Peer Review File

Atlantic Multidecadal Variability amplifies decadal variability in the Kuroshio-Oyashio Extension region under global warming

Corresponding Author: Dr Shujun Li

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

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

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Li,

Please accept our apologies for the delay in sending a decision on your manuscript. Your manuscript titled "Atlantic Multidecadal Variability amplifies decadal variability in the Kuroshio-Oyashio Extension region under global warming" 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.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

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:
Link Redacted
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

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,

Weiqing Han, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0003-3633-9105

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

For Manuscripts that fall into the following fields:
• Behavioural and social science
• Ecological, evolutionary & environmental sciences
• Life sciences
An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
You can download the form here:
https://www.nature.com/documents/nr-reporting-summary.pdf

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide .

*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This manuscript investigates how Kuroshio–Oyashio Extension (KOE) SSH decadal variability responds to global warming, emphasizing the strengthened role of Atlantic Multidecadal Variability (AMV). The authors propose that intensified AMV teleconnections due to a shallower oceanic mixed layer over North Atlantic contribute to enhanced and poleward-shifted KOE SSH variability under the high-emission scenario. The topic is highly relevant, and the analyses are overall thorough, combining CMIP5/CMIP6 analyses and reduced-gravity ocean model experiments. However, before the manuscript can be considered for publication, I believe a major revision is required.

Major Comments
1. Model Bias
Model biases are not adequately addressed, particularly regarding the representation of the Kuroshio axis, which is known to overshoot in low-resolution climate model simulations (Kim et al., 2023). This overshooting bias can significantly alter upper-ocean stratification, Rossby wave dynamics, and the magnitude and spatial structure of decadal SSH variability in the KOE region. This is likely one reason why prior studies (e.g., Joh et al., 2022) employed high-resolution model simulations specifically designed to mitigate such biases. In contrast, the present manuscript relies on relatively low-resolution CMIP5/CMIP6 multi-model ensemble outputs. However, the manuscript does not evaluate how these model biases may influence the results. Although the available period is relatively short (Historical: 1950-2014, SSP585: 2015-2050), it would still be beneficial to include CMIP6 HighResMIP in the analysis.
- Kim, W. M., Yeager, S. G., Danabasoglu, G., & Chang, P. (2023). Exceptional multi-year prediction skill of the Kuroshio Extension in the CESM high-resolution decadal prediction system. npj Climate and Atmospheric Science, 6(1), 118.
- Joh, Y., Delworth, T. L., Wittenberg, A. T., Cooke, W. F., Rosati, A. J., & Zhang, L. (2022). Stronger decadal variability of the Kuroshio Extension under simulated future climate change. npj Climate and Atmospheric Science, 5(1), 63.

2. Role of Tropical Pacific Pathway
As the authors noted in the introduction (Lines 72-76), AMV can influence North Pacific atmospheric circulation patterns through two pathways: a tropical pathway and an extratropical pathway. However, the manuscript mainly focuses on the extratropical pathway (Fig. 3 and Lines 159-169). It would be helpful to discuss whether the tropical pathway also contributes to the AMV-induced strengthened North Pacific high-pressure anomalies under SSP585. In addition, a comparison of the relative roles of the two pathways would further clarify the mechanisms driving the projected circulation changes.

Specific Comments
1. Line 99 The manuscript refers to ORAS5 as “observation-based,” but ORAS5 is an observational reanalysis. In particular, it does not directly assimilate SSH variables, so it would be more accurate to describe it as an observational reanalysis rather than an observation-based product.

2. The authors use a 71-year moving standard deviation in Fig. 1d, whereas an 11-year moving window is applied in other analyses. Considering the mechanisms discussed in the Introduction, such as PDO variability and Rossby wave dynamics, it would be more consistent and physically appropriate to use the 11-year window throughout the analysis rather than the 71-year window.

3. Supplementary Fig. 1a The figure caption states: “a Decadal variability intensity of SSHa at each grid point during 1901-2023, measured as its standard deviation (shading; unit: cm). The SSHa time series are quadratically detrended and smoothed with an 11-year running mean, based on ECMWF ORAS5 data for 1979-2014.” This description is confusing because it is unclear which period was actually used to compute Fig. 1a. ORAS5 is only available from 1958 onward, so the caption appears inconsistent with the stated 1901-2023 period. I recommend revising the caption to clearly specify the dataset and time period used for generating Supplementary Fig. 1a to avoid confusion.

