dec) as the observations but extend it over a longer period, making the total imposed change in the model 10 times larger than in reality?

Line 99: This doesn't seem to hold for JJA and DJF.

Line 158: what is the pattern correlation level for SLP in JJA? Any thoughts on why the pacemaker runs better reproduce the observed patterns in other seasons but not JJA?

Line 193: But this *seasonally robust* simulated sea-ice feature is not in observation.

Line 265: Does this imply that the Atlantic SST effect, derived from these two sets of coupled pacemaker runs, is biased?

Line 288-291: I am not sure I follow this... Isn't the Atlantic/Indian Ocean effect obtained by subtracting the Pacific effect from the global SST simulation? If so, why is it still related to Pacific SST variations?

Fig. 298 Fig. S10.

Fig. 6: The ocean temperatures shown are averaged over 50-65°S. However, the simulations nudge SSTs all the way to 60°S. Doesn't this mean that more than half of these "responses" are prescribed forcing rather than the actual response?

Line 353-355: How should we interpret the remarkable differences between the simulation forced by observed decadal SST trends (Fig. 3) and the simulation forced by PDV phase change (Fig. S16)? What does it imply for the observed SST trends? The authors mention the ensemble average. However, I assume that the ensemble averaging primarily removes random atmospheric variability and can still yield a robust "forced response" to the imposed PDV SST variation. Therefore, I wonder if other dominant factors are at play. For example, it could suggest that the observed SST trends are not solely driven by a negative PDV or that random atmospheric variability also plays a major role here.

(Remarks on code availability)

The website requires account registration.

Reviewer #3

(Remarks to the Author)

Most concerns have been addressed except that some Results/Analysis could be split up by sub-heading to make it easier to read and refer to figures. For example 'observations' and 'model'

Otherwise I suggest accepting the paper.

I am uneasy about the use of sea ice extent when ice area is a better diagnostic. The ice edge might retreat but the ice concentration increase. However, I do not expect the authors to change the assessment method at this point.

The authors refer to the difference in longitude of the ASL in models and observations, which can alter the poleward heat transport into the Weddell Sea. However, it is worth noting that the 2023 low extent was associated with a real shift in the ASL towards 90W and hence large heat transports and loss of sea ice in the Weddell. As well as the depth of the ASL has there been a drift in its longitude? Again, not essential that this be investigated in this paper.

(Remarks on code availability)

Adequate use of readme files, but with few inline comments.

Version 2:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

Thanks for the response and the revision. I am pleased to recommend publication.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)

The paper is much improved and results more robust in this latest iteration due to the inclusion of the pacemaker simulations. I recommend accepting the submission.

I have only two issues

1. the use of the term 'Ekman suction' it is normally referred to as 'Ekman pumping'.
2. There are no DOI in the references.

(Remarks on code availability)

Improved inline comments make the purpose of the code easier to understand

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REVIEWER COMMENTS

We thank three reviewers for their insightful and helpful comments. We have considered all comments and significantly revised the manuscript. We perform two sets of 100-year coupled pacemaker experiments and are able to simulate realistic atmospheric and sea ice responses to Pacific and global sub-decadal SST variations. All results of previous AGCM simulations are deleted. All changes and discussions of results from the coupled Pacemaker experiments in the manuscript text file are shown with color highlighting.

Reviewer #1 (Remarks to the Author):

This is a timely and interesting study that addresses some of the questions raised recently in the literature concerning the decline in Antarctic sea ice extent over the last few years. The study provides insights into the role of different ocean basins as the source of teleconnections that modify atmospheric circulation and ultimately sea ice extent around Antarctica. The authors follow a standard modelling method for assessing the role of teleconnections and conclude that sea surface temperature variability in the Pacific Ocean, with a smaller contribution from the Atlantic Ocean have forced changes to sea level pressure and therefore the wind regime that have ultimately tended towards less sea ice in recent years. The pattern of changes in the tropical ocean reflects the negative phase of the IPO and a typical La Niña condition. The major influence of the teleconnection on the Antarctic atmosphere over the last decade is a deepening of the ASL and increased pressure over the Weddell Sea and West Pacific region.

The introduction gives a concise but well-researched description of Antarctic sea ice variability. I didn't notice any missing studies and have discovered a couple of studies that I wasn't aware of. Overall, I find this to be an interesting piece of work that adds to the ongoing discussions regarding the drivers of Antarctic sea ice variability. The suggestion that the negative IPO is a driver of Antarctic sea ice change is not new, but this study applies a modelling study to demonstrate how the trends in Pacific SSTs link to the patterns in Antarctic sea ice extent change, which gives some extra weight to the suggestion that the IPO is a major drive of sea ice variability when this is a climate mode of decadal variability that is challenging to compare to the short Antarctic sea ice record. I outline a couple of major concerns below but would be interested to see this article published if the authors address these. I also list some minor comments below.

Major Concerns

Other recent work has highlighted the potential role of the ocean in driving recent sea ice change, e.g. Hobbs et al., 2024 and Purich and Doddridge, 2023 (see references listed below), but so far there is a lack of evidence as to how and why. This study concludes that that teleconnections from the Pacific and Atlantic have increased subsurface warming (lines 206–208). However, the only evidence I see for this link is that these mechanisms have decreased sea ice and the inference is that therefore there would be ocean warming as there is less sea ice. I do not see how this definitively shows why the ocean has warmed. During spring, an early retreat, or more extensive retreat allows more solar energy to warm the ocean mixed layer. But, subsequent sea ice melt forms a well-stratified surface layer, which does would have to be overcome to lead to increased melting of sea ice. This study does not give evidence of any mechanism for overcoming the increased stratification. Either the statement should be revised or more evidence provided for the role of the teleconnections in driving the ocean warming.

We thank the reviewer for her/his support. All issues are addressed in the answers (and associated modifications of the manuscript) to the specific comments below. In the revised manuscript, we perform two sets of 100-year coupled pacemaker experiments and simulate similar atmospheric responses as that in the AGCM simulations of the old manuscript, but realistic sea ice responses to Pacific and global sub-decadal SST trends.

In the old manuscript, we performed AGCM simulations and demonstrated that Pacific and Atlantic sub-decadal SST variations contributed to the observed deepening of the Amundsen Sea Low and anomalous high pressure over the Weddell Sea and West Pacific sectors, which substantially induced Southern Ocean surface air temperature warming (not the ocean warming), leading to Antarctic SIE decline. Therefore, Pacific and Atlantic sub-decadal SST variations and subsurface warming have acted in concert to drive the observed sea ice loss in the recent decade.

In the revised manuscript, we perform the coupled pacemaker experiments and demonstrate that La Niña-like Pacific sub-decadal SST variations have dominantly driven Southern Ocean atmospheric circulations through tropical–polar teleconnections and significantly contributed to Southern Ocean surface (SST) and subsurface warming and Antarctic SIE decline in the recent decade. There is a warmer upper ocean column from the surface down to 500 m depth in the Southern Ocean and all five sectors that contributed to the sustained retreat of Antarctic sea ice (Figs. 5 and S11).

It is true that sea ice melt forms a well-stratified surface layer, which suppresses vertical instabilities and upwelling of subsurface warm water to the surface, potentially reducing sea ice loss. However, such negative effects of enhanced stratification and

weakened deep convection may be small in the sub-decadal time scales. Responses of these warmer Southern Ocean surface air temperatures and upper ocean temperatures to La Niña-like Pacific and global SST trends, combined with the direct effects of surface wind forcing on the sea ice, have produced the rapid decrease of Antarctic sea ice extent in the recent decade.

I don't know much about the CESM1.2 model. The authors do not show the modelled sea ice extent, perhaps because the model does not adequately reproduce the sea ice extent. This may not be important as all models struggle to reproduce Antarctic sea ice extent. However, it would be helpful to show that the atmosphere is well represented, either through a direct comparison with ERA5 or with reference to articles that support the use of the model in this way.

In the old manuscript, we perform AGCM to examine the SH atmospheric circulation responses to Pacific sub-decadal SST variations, in which observed trends of SST over the Pacific (or Atlantic and global ocean) from June 2013 to May 2023 are added to the model simulated SST, and the climatological SST over other basins and sea ice concentration is specified. We showed that observed SLP and UV850 trends are well represented in these AGCM experiments.

In the revised manuscript, we perform two sets of 100-year coupled pacemaker simulations in which observed trends of SST anomalies over the Pacific and global ocean between 60°S to 60°N from June 2013 to May 2023 are added to the model simulated SST, respectively. These pacemaker experiments only assimilate prescribed observed SST trend anomalies into the ocean component of the coupled model, and the sea ice component fully responds to atmospheric and ocean variations.

We demonstrate that the coupled experiments simulate realistic atmospheric and sea ice responses to La Niña Pacific and global sub-decadal SST variations.

Is there a particular reason that you chose 2013–2023 for your analysis? It may be perfectly reasonable to pick any time period you like, but I ask because Purich and Doddridge, 2023 found a transition in Antarctic sea ice state in 2007, which could be an interesting break point.

We agree that the transition in Antarctic sea ice state in 2007 was an interesting break point. There are two reasons we chose 2013–2023. First, we focus on the tremendous Antarctic sea ice decline since the peak of 2014. Second, we hope to maximize the observed impacts of Pacific sub-decadal SST variations on the tremendous sea ice decline in the recent decade. The Pacific sub-decadal SST variations mainly originated from the evolution of ENSO variations and the shift of the IPO from the positive phase in 2014–2016 to the negative phase after 2016. During 2014–2016, the tropical Pacific experienced persistent warm conditions that included a weak El Niño in 2014 and an extreme El Niño in 2015–2016, while the prolonged 2020–2023 La Niña conditions

developed and decayed in autumn 2023. During June 2013-May 2023, the observed SST trend patterns over the Pacific (Fig. 2a and Figs. S2a-d) resemble the typical La Niña conditions and the negative phase of the IPO.

Since June 2023, a strong El Niño condition has developed, and cold La Niña-like cold conditions in the central-eastern tropical Pacific in the 10-yr SST trends in winter and spring during 2014-2023 are much weaker than those during 2013-2022, likely mitigating sub-decadal impacts of Pacific SST anomalies on the Antarctic SIE in these two seasons. In the last section, we discuss the roles of the atmospheric and subsurface ocean warming forcing in the sea ice decline since June 2023. Above discussions can be found in the method part.

Minor comments

Line 40: suggest replacing "middle" with "mid"

It is changed.

Line 155: refers to "divergence" but on line 152, the text talks about anomalous convergence, not divergence.

In the old manuscript, tropical Atlantic warming strengthens local Hadley circulation and zonal Walker circulation, causing anomalous divergence over upper troposphere divergence over the subtropical Atlantic (line 155), and anomalous convergent flow across the upper troposphere in the central-eastern Pacific (line 152). Similar atmospheric responses to Atlantic and Indian Ocean SST trends are found in the coupled pacemaker experiment (Fig. S7). We revised these descriptions in the revised manuscript.

Line 173: suggest to add "activity" after "anticyclonic"

It is added.

Line 174: Why does the fact that the GLTrend experiment is similar to the PACTrend experiment mean that the model captures the observed atmospheric circulation trend features remarkably well?

It is edited in the revised manuscript.

Line 189: suggest adding Hobbs et al., 2024 to the references 27 and 28.

A regime shift in Antarctic sea ice is discussed in the last session and the reference Hobbs et al. (2024) is added there.

Line 194: The similarities are broad scale, It is interesting that the

Amundsen-Bellingshausen Seas have an overall decreasing trend while showing such hotspots of warming during 2006, 2016 and 2020. The decadal trend masks a large amount of interannual variability. How much data is there for each ocean basin? I.e., are there many data point between 50 and 65 S in the Amundsen Sea?

The numbers of grid points from Argo are 360*15, 70*25, 70*15, 80*15, 70*15 and 70*15 in the whole Southern Ocean, Ross Sea, Amundsen-Bellingshausen Seas, Weddell Sea, Indian Ocean and Western Pacific Ocean, respectively. We have enough data for analysis in all five sectors.

References

Hobbs, W., Spence, P., Meyer, A., Schroeter, S., Fraser, A. D., Reid, P., Tian, T. R., Wang, Z., Liniger, G., Doddridge, E. W., & Boyd, P. W. (2024). Observational evidence for a regime shift in summer Antarctic sea ice. *Journal of Climate* 37, 2263 – 2275. <https://doi.org/10.1175/JCLI-D-23-0479.1>

Purich, A., and E. W. Doddridge, 2023: Record low Antarctic sea ice coverage indicates a new sea ice state. *Communications Earth & Environment*, 4, 314, 10.1038/s43247-023-00961-9.

Reviewer #1 (Remarks on code availability):

The climate model code is a standard code so anyone who wanted to run this model would be able to do so. The modifications made by the authors are available on request, but someone could reproduce these experiments by using the forcing data as described by the authors.

The NCL codes used to analyze the data and generate the main results presented in this study can be obtained from <https://codeocean.com/capsule/0103116/tree>.

Reviewer #2 (Remarks to the Author):

This study focuses on the observed decline in Antarctic sea ice extent (SIE) in the recent decade (2013–2023). The authors propose that the recent SIE decline has been significantly influenced by atmospheric circulation changes near Antarctica. Using a set of prescribed SST simulations with CESM1, the authors further conclude that the observed circulation changes, including a deepening of the Amundsen Sea Low and associated northerly winds that are conducive to reducing SIE, were mainly forced by the sub-decadal Pacific SST changes (notably the negative phase of IPO), with additional contributions from Atlantic SST changes. The atmospheric circulation impact on SIE has enhanced the Southern Ocean subsurface warming effect, altogether contributing to the total observed Antarctic climate changes.

Overall, I find the paper to be interesting and the topic to be important. However, I have several major concerns about the foundation of the main argument and the experiments used to support the story, which I will elaborate on below. These concerns led me to worry that the current version of the manuscript is not suitable for publication.

We thank the reviewer for her/his support. We carefully considered all your comments and significantly modified the manuscript accordingly. In the revised manuscript, we perform two sets of 100-year coupled pacemaker experiments and simulate similar atmospheric responses as that in the AGCM simulations of the old manuscript, but realistic sea ice responses to Pacific and global sub-decadal SST trends.

Major concern 1.

Regarding the recent decline of Antarctic SIE, previous studies have proposed the role of Southern Ocean subsurface warming (e.g., Zhang et al. 2022). Here the authors propose that the decadal-long SIE decline can be additionally caused by atmospheric circulation changes, which are forced mainly by Pacific SST variations. The authors have done a great job establishing the link between Antarctic circulation changes and their corresponding SST forcing. Although I appreciate the thorough discussion in the paper, I don't think this atmospheric bridge mechanism is a new piece. There have been many papers showing how tropical Pacific SST anomalies remotely modulate Antarctic circulation (e.g., Ding et al. 2011, Meehl et al. 2016 for the early SIE expansion period). On the contrary, the other part of the proposed causal connection – atmospheric circulation changes drive SIE changes – is not well discussed and validated. The authors put forward the hypothesis that “the forcings of atmospheric circulation changes have played a key role in driving the rapid decline of Antarctic SIE in the recent decades” (line 71). However, this main argument seems built simply on a qualitative speculation that the

SLP-associated wind anomalies induce anomalous advection, resulting in SIE changes (Fig. 1). The simulations and analysis in the rest of the paper, awkwardly, fail to verify this hypothesis. That is, the prescribed SST (presumably also fixed SIE) simulations are unable to provide the actual SIE response to the SST-driven circulation forcing by construction. Thus, I find that the inconsistency between the modeling evidence and the conclusion makes the paper less convincing.

Furthermore, the conclusion that atmospheric circulation plays a significant role in driving SIE changes is weakened by the finding that the SIE decline appears to be indeed associated with Southern Ocean subsurface warming, most pronounced in the Weddell Sea (Fig. 4), as previously proposed. This raises a key question for this paper: to what extent does the proposed atmospheric circulation effect contribute to the recent SIE decline? Is it a major contributor or only a secondary player compared to the subsurface warming effect? In my opinion, the argument would have been more novel and impactful if the authors had quantified the relative roles of atmospheric circulation and ocean subsurface warming effects on the recent SIE decline.

We agree with Reviewer #2 about all his/her concerns. In this revised manuscript, we perform two sets of 100-year coupled pacemaker simulations in which observed trends of SST anomalies over the Pacific or global ocean between 60°S to 60°N from June 2013 to May 2023 are added to the model simulated SST, respectively. We find the dominant forcing of La Niña-like Pacific sub-decadal SST variations on the deepening of the ASL and positive SLP trends over the South Pacific and Indian Ocean sectors in all seasons, and the joint forcing of Pacific and tropical Atlantic sub-decadal SST variations on Southern Ocean surface and subsurface warming and consequent Antarctic SIE retreat. The Pacific and global SST-induced annual Antarctic SIE decreases accounted for about 22% and 40% of the observed annual SIE trend, respectively. Through decadal hindcasts initialized in 2014 and 2015, Zhang et al. (2022) suggest that approximately half of the SIE difference between low ice states in 2017–2020 and high ice states in 2012–2015 can be attributable to Southern Ocean subsurface warming. We conclude that both Pacific and tropical Atlantic sub-decadal SST variations and the Southern Ocean subsurface ocean play crucial roles in the tremendous Antarctic SIE decline from June 2013 to May 2023, while the warming effect of anthropogenic radiative forcing plays a much smaller role that only accounts for ~12% of the total SIE reduction.

Major concern 2.

Related to the above, the limitation of this work seems to in part arise from the caveat that the prescribed-SST simulations do not allow one to estimate the SIE response. The authors also invoke results from a set of fully-coupled pacemaker simulations with PDV-associated SST anomalies in the Pacific,

although the SIE decline response in the Weddell Sea appears to be much weaker and the SIE increase in the Amundsen Sea and Ross Sea appears to be too strong than those observed. I wonder why the authors don't use more realistic pacemaker simulations, with SSTs in the Pacific/Atlantic sectors nudged towards observed transient anomalies over the targeted period (2013–2023). This way, the authors could isolate and quantify the impacts of realistic SST variations on Antarctic SIE in the coupled system. These are likely to be better than the AGCM runs (which don't allow dynamic SIE response) and the idealized PDV–SST pacemaker runs (which only provide the SIE response to PDV phase transitions rather than the realistic full SST variations).

We agree with all your concerns about the AGCM simulations and follow your suggestion in the revision. We first performed 10-member coupled model ensembles of Pacific “Pacemaker” simulations with the NCAR CESM1 model, similar to that in Purch et al. (2016). In the simulations, the temporal history of observed 1979–2023 ERSSTv5 SST anomalies in the Pacific basin (40°S–60°N) is nudged to observations. We find that the Pacemaker ensemble members show considerable diversity in their trend patterns and amplitudes of atmospheric circulation for the 10-yr trends from 2013–2023 in the Southern Hemisphere high latitudes, and thus fail to reproduce the observed Antarctic sea ice decline.