4. As the ocean stratification is important for Rossby wave propagation speed, it would be helpful to include a Hovmöller diagram of the SSH anomalies from the reduced-gravity model.

Reviewer #2 (Remarks to the Author):

By analyzing outputs from a set of CMIP5 and CMIP6 models, this paper mainly investigates the possible reasons for the increased decadal variability of ssha in KOE region. According to this manuscript, the decadal variability of ssha in KOE is mainly affected by AMV, PDO and the ocean stratification. And through statistical analyses, the authors claim that the increased AMV variability would enhance the decadal variability of ssha in KOE region through enhanced AMV teleconnection; while impacts of PDO are reduced and much uncertain, and the stratification shows a damping effect. The thoughts and results are quite novel and interesting since the AMV associated climate impacts and their changes under global warming is always a hot topic due to their profound climate impacts. However, I would not recommend to publish this manuscript at its current stage. Because the evidences are not convincing enough, some key evidences are missing and some results are even contradicting with each other. In addition, the authors should examine the manuscript more carefully since many important definitions (for example, the MMEM, Monte-Carlo test etc.) are missing. Therefore, more calculations should be provided to make results reasonable and more explanations should be provided to make the manuscript

understandable. My concerns and comments are listed as follows in detail.
Major comments:
1. In this study, authors compare outputs from PiControl and SSP585/RCP85 simulations in CMIP5 and CMIP6 to address the changes of decadal variability in the present-day in the KOE region under global warming. However, the PiControl is not suitable to represent the present-day climate since it simulates states in pre-industrial periods. To represent the present-day climate, people often use the historical simulations, which are available from both CMIP5 and CMIP6.
2. Authors often show the results of multiple model ensemble mean, i.e., MMEM, while with no clear statements regarding to the process of how MMEM is formed.
3. Figure 4 is critical to support the authors arguments. While many clarifications should be made about figure 4. First, authors used equilibrium climate sensitivity in panel c and d, but with no statements explaining how it is being calculated and why it is used here. More details should be given. Second, results in Figure 4b and 4c seem to be replicates of those in Li et al. (2025) and no need to be displayed here again. If it is necessary to show them, please give the reasons in detail. Third, the relationship of ssha std and AMV std in SSP585 should also be given as scatter plots. Fourth, the relationship between AMV and ssha in KOE in Figure 4a seems to be dominated by ACCESS-ESM1-5, IPSL-CM6A-LR and CESM2-WACCM. However, the 3 models show insignificant relationship regarding to MLD changes vs AMV changes in Figure 4c. And in Figure 4d, the 3 models also show insignificant or negative relationship in ssha changes vs AMV changes. This doesn’t support the main arguments that AMV changes enhance the ssha changes in KOE regions. In addition, this issue also occurs in Figure 5d,e.
4. Authors often show and compare the 71-year running standard deviation and claim that the choice of 71-year is based on its ability to capture the long-term, multidecadal oscillations of oceanic processes. This seems not very consistent with the decadal variability of KOE mentioned in their title. How sensitive are the results to different length of the running window?
Minor comments:
Figure 1d. In PiControl, there seems no multidecadal oscillation in the ssha index in the first 150years.
Figure 2. The while dots are hard to see clearly. Monte Carlo test should be clearly stated in section of Methods. How are the regressions obtained? Besides, statistical level of the regressions should be displayed clearly.
Figure 3. TN flux and WAF flux should be consistently used. Statistical level of the regressions should be displayed clearly.
Figure 5. The relationship of ssha std and PDO std in SSP585 should also be given as scatter plots.
Supplementary Figure 1b. Details of how Figure 1b is generated should be clearly stated.
Line 102-105: PiControl doesn’t represent the present-day climate.
Line 115-117: Comparison between PiControl and SSP585 doesn’t lead to difference of future relative to present-day
Line 135-137: People often refer the MMEM results in historical simulations as the forced component of AMV. A consistency between the MMEM and observation would then lead to an inappropriate conclusion, i.e., the AMV is mostly externally forced rather than internally generated.
Line 151-156: It can be understood that the increased northward Ekman heat transport an increase the local ssh mean. But why does the enhanced northward Ekman heat transport can increase the local ssha variance? In addition, authors argue that the signal (changes in mean ssh or ssha variance?) could be transferred westward to KOE region by Rossby waves. But the discussion is too vague to understand. More evidence should be provided.
Line 164-167: the statement is not consistent with the results shown in Figure 3a.
Line 172-177: does this also hold in SSP585 and RCP85?
Line 178-196: this seems to explain the changes of AMV amplitude, rather than how AMV changes module decadal ssh variability in KOE regions. And most of the contents are replicates from Li et al. (2025). A reference would be enough.
Line 202-212: The results in Supplementary Fig.6 doesn’t support the statement that the AMV-induced atmospheric teleconnection exhibits a northward shift under the SSP585 scenario since the air temperature, precipitation and wind stress shown in Supplementary Fig.6 contains contribution not only from AMV but also many other factors. The longitudinal shifts of the AMV-induced atmospheric teleconnection could easily be obtained by calculating the difference between Figure 3a and Figure 3b, which seems to be inconsistent with the results the authors claim here.
Line231-233: Authors argue that the AMV is important to ssha in KOE region by discussion the secondary importance of the PDO and the damping of stratification. While here they refer it to the local ocean-atmosphere interactions. What exactly are the local ocean-atmosphere interactions? How are they related to the AMV, PDO and the stratification?
Line 291: The increased AMV amplitudes accounts for 34% of the increased variance of ssha in KOE. It seems that AMV is still a secondary factor to the increased variance of ssha in KOE. Can authors give more discussion in details what other factors could be?
Line 338-339: To isolate the impacts of PDO or AMV, people often regressing out the PDO/AMV signal from the variables at each grid, then conduct the regression analysis.
Line 342-343: why the H in EHT formula is set to be the MLD instead of Ekman layer depth?