In this revised manuscript, we present results from two sets of 100-year coupled pacemaker simulations in which SST anomalies corresponding to observed ERSSTv5 SST trends from June 2013 to May 2023 are imposed over the Pacific and global ocean between 60°S to 60°N, respectively, with preindustrial radiative forcings. In these experiments, the model SST is restored to the observed trend anomalies superimposed on the model's own climatology over the Pacific or global region from 60°S to 60°N. This nudging method significantly reduces internal variability and enables us to reproduce the observed forcing of Pacific and tropical Atlantic sub-decadal SST variations on the SH atmospheric circulations and consequent Antarctic SIE decline.

Minor comments:

Line 111: when introducing the “pacemaker” simulations, it would be helpful to highlight that these are “coupled” simulations, distinct from the above AGCM simulations.

It is changed.

Line 117: I would suggest adding pattern correlation here to quantify the level of resemblance between the observed circulation pattern and the SST-driven circulation pattern.

The patterns correlations are added and discussed in the revised manuscript.

Line 184: northwesterly -> southerly?

It is changed to southerly.

Line 225 - 226: I do not follow why this suggests the SIE decline results from internal variability. The IPO pacemaker simulations show a weaker SIE response compared to observations and the PACTtrend simulation. Doesn't this suggest the observed SST forcing on SIE may have involved some forced response beyond just the IPO SST forcing?

The observed SST trend patterns over the Pacific (Fig. 2a and Figs. S2a-d) resemble the typical La Niña conditions and the negative phase of the IPO. The observed SST forcing on SIE involved some forced response to the evolution of ENSO variations from persistent warm conditions that included a weak El Niño in 2014 and an extreme El Niño in 2015–2016 to the prolonged 2020–2023 La Niña conditions developed and decayed in autumn 2023. The SIC and atmospheric responses to the IPO phase shift from positive to negative (Fig. S16) are much weaker than those to the total Pacific 10-yr SST trends in the PACTrend experiment (Fig. 3).

Line 288: how is SIE handled in these AGCM runs? Is it fixed to the observed climatology?

In the AGCM simulations, the climatological SST outside of areas with prescribed SST trends and sea ice concentration are specified.

Line 291–292: I would suggest adding a plot to show the regions of the SST forcing specified in AGCM runs (if the authors were to continue using these simulations).

Figure 2 is replotted and the regions of the SST forcing in the coupled pacemaker are now clearly shown.

Reference:

Ding, Q., Steig, E. J., Battisti, D. S., & Küttel, M. (2011). Winter warming in West Antarctica caused by central tropical Pacific warming. *Nature Geoscience*, 4(6), 398–403.

Meehl, G. A., Arblaster, J. M., Bitz, C. M., Chung, C. T., & Teng, H. (2016). Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. *Nature Geoscience*, 9(8), 590–595.

Zhang, L., Delworth, T. L., Yang, X., Zeng, F., Lu, F., Morioka, Y., & Bushuk, M. (2022). The relative role of the subsurface Southern Ocean in driving negative Antarctic Sea ice extent anomalies in 2016–2021. *Communications Earth & Environment*, 3(1), 302.

Reviewer #2 (Remarks on code availability):

The code used in this paper is not provided in the current version of the paper (it is available only upon request).

The NCL codes used to analyze the data and generate the main results presented in this study can be obtained from <https://codeocean.com/capsule/0103116/tree>.

Reviewer #3 (Remarks to the Author):

Review Qigang Wu et al : Nature Communications

Contributions of Sub-Decadal Pacific Sea Surface Temperature Variations to Rapid Antarctic Sea Ice Decline in the Recent Decade

There have been several papers written on the 2023 sea ice anomaly, which have come into press after the writing of this paper, but now cannot be ignored. However, there is still a requirement for a paper on the remote drivers of the changes. Unfortunately, such drivers can be quite complicated (similar to what the drivers are of PDO). Attempting to do this through a trend analysis is, I feel, not the correct method for the reasons given below.

39 & 44: The low of 2016 does not persist but recovers such that the ice is back at the climatic mean by 2021 (Fig 1). This confirms a subsurface ocean heat source being depleted. Why do the authors now plot a trend line through the 2013–2023 when clearly this is not a sustained trend? To do so is an oversimplification. The decadal trend theme, rather than intermittent events, as most other papers on the subject describe, possibly associated with different mechanisms, is a weakness of this paper. It requires a complex sequence of drivers, as evidenced by the number of supplementary plots, none of which is convincing. As a consequence, the paper is confusingly written, attempting to describe too much in words when a schematic diagram such as Fig3 in Scott Power's paper Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects | Science would greatly simplify and clarify the process. The intermittency of the events would also make the use of causal networks (were they to be used) to solve the remote forcing very difficult.

We thank the reviewer for her/his insightful comments and have significantly modified the manuscript accordingly. The above concerns are addressed as follows (and associated modifications of the manuscript).

First, we agree that the abrupt 2016 spring decline and 2023 all-year record lows are intermittencies of the extreme SIE events, which contribute to strong interannual variability of Antarctic SIE and also the downward trend. Several recent studies have examined the roles of atmospheric forcing and subsurface warming in the 2016 rapid loss and the 2023 record low, as we discuss in the last section of our revised manuscript. However, as shown in Figure 1 in the next figure, the seasonal mean Antarctic SIE has clearly exhibited significant downward trends in all four seasons since the peak in 2014 (Fig. S1). The evolutions of observed Antarctic SIE anomalies include components of both sub-decadal and strong interannual variations. We also agree that the mechanisms for the decadal trend theme and intermittent events are different.

Second, the old manuscript examines atmospheric responses to Pacific or Atlantic sub-decadal trends using AGCM simulations. We now perform two sets of 100-year coupled pacemaker experiments and simulate realistic atmospheric and sea ice responses to Pacific and global sub-decadal SST trends in the revised manuscript. We demonstrate that Pacific sub-decadal SST trends have dominantly driven these atmospheric circulation changes through tropical–polar teleconnections and also significantly contributed to Southern Ocean subsurface warming in the recent decade. About 40% of observed annual Antarctic SIE decline is attributed to Pacific and relevant Atlantic and Indian Ocean sub-decadal SST variations, and also tropical Atlantic SST warming. Such impacts have amplified the warming effect of Southern Ocean subsurface on Antarctic SIE decline, together explaining why Antarctic SIE has dramatically declined in the recent decade. Decadal hindcasts initialized in 2014 and 2015 indicate that approximately half of the SIE difference between low ice states in 2017–2020 and high ice states in 2012–2015 can be attributable to subsurface warming (Zhang et al. 2022).

Third, sub-decadal trend theme is used to examine the driver of low-extent state since 2014. Our trend analysis is comparable to the SIE difference between low ice states in 2017–2020 and high ice states in 2012–2015 in Zhang et al. (2022). We realize that our method is not suitable for examining intermittent events like abrupt 2016 spring decline and 2023 winter record low, which can only be reproduced in the coupled experiments when observed winds are nudged (Zhang et al. 2022; Espinosa et al. 2024).

We also performed 10-member coupled model ensembles of historical Pacific “Pacemaker” simulations with the NCAR CESM1 model, in which the temporal history of observed 1979–2023 ERSSTv5 SST anomalies in the Pacific basin is nudged to observations. We find that the historical Pacemaker ensemble members show considerable diversity in their trend patterns and amplitudes of atmospheric circulation for the 10-yr trends from 2013–2023 in the Southern Hemisphere high latitudes, and thus fail to reproduce the observed Antarctic sea ice decline, mainly due to large internal variability. Extreme sea ice decline events in 2016 and 2023 are not captured in the simulations.

Breaking up the description into smaller paragraphs and making a distinct connection in each paragraph would help clarify the argument. As it stands the argument is a mess, and very hard to follow.

Thanks for the suggestion. We have carefully revised the manuscript. We agree that some descriptions seem messy since we discuss seasonal changes in atmospheric circulation and sea ice.

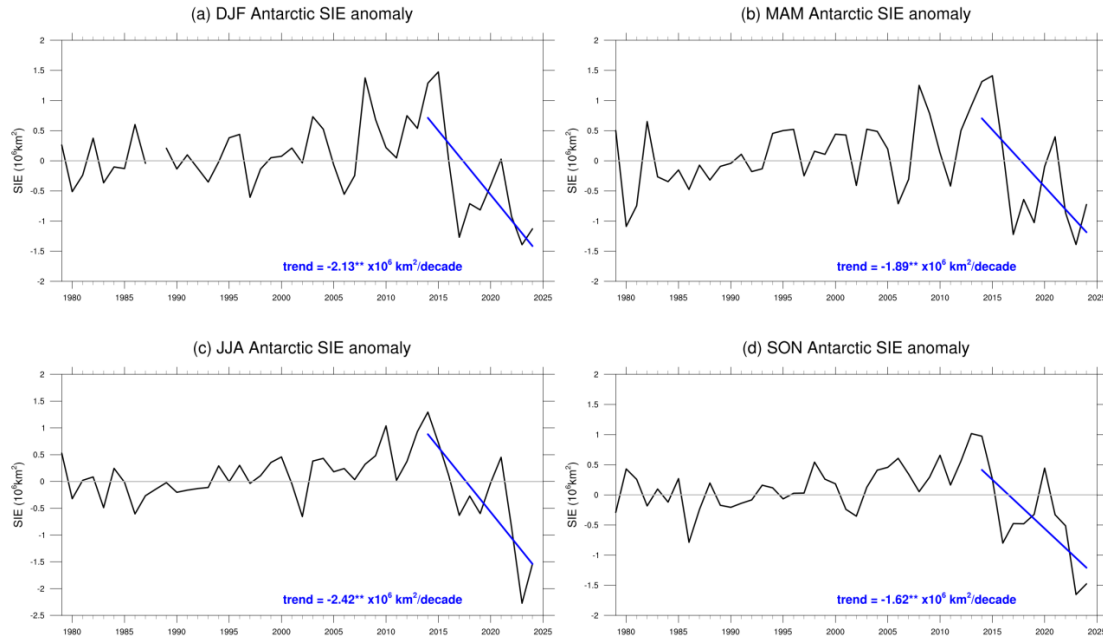


Figure 1. Seasonal time series of SIE in the whole Antarctic from 1979 to May 2023, and the linear trend fit to the ten years from June 2013 to May 2023 (blue line) is shown.

51-69: Monica Ionita (Frontiers | Large-scale drivers of the exceptionally low winter Antarctic sea ice extent in 2023 (frontiersin.org)) makes a compelling case that the event of 2023 was associate with a wave mode 3 pattern. It is possible that a deepening and shift of the Bellingshausen Sea Low is associate with this pattern, but this would need to be demonstrated. Your description here is rater messy and would be better summarized by the wave mode 3 analogy. Of course, the driver of the wave mode 3 is not discussed in Ionita' s paper and needs investigation.

We realize that the observed atmospheric forcing of the Antarctic sea ice loss in Figs. 1 and S2 cannot be summarized by the single wave mode 3 analog and have distinct structures in four seasons, which complicates our description. The seasonal Z300 trend is characterized by a zonal wave two (ZW2) pattern in JJA, a negative SAM in SON and DJF, and a zonal wave one (ZW1)-like pattern in MAM. Detailed descriptions are needed to address these differences.

Goyal et al. (2021) suggest that changes in tropical deep convection fundamentally control the ZW3 pattern. Wang et al. (2019) find that the record negative Indian Ocean Dipole played a key role in generating the ZW3 pattern from September to October 2016. In the second paragraph of the discussion session, we point out that the strong stationary ZW3 pattern in the 2023 austral winter found in Ionita (2024) was mainly driven by deep convection in the tropical Pacific associated with the developing El Niño. The shift from a triple-dip La Niña early in the year to El Niño conditions by May resulted in substantial surface warming of over 1.5°C in the

eastern equatorial Pacific. The tropical precipitation anomalies is characterized by strongly increased rainfall in the western equatorial Pacific elongated into the eastern equatorial Pacific and weakly decreased rainfall over the tropical Indian Ocean to maritime continent of Indonesia and tropical Atlantic Ocean (Figure 2 on the next page).

To examine the potential roles of the tropical rainfall anomalies in driving 2023 winter SH circulation patterns, we construct four normalized precipitation indices averaging the precipitation anomalies over Western Pacific warm pool and central-eastern tropical Pacific in observational CMAP data in JJA. Then, we calculated regression maps of observed precipitation and ERA5 Z300 anomalies onto the corresponding normalized precipitation index during 1979-2023. The regression maps, scaled by the corresponding observed magnitudes of the 2023 anomaly precipitation index values, indicate that both increased precipitation anomalies in western and eastern tropical Pacific dominantly contribute to the observed ZW3-like pattern and the PSA teleconnection (Figure 3 on the last page).

Another characteristic on the sea ice changes, as discussed by Hobbs et al (2024) *Observational Evidence for a Regime Shift in Summer Antarctic Sea Ice* in: *Journal of Climate* Volume 37 Issue 7 (2024) (ametsoc.org) is that the Antarctic sea ice has recently become predictable season by season. This would need to be explained within a remote forcing context.

Sea ice responds fast to anomalous atmospheric circulation forcing and associated predictability is low. The increased autocorrelation and predictability of Antarctic sea ice season by season during the last 15 years found by Hobbs et al. (2024) are likely related to a slower and lagged response to SST and subsurface temperature anomalies. Espinosa et al. (2024) demonstrate that the 2023 winter sea ice anomalies were largely driven by warm Southern Ocean conditions that developed prior to 2023 and were predictable six months in advance. Their ensemble forecast correctly predicted that near-record low sea ice would persist in austral winter 2024, due to persistent warm Southern Ocean conditions. Their results support the hypothesis that the changes in sea ice variability herald a shift in seasonal sea ice–ocean mixed layer interactions pointed out by Hobbs et al. (2024).

Pacific sub-decadal SST variations in our study have significantly contributed to the Southern Ocean subsurface warming and likely to high predictability of Antarctic sea ice in the recent decade. We add these discussions in the last session of the revised manuscript. However, our pacemaker experiments are not designed to explain the increased Antarctic SIE persistence. We didn't see significant changes in lag=1 correlations of the 100-year seasonal mean SIE anomalies between the control run and Pacific pacemaker experiments.

Reference

- Espinosa, Z. I., Blanchard-Wrigglesworth E., Bitz, C. M. Understanding the drivers and predictability of record low Antarctic sea ice in austral winter 2023. *Commun. Earth Environ.* **5**, 723 (2024).
- Goyal, R., Jucker, M., Sen Gupta, A., Hendon, H. H., England, M. H. Zonal wave 3 pattern in the Southern Hemisphere generated by tropical convection. *Nat. Geosci.* **14**, 732–738 (2021).
- Wang, G. et al. Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. *Nat. Commun.* **10**, 13 (2019).

Reviewer #3 (Remarks on code availability):

The code has not been made available and although this is reasonable for climate model data which care very large datasets, the analysis code should be made available

The NCL codes used to analyze the data and generate the main results presented in this study can be obtained from <https://codeocean.com/capsule/0103116/tree>.

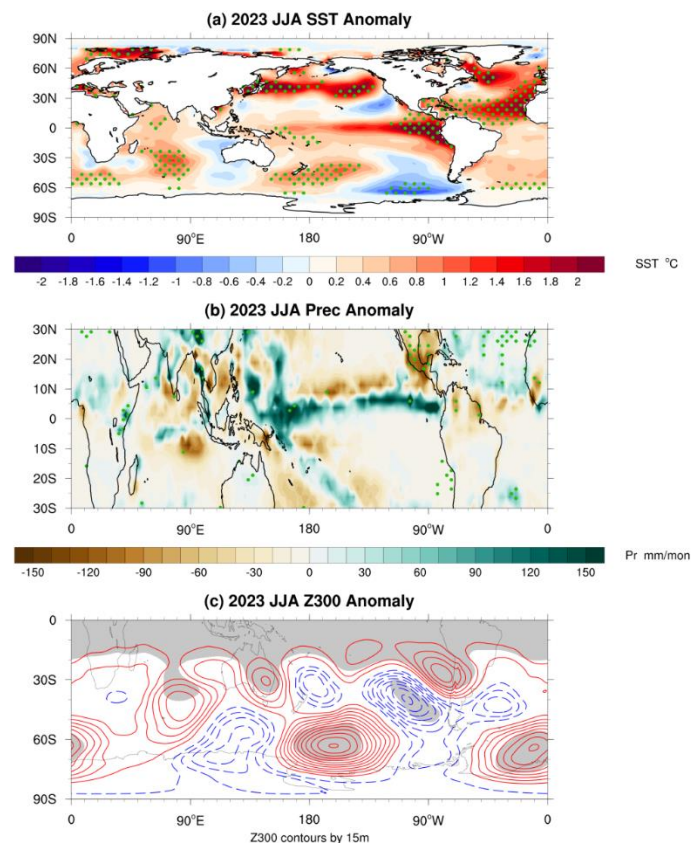


Figure 2. Austral winter mean (a) ERSST V5 SST, (b) CMAP rainfall and (c) ERA5 Z300 anomalies relative to the 1979–2023 long-term mean. Shaded or dotted areas indicate that SST or rainfall anomalies exceed the corresponding one standard deviation.