the scientific community achieve unambiguous attribution of all scholarly contributions. You can create and link your ORCID from the home page of the Manuscript Tracking System by clicking on ‘Modify my Springer Nature account’ and following the instructions in the link below. Please also inform all co-authors that they can add their ORCIDs to their accounts and that they must do so prior to acceptance.
https://www.springernature.com/gp/researchers/orcid/orcid-for-nature-research

For more information please visit http://www.springernature.com/orcid

If you experience problems in linking your ORCID, please contact the Platform Support Helpdesk.

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Li,

Your manuscript titled "Atlantic Multidecadal Variability amplifies decadal variability in the Kuroshio-Oyashio Extension region under global warming" has now been seen by 2 reviewers, and we include their comments at the end of this message. Both reviewers have raised significant concerns about the revised manuscript. We remain interested in the possibility of publishing your study in Communications Earth & Environment; however, these concerns must be thoroughly addressed. We would like to evaluate your responses to these comments and assess a revised version of the manuscript before making a final decision regarding publication.

Specifically, we require that you justify the relationship between AMV and KOE, justify the poleward shift in CESM-HR, and clarify the mechanisms around Rossby wave propagation.

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.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

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:
Link Redacted
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

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,

Weiqing Han, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0003-3633-9105

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

For Manuscripts that fall into the following fields:
• Behavioural and social science
• Ecological, evolutionary & environmental sciences
• Life sciences
An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
You can download the form here:
https://www.nature.com/documents/nr-reporting-summary.pdf

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide .

*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

I thank the authors for the additional CESM-HR analysis and the decomposition of the AMV contribution. These analyses improve the clarity of the manuscript regarding model biases and the underlying mechanisms. However, I believe that a few additional points should be addressed prior to publication.

Major comments:
1. CESM-HR analysis
1-1) Poleward shifted KOE decadal variability
The intensified and poleward-shifted KOE decadal variability under global warming is a key result emerging from the CMIP ensemble. In this context, the lack of explicit discussion on whether CESM-HR projects the associated meridional shift makes it difficult to assess its consistency with the CMIP results. The comparison between Fig. 1c and Fig. 7c alone may not be sufficient to fully assess whether CESM-HR reproduces the poleward-shift feature. A figure similar to Fig. 1e for CESM-