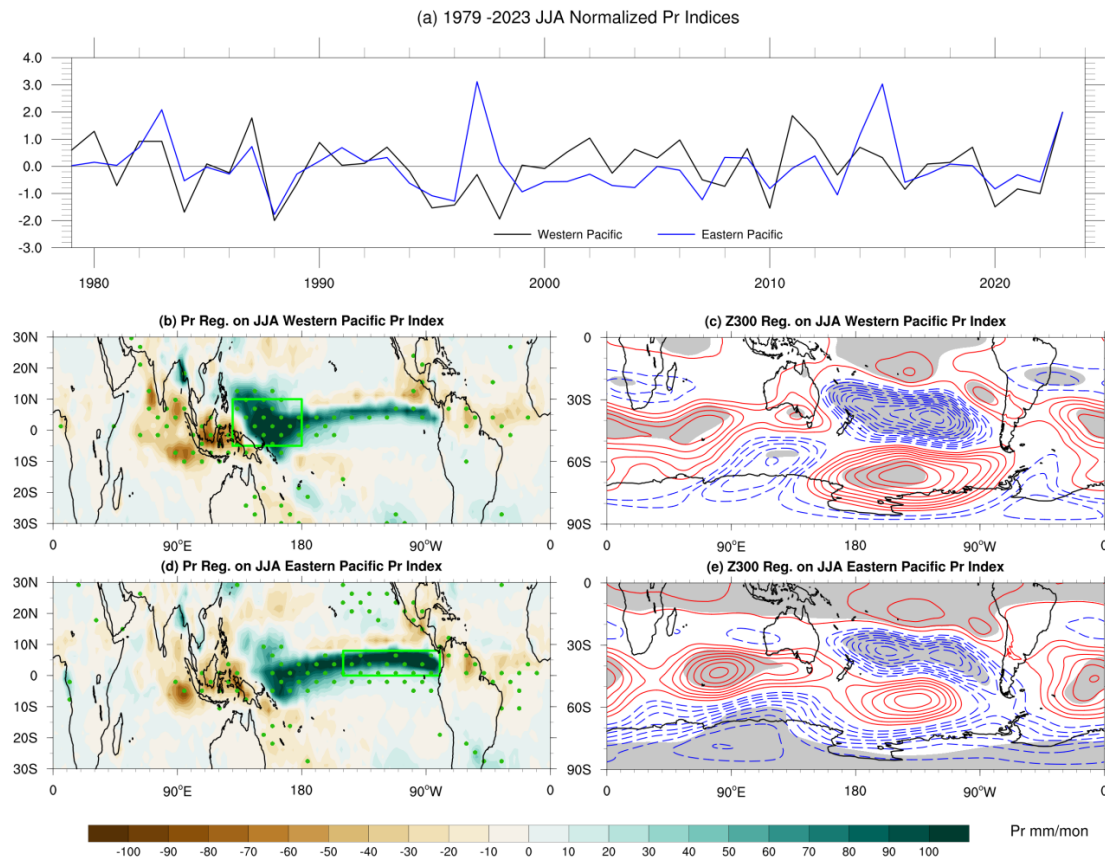


Figure 3. Observed impacts of tropical Pacific precipitation anomalies on Z300 in JJA. (a) Winter (JJA) normalized observed precipitation indices during 1979-2023 calculated over two boxes with large precipitation anomalies in Figure 2b) in the western (130–180°E, 5°S–10°N) and eastern (210–280°E, 0–8°N) tropical Pacific. Regressed patterns of JJA seasonal mean (b,d) precipitation and (c,e) Z300 anomalies on the two indices in (a) during 1979-2023, scaled by the corresponding observed magnitudes of the 2023 anomaly precipitation index values. The Z300 contour interval is 10m, with red solid (blue dashed) contours denoting positive (negative) values, and zero contours are omitted. Shading areas indicate Z300 values significant at the 95% confidence level.

REVIEWER COMMENTS

We thank three reviewers for their support! We have considered all comments and carefully revised the manuscript. In the revised manuscript, we add observed trends of wind stress curl and the corresponding responses to Pacific and global SST trends in Fig. 7. All changes in the manuscript text file are shown with red color highlighting.

Reviewer #1 (Remarks to the Author):

I have reviewed the revised manuscript, which has been substantially improved to address the concerns raised in my initial review. The manuscript investigates the causes of the significant decline in Antarctic sea ice extent from June 2013 to May 2023, focusing on the roles of Pacific sub-decadal sea surface temperature trends, atmospheric circulation changes, and the influence of tropical polar teleconnections. This is an interesting manuscript, and the topic is important given the need to understand the drivers of the recent low sea ice cover around Antarctica.

In particular, the methodology has been strengthened by switching from AGCM simulations to coupled pacemaker experiments, providing more robust evidence for the proposed mechanisms. The authors employ a multi-method approach. They analysed satellite-derived sea ice concentrations and atmospheric variables (ERA5 reanalysis) to demonstrate that the decline in Antarctic sea ice is closely linked to a strengthened ASL and associated wind anomalies. They use a heat budget analysis to evaluate the mixed layer temperature in the Southern Ocean and demonstrate the role of subsurface ocean heat flux in driving the decline of Antarctic sea ice, with wind-driven upwelling and Ekman transport as key mechanisms. The revised manuscript now includes coupled ensemble pacemaker simulations to impose Pacific and global SST anomalies over the 10-year study period (June 2013 to May 2023). The PACTrend experiments impose observed SST from the Pacific Ocean, while the GLTrend experiment imposes global SST anomalies. The pacemaker experiments provide robust evidence of the link between Pacific SST trends and Antarctic sea ice variability by demonstrating a clear mechanistic connection between tropical SST anomalies and the decline of Antarctic sea ice through tropical-polar teleconnections. By controlling these external forcing patterns, the experiment can simulate the atmospheric and oceanic responses and isolate regional contributions. They subsequently examine the responses to radiative forcing under historical and SSP370 scenarios from 17 CMIP6 models to independently validate their findings by confirming that natural variability, particularly driven by Pacific SST anomalies, is the dominant factor behind the recent decline in Antarctic sea ice.

Their key findings reveal that Pacific sub-decadal sea surface temperature (SST) trends were the primary driver of changes in Southern Ocean atmospheric

circulation and subsurface ocean warming and that these SSTs, through tropical-polar teleconnections, significantly contributed to the decline of Antarctic sea ice. Approximately 40% of the observed decline in Antarctic sea ice extent (SIE) is attributed to variations in Pacific and Atlantic SSTs. Radiative forcing contributed about 12% to the overall reduction in SIE, emphasising the dominant influence of teleconnections.

My main concern with the previous version of the manuscript was the lack of robust evidence for the teleconnection in driving ocean warming. The revised (and strengthened) approach to using pacemaker experiments has addressed this concern with the PACTrend simulation reproducing warming in the Southern Ocean subsurface layers (100–500 m depth) in response to tropical Pacific SST anomalies. The authors acknowledge my point about stratification, and I accept that these effects may be small at the timescales this work is looking at (sub-decadal). The model agreement with observations strengthens the evidence for this mechanism. Warmer Pacific SSTs strengthen the IPO in its negative phase, creating a La Nina-like state. These anomalies intensify the ASL, enhancing cyclonic wind patterns over the Southern Ocean. Strengthened winds drive Ekman transport, upwelling warm subsurface water that melts sea ice.

I also queried how well the model represented the atmosphere, and the revised manuscript demonstrates that the atmospheric and sea ice responses in the new coupled pacemaker experiments align well with the reanalysis data and satellite observations. The coupled experiments capture the spatial and seasonal patterns of Antarctic sea ice concentration decline, particularly the significant ice loss in the Amundsen-Bellingshausen Sea and the Weddell Sea, especially in austral spring and summer when tropical-polar teleconnections are strongest. The simulations also reproduce the strengthening of the ASL in all seasons, positive sea-level pressure anomalies over the Weddell Sea and the western South Pacific, and PSA-like Rossby wave patterns. The model reproduces the spatial and seasonal patterns of subsurface warming seen in the Argo observations with high fidelity but underestimates the magnitude of warming in certain regions. The agreement between observed and simulated warming trends provides strong support for the proposed mechanisms linking tropical Pacific SST anomalies, Southern Ocean circulation changes, and Antarctic sea ice decline.

The choice of study period has been justified with clear reasoning related to ENSO evolution and IPO phase shifts.

I recommend this manuscript for publication. The authors have successfully addressed all major concerns and significantly improved the scientific quality of their work. The revised analysis presents a comprehensive and well-supported understanding of ocean-atmosphere-sea ice interactions in Antarctica.

Reviewer #1 (Remarks on code availability):

This is a well-laid out repository with clear instructions. It contains NCL programs and datasets to reproduce the figures in the manuscript.

We thank the reviewer for his/her encouragement and support. His/her deep understanding of our results helps us to improve our manuscript. We really appreciate it.

Reviewer #2 (Remarks to the Author):

I appreciate that the authors considered my suggestion and added the new set of fully-coupled pacemaker runs. These new simulations have greatly strengthened the paper and provided valuable modeling evidence. Overall, I find the paper in much better shape.

Regarding the results of these new simulations, I have some additional concerns. As listed below, some of them may be critical for interpreting the modeling results. I may have some misunderstandings here, in which case, clarifications would be helpful (potentially also for the broader audience).

We thank the reviewer for his/her support and insightful comments. We really appreciate it.

Line 473 - 483: The method section describing the coupled pacemaker runs would benefit from further clarification. For example, what SSTs are exactly restored in the model? The SST climatology + linearly ramping anomalies that amount to the observed trend at each grid box? If so, why are the simulations 100-years long while the targeted observational SST trends span only 10 year (2013-2023)? In other words, do the pacemaker runs maintain the same trend (K/dec) as the observations but extend it over a longer period, making the total imposed change in the model 10 times larger than in reality?

We follow the numerical methods of Deser et al. (2015, 2016), who run 200 years of coupled experiments to examine the role of ocean-atmosphere coupling in the atmospheric responses to projected Arctic sea ice loss. In the pacemaker simulations, the SST anomaly that amounts to the observed 10-year trend at each grid box is added to the model-simulated SST climatology in the Pacific or global ocean between 60°S to 60°N. Each set of pacemaker simulations runs for 100 years, and the prescribed SST forcing repeats annually. Each year is considered to be an ensemble member. The climate response of any variable is the difference between the seasonal means from the last 80 years of each coupled forced run and the 80 years of the coupled control run. An alternative numerical method is to run each ensemble member using the different ocean and atmospheric initial conditions chosen from the long control runs, and very similar results should be simulated. Both numerical methods have been widely used in AGCM

experiments to examine the impacts of SST trends or anomalies on atmospheric circulation.

Due to strong SST forcing (Figs. 2a and S2a-d, averaged trends over the Nino34 region are about -1.60K and -1.80K/decade in DJF and SON, respectively), we find that the ensemble mean sea ice and atmospheric responses (Figs. 3 and 4) are robust for the 80 ensemble members. When 120 ensembles (from 120 years of forced runs) are used, very similar responses are found (e.g., Fig. 1 on the next page for the 120 years of the GLTrend experiment). Similar ensemble mean responses are obtained for 1-60 ensembles and 61-120 ensembles in the 120 years of forced runs (e.g., Figs. 2-3 on the next two pages for the 120 years of the GLTrend experiment), indicating that the impacts of initial ocean conditions on sea ice and atmospheric responses are small in our study. We revise the description of pacemaker experiments in the method section (Lines 551-557 and 561-565) in the revised manuscript.

References

- Deser, C., R. A. Tomas, and L. Sun (2015), The role of ocean-atmosphere coupling in the zonal-mean atmospheric response to Arctic sea ice loss, *J. Clim.* 28, 2168–2186.
- Deser, C., L. Sun, R. A. Tomas, and J. Screen (2016), Does ocean coupling matter for the northern extratropical response to projected Arctic sea ice loss?, *Geophys. Res. Lett.*, 43, 2149–2157.

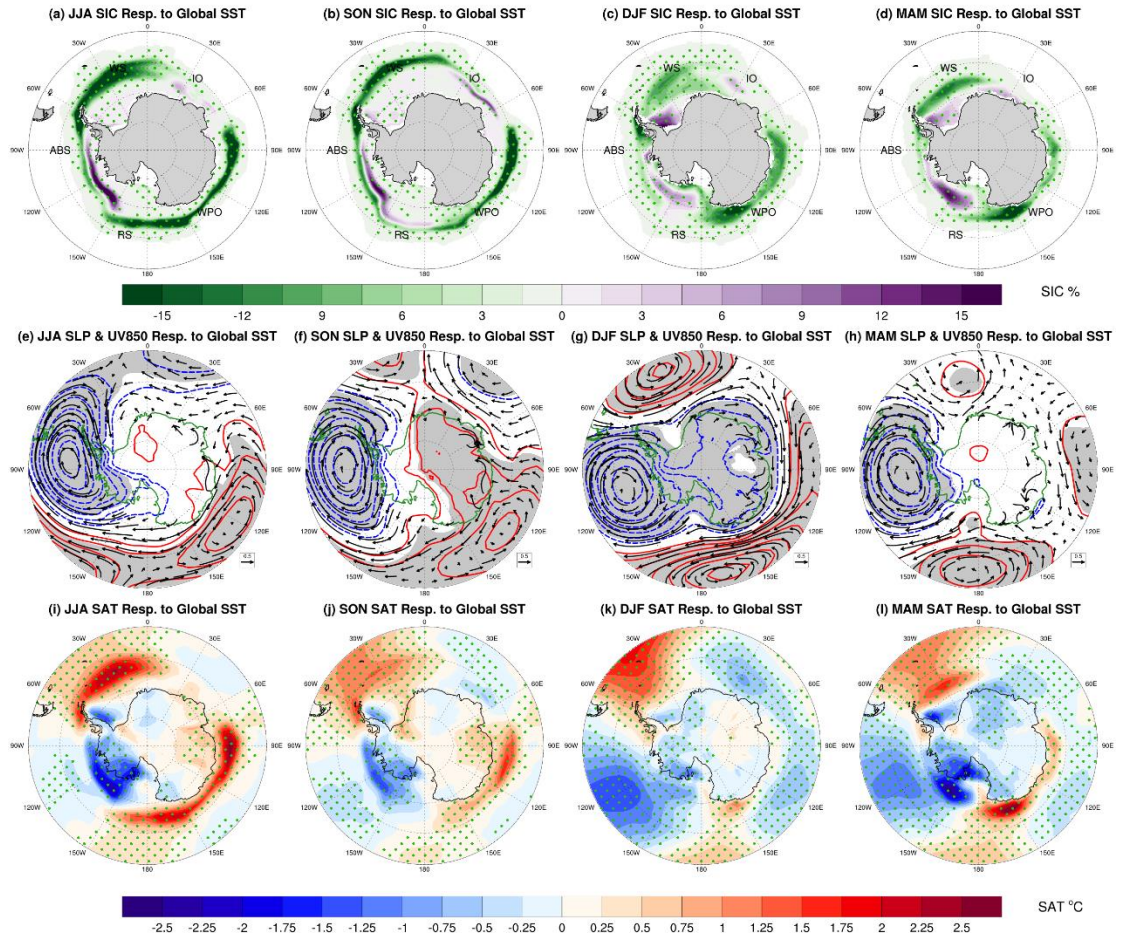


Figure 1. Same as Figure 4 in the manuscript except for 120 ensemble mean SIC and atmospheric responses to the global SST trend anomalies in the 120-year GLTrend experiment.

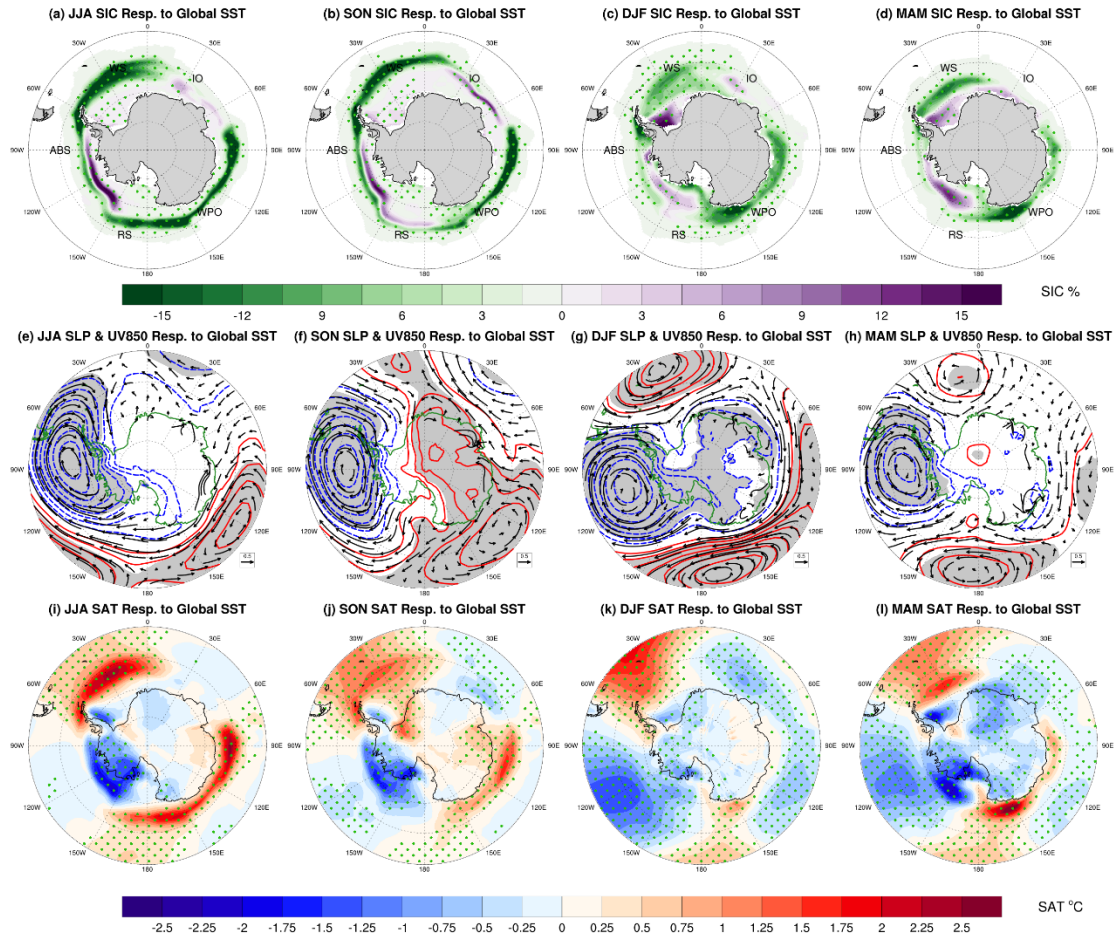


Figure 2. Same as Figure 1 except for 1-60 ensemble mean SIC and atmospheric responses to the global SST trend anomalies in the 120-year GLTrend experiment.