HR, together with relevant discussion, would help clarify the consistency between the CMIP and CESM-HR results.
1-2) Role of the model resolution
Due to data availability within HighResMIP, only one high-resolution model is analyzed in this study. In this context, it may be difficult to generalize that the results are “not altered by model resolution-related biases”. Even among HighResMIP models, systematic biases can arise from differences in model physical parameterizations rather than model resolution (Sobel et al., 2023; Dhame et al., 2025). Therefore, it would be appropriate to acknowledge this limitation and clarify that the inferred robustness is based specifically on CESM-HR, rather than high-resolution models more broadly.
- Dhame, S., Olonscheck, D., & Rugenstein, M. (2025). Higher-resolution climate models do not consistently reproduce the observed tropical Pacific warming pattern. Journal of Climate, 38(13), 3131-3149.
- Sobel, A. H., Lee, C. Y., Bowen, S. G., Camargo, S. J., Cane, M. A., Clement, A., ... & Tippett, M. K. (2023). Near-term tropical cyclone risk and coupled Earth system model biases. Proceedings of the National Academy of Sciences, 120(33), e2209631120.
1-3) SLP regression patterns
The caption of Fig. 7f refers to “Changes in SSHa/SLPa regression onto AMV from CESM-HR”; however, the SLPa pattern does not appear to be clearly shown in the panel. Including SLP regression contours consistently in Fig. 7d-f would facilitate a more complete interpretation. For example, when comparing Fig. 2f and Fig. 7f, the atmospheric circulation pattern centered around 150°W and 50°N appears markedly different, with one exhibiting a cyclonic anomaly and the other an anticyclonic anomaly. Given that this region serves as a forcing area in the reduced-gravity model and plays a key role in baroclinic Rossby wave propagation, further discussion of the relevant mechanisms would strengthen the interpretation of the consistency between CESM-HR and CMIP results.

2) Decomposition of the AMV contribution
The additional analysis decomposes AMV into tropical (20°S-20°N) and extratropical (20°N-70°N) components and evaluates their respective impacts on KOE SSH variability. While this framework is useful, further justification for this separation would strengthen the analysis. In particular, providing relevant references to support this decomposition, or demonstrating its robustness using piControl simulations, would enhance confidence in the results.

Specific comments:
Line 39 in climate system > in the climate system
Line 55: trigger baroclinic Rossby waves > triggers baroclinic Rossby waves
Line 87: However, affects from other processes > However, effects from other processes
Line 329: support our central conclusion > supports our central conclusion
Line 330: are robust > is robust
Line 431: two scenario > two scenarios

Version 2:

Decision Letter:

Dear Dr Li,

Your revised manuscript titled "Atlantic Multidecadal Variability amplifies decadal variability in the Kuroshio-Oyashio Extension region under global warming" has now been seen by 2 reviewers, whose comments are appended below. A new reviewer has been recruited to adjudicate, due to a previous reviewer no longer being available for further review. In the light of their advice we regret to inform you that we cannot publish your manuscript in Communications Earth & Environment.

You will see that the reviewers find that concerns have not been met; specifically, the demonstration of a statistically significant relationship between the ocean stratification and KOE SSHa, and a statistically significant relationship of decadal variability signals. Taking these points together with our editorial considerations, we are unable to conclude that your manuscript represents a sufficiently novel and compelling advance over the body of related work in the literature. Unfortunately, these reservations are sufficiently important to preclude publication of this study in Communications Earth & Environment.

We are sorry that we cannot be more positive on this occasion and thank you for the opportunity to consider your work.

Best regards,

Weiqing Han, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0003-3633-9105

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

I thank the authors for the additional analysis and revisions in response to my previous comment. While I believe most of my previous questions have been addressed, I would appreciate clarification regarding the following point related to my earlier question before publication.

Comments
1) Mismatch in wind stress curl forcing for oceanic Rossby wave generation among CMIP6, CESM-HR, and the reduced-gravity ocean model
In lines 354-357, the authors state that the strength of basin-scale wind stress curl forcing, rather than its local structure, is important for enhancing local surface Ekman convergence and generating stronger positive SSH anomalies over the KOE region. Nevertheless, in the specific region associated with baroclinic Rossby wave generation, the sign of the wind stress curl forcing appears to be opposite between CMIP6 and CESM-HR.
Specifically, the reduced-gravity ocean model presented in Fig. 6 prescribes wind stress forcing at 150°W, 50°N based on the results shown in Fig. 2f from CMIP6, corresponding to an anticyclonic wind stress curl. In addition, the authors stated (lines 156-157) that this anticyclonic wind forcing induces surface Ekman convergence, deepens the thermocline, and generates and propagates positive SSH anomalies westward. However, Fig. 7f from CESM-HR shows a cyclonic wind stress curl forcing at the same location (150°W, 50°N). Given this discrepancy, a more consistent explanation is needed to reconcile the results from CMIP6, CESM-HR, and the reduced-gravity ocean model.

Reviewer #4 (Remarks to the Author):

In this manuscript, the authors study the influence of AMV on KOE SSHa variability using CMIP6 models under PI and SSP585 conditions. They show a northward movement of KOE under a warmer state and intensified decadal variability of KOE ssha. They have attributed this intensification to the increased variability of AMV. The overall results are interesting, but