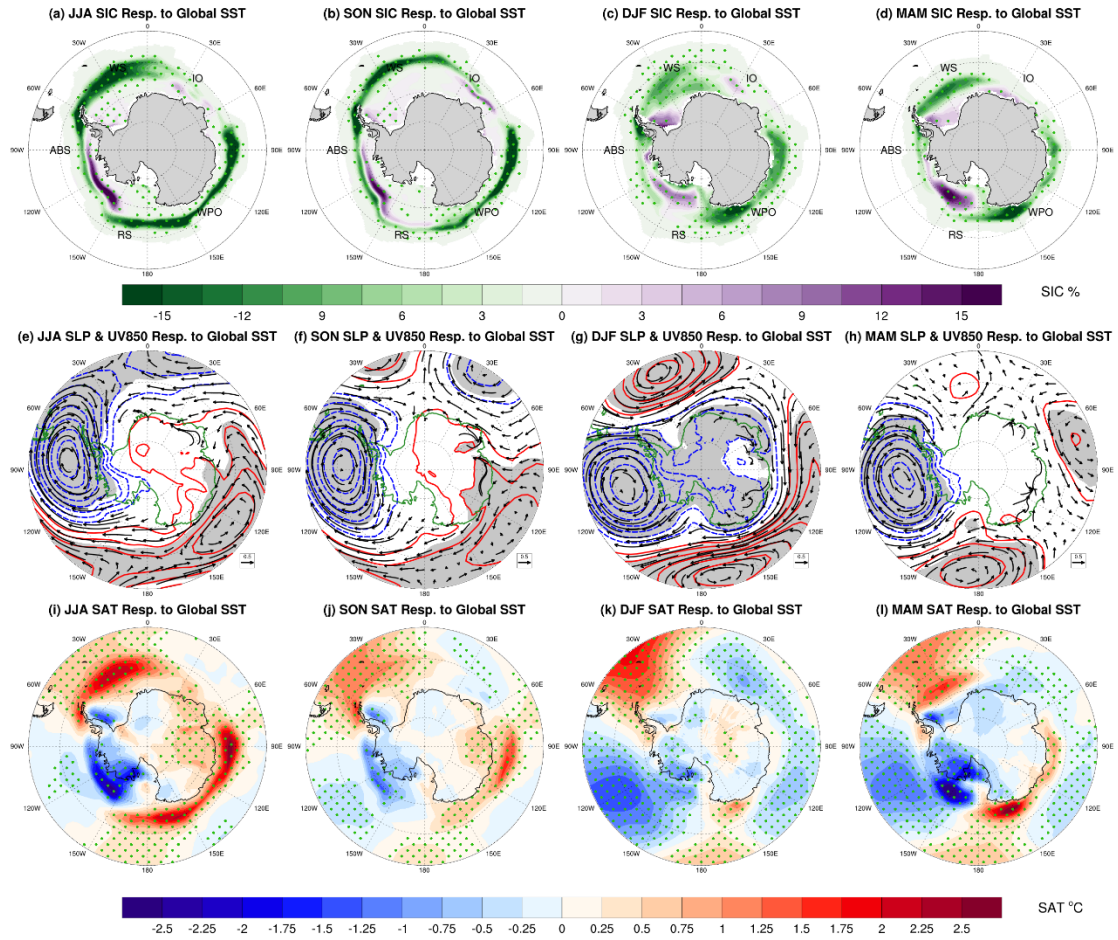


Figure 3. Same as Figure 2 except for 61-120 ensemble mean SIC and atmospheric responses to the global SST trend anomalies in the 120-year GLTrend experiment.

Line 99: This doesn't seem to hold for JJA and DJF.

It is revised as “There is a striking coherence of the trends in SAT and SIC over most areas”. In JJA and DJF, the concurrence of the cold or weak warm SAT and large SIC decline indicates that subsurface warming might have driven the sea ice decline there, as discussed in the revised manuscript (Lines 131-134 and 340-342). Meehl et al. (2019) suggest that the trend in wind stress curl on decadal timescales associated with negative IPO/positive SAM produces upward advection of warmer subsurface water through Ekman suction. In DJF, the negative trend in wind stress curl over the Weddell Sea and Western Pacific Ocean (Figure 4 on the next page) would produce a trend in Ekman suction, resulting in more upwelling of warm subsurface water, and contribute to sea ice decline in these two areas. In fact, significant warming trends of upper ocean temperature are found over Weddell Sea and Western Pacific Ocean in DJF (Fig. S14c), which is consistent with the large sea ice decline there in the recent decade (Fig. 1d). In contrast, the DJF negative responses of wind stress curl over the Weddell Sea in PACTrend and GLTrend experiments are much weaker than observed trend in wind

stress curl, partially explaining why a smaller sea ice decline is simulated over the Weddell Sea.

In all four seasons, significant negative trends in wind stress curl were observed in the ABS, which weakened the sea ice gain over the Amundsen and Ross Sea due to the strengthened ASL. Similar Ekman suction effects are also found in the simulations. We insert the wind stress results as Fig. 7 and above discussions in a new paragraph in the revised manuscript (Lines 362-388).

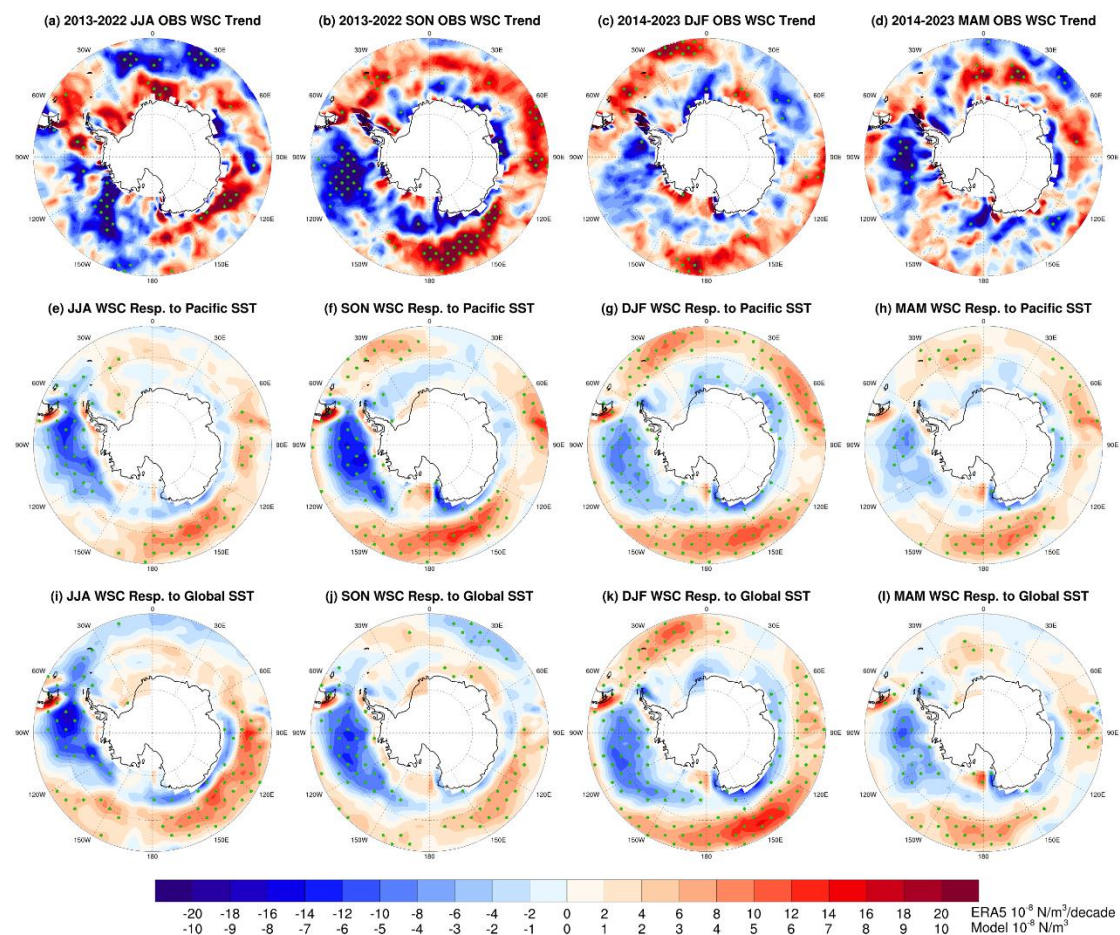


Figure 4. Observed changes and model responses in wind stress curl. (a-d) Linear seasonal mean trend from 2013/06 to 2023/05 of wind stress curl ($\text{Nm}^{-3} \times 10^{-8} \text{ decade}^{-1}$), computed from ERA5 turbulent wind stress, negative trend values denote areas of Ekman suction that would move water upward in the column; (e-i) seasonal mean responses of wind stress to the Pacific and global SST variations in the PACTrend and GLTrend experiments. Dotted areas denote observed trend (model response) values significant at the 90% (95%) confidence level.

Line158: what is the pattern correlation level for SLP in JJA? Any thoughts on why the pacemaker runs better reproduce the observed patterns in other seasons but not JJA?

The pattern correlation is 0.01 (-0.08) in JJA between the observed SLP trend and forced SLP response in the PACTrend (GLTrend) experiment. Two sets of pacemaker runs thus better reproduce the observed SLP trends in the other three seasons, but simulate a deepening of the ASL with a 45° longitude phase shift from observations in austral winter. This indicates that Southern Ocean atmospheric circulation changes are mainly induced by Pacific sub-decadal SST variations in the other three seasons in the recent decade, but also by other factors in winter, such as atmospheric internal variability. We insert these discussions in Lines 232-237 in the revised manuscript.

Line193: But this *seasonally robust* simulated sea-ice feature is not in observation.

The La Niña Pacific sub-decadal SST variations have dominantly driven these atmospheric circulation changes through tropical–polar teleconnections in the recent decade, but Antarctic sea ice was also significantly influenced by other factors. We mainly discuss the roles of (1) Atlantic and Indian Oceans, and (2) Southern Ocean subsurface warming in Antarctic sea ice changes. The expected sea ice gain over the Amundsen and eastern Ross Seas due to the strengthened ASL resulting from the La Niña Pacific sub-decadal SST trend (Figs. 3a-h) is reduced by the warming effects of the Atlantic and Indian Ocean SST forcing (as shown in Fig. S9), and also offset by the subsurface ocean warming effect in Fig. 6. By comparing the observed trends and model responses of wind stress curl (WSC) in Fig. 7, we argue that both experiments underestimate responses in wind stress curl and produce less upward advection of warmer subsurface water through Ekman suction (Lines 371-382 in the revised manuscript).

Line 265: Does this imply that the Atlantic SST effect, derived from these two sets of coupled pacemaker runs, is biased?

The cooling tropical Atlantic SST response to the La Nina Pacific sub-decadal SST trends in Fig. S10 is consistent with the previous findings. When an El Nino event is developed and matured, both the Pacific and Atlantic Walker circulations are weakened, and the regional Hadley circulation is weakened over the Atlantic and Indo-Western Pacific. A basin-side warm Indian Ocean (IOB) and a warm tropical North Atlantic Ocean occur in boreal winter or in the following spring (Wang 2019, ref. 43). On the decadal time scale, there is a same-sign SST response in the tropical Atlantic when observed SSTs are specified in the tropical Pacific in the idealized IPO and historical tropical Pacific pacemaker experiments (Meehl et al. 2021, ref. 44, see our Fig. 2c). Meehl et al. (2021) suggest that the weakening Atlantic Walker circulation and midlatitude PNA and PSA responses to the positive IPO forcing contributes to the tropical Atlantic warming by weakening the trade winds and increasing net surface heat flux. We add these discussions in Lines 299-302 in the revised manuscript.

In observations, tropical Atlantic SST warming may be mainly associated with positive Atlantic Multidecadal Oscillation (AMO), which showed positive trends during 2013-2023. Our results indicate that Pacific SST variations have reduced the warming amplitude of tropical Atlantic SST in the recent decade.

Line288-291: I am not sure I follow this... Isn't the Atlantic/Indian Ocean effect obtained by subtracting the Pacific effect from the global SST simulation? If so, why is it still related to Pacific SST variations?

The Atlantic/Indian Ocean effect is obtained by subtracting the Pacific effect from the global SST simulation. Figures 5 and S10 suggest that the Pacific sub-decadal SST variations contributed to observed North and South Atlantic SST warming and tropical to subtropical (midlatitude) Indian Ocean cooling (warming). Therefore, we argue that the impacts of the Indian Ocean and high-latitude Atlantic sub-decadal SST variations on atmospheric circulation and the consequent rapid decline in Figs. S7-9 from the GLTrend experiment are likely relevant to that of the contemporary Pacific sub-decadal variations in Figs. 2 and S2.

Fig. 298 Fig. S10.

It is changed to Fig. S10e-h.

Fig. 6: The ocean temperatures shown are averaged over 50–65° S. However, the simulations nudge SSTs all the way to 60° S. Doesn't this mean that more than half of these “responses” are prescribed forcing rather than the actual response?

It is true that the ocean temperature responses in the GLTrend experiment in Fig. S13 are related to prescribed SST forcing. However, the PACTrend experiment nudges observed SST trends only in the Pacific basin between 60°S to 60°N and reproduces observed SST increases and warming temperature profiles of the upper 1000m of the ocean over the South Atlantic and Indian Oceans (right panels in Fig. S10, Fig. 5e and Figure S11). Although a cold SST anomaly is nudged in the ABS and Ross Sea, 100-500m subsurface warming is also simulated, which is contributed by the oceanic poleward heat advection and upwelling Ekman suction bringing warmer water upward (See inserted discussions in Lines 328-332 in the revised manuscript). In the manuscript, we extensively examine the impacts of the La Niña-like Pacific sub-decadal SST variations in Southern Ocean subsurface warming in the PACTrend experiment, but briefly discuss the subsurface responses in the GLTrend experiment.

In our pacemaker experiments, we follow the numerical methods of ocean assimilation by Purch et al. (2016, ref. 10) and Zhang et al. (2022, ref. 28). Purch et al. (2016) ran the historical global ocean pacemaker experiment CESM1-GLOB, with the global ocean assimilated, excluding sea ice regions. Zhang et al. (2022) performed the

atmosphere and ocean assimilation experiment SPEAR_atm_sst_restore, in which the SST within 60°N–60°S was restored toward the time-varying NOAA ERSSTv5.

Line 353–355: How should we interpret the remarkable differences between the simulation forced by observed decadal SST trends (Fig. 3) and the simulation forced by PDV phase change (Fig. S16)? What does it imply for the observed SST trends? The authors mention the ensemble average. However, I assume that the ensemble averaging primarily removes random atmospheric variability and can still yield a robust “forced response” to the imposed PDV SST variation. Therefore, I wonder if other dominant factors are at play. For example, it could suggest that the observed SST trends are not solely driven by a negative PDV or that random atmospheric variability also plays a major role here.

Observed Pacific sub-decadal SST trends prescribed in the PACTrend experiment originated from the evolution of ENSO variations and the shift of the IPO from the positive phase in 2014–2016 to the negative phase after 2016. During 2014–2016, the tropical Pacific experienced persistent warm conditions that included a weak El Niño in 2014 and an extreme El Niño in 2015–2016, while the prolonged 2020–2023 La Niña conditions developed and decayed in autumn 2023 (as discussed in the 3rd paragraph and the first paragraph of the discussion section in the old manuscript). The amplitudes of observed SST trends in the Pacific in Fig. 2a are much stronger than those associated with the IPO forcing in Fig. 2c. Note that the contour interval is 0.2 C/decade in Fig. 2a and 0.1 C in Fig. 2c. Since the overall impacts of a negative PDV are much smaller than those of the ENSO forcing, we use the total SST trends as the forcing in both pacemaker experiments.

We now revise the first paragraph of the discussion section and clearly state that “Pacific sub-decadal SST variations originated from the ENSO evolution (from the 2014–2016 El Niño to the 2020–2023 La Niña conditions) and the IPO shift (from the positive phase in 2014–2016 to the negative phase after 2016).” (Lines 415–418).

Reviewer #2 (Remarks on code availability):

The website requires account registration.

Sorry for this problem. The other two reviewers could access the website. We will check if the website is available every day and contact support@codeocean.com for any problems.

Reviewer #3 (Remarks to the Author):

Most concerns have been addressed except that some Results/Analysis could be split up by sub-heading to make it easier to read and refer to figures. For example 'observations' and 'model'.

Otherwise I suggest accepting the paper.

We thank the reviewer for his/her support and suggestions. We really appreciate it.

Subheading “Impacts of Pacific and global sub-decadal SST trends on SIE decline” is changed to “Modeling impacts of Pacific and global sub-decadal SST trends on SIE decline.” Observed or model is added to the short titles of most figures.

I am uneasy about the use of sea ice extent when ice area is a better diagnostic. The ice edge might retreat but the ice concentration increase. However, I do not expect the authors to change the assessment method at this point.

We agree that sea ice area (SIA) is a good diagnostic. We calculate the observed SIA trends and model SIA response (Table 1 next), and find that the main conclusions are not changed. The Pacific and global sub-decadal SST variations have also significantly contributed to observed SIA decline in the recent decade. We decided to follow most references and mainly discuss observed SIE changes and SIE responses in the manuscript.

Table 1. Same as Table S1 in the manuscript but for observed and simulated Antarctic sea ice area (SIA) decline (unit $\times 10^6 \text{ km}^2/\text{decade}$ for OBS and $\times 10^6 \text{ km}^2$ for model responses) are listed in the second row.

	JJA	SON	DJF	JJA	Annual
OBS	$-1.52^{**} \pm 1.41$	-1.25 ± 1.66	$-1.98^{**} \pm 1.42$	$-1.93^{**} \pm 1.85$	$-1.67^{**} \pm 1.44$
PACTrend	$-0.21^{**} \pm 0.10$	$-0.35^{**} \pm 0.07$	$-0.13^{**} \pm 0.09$	0.04 ± 0.13	$-0.16^{**} \pm 0.08$
GLTrend	$-0.68^{**} \pm 0.09$	$-0.59^{**} \pm 0.06$	$-0.56^{**} \pm 0.09$	$-0.27^{**} \pm 0.12$	$-0.52^{**} \pm 0.07$

The authors refer to the difference in longitude of the ASL in models and observations, which can alter the poleward heat transport into the Weddell Sea. However, it is worth noting that the 2023 low extent was associated with a real shift in the ASL towards 90W and hence large heat transports and loss of sea

ice in the Weddell. As well as the depth of the ASL has there been a drift in its longitude? Again, not essential that this be investigated in this paper.

Thanks for pointing out this. We find that the 2023 DJF and MAM SLP anomalies from the ABS to Weddell Sea resemble the corresponding observed trends in Figs. 1h-i. We add these discussions in the second paragraph of the discussion section in the revised manuscript (Lines 440-443).

Reviewer #3 (Remarks on code availability):

Adequate use of readme files, but with few inline comments.

Thanks for pointing out this. We add more comments in all ncl programs. For example, we add the following inline comments in Figure1.ncl: (1) We first calculate the SIE anomaly and SIE trends from June 2013 to May 2023 in Fig. 1a. (2) We draw plots of SAT trends calculated in advance in Figs. 1j-m. (3) We calculate the seasonal trends of SIC in Figs. 1b-e. (4) We now draw plots of SLP&UV850 trends calculated in advance in Figs. 1f-i.

REVIEWER COMMENTS

Reviewer #2 (Remarks to the Author):

Thanks for the response and the revision. I am pleased to recommend publication.

We thank the reviewer #2 for his/her encouragement and support.

Reviewer #3 (Remarks to the Author):

The paper is much improved and results more robust in this latest iteration due to the inclusion of the pacemaker simulations. I recommend accepting the submission.

We thank the reviewer #3 for his/her comments and support. We really appreciate it.

I have only two issues

1. the use of the term 'Ekman suction' it is normally referred to as 'Ekman pumping'.

“Ekman suction” is changed to “Ekman pumping” in the revised manuscript. Ekman suction is mentioned in the method section as follows: “Negative trend or response values of WSC denote areas of Ekman suction that would move water upward in the column and cause sea ice decline”. Thanks for pointing it out!

2. There are no DOI in the references.

We follow the format of the recent papers published in Nature Communications and do not add DOI in the references.

Reviewer #3 (Remarks on code availability):

Improved inline comments make the purpose of the code easier to understand

Thanks again for your support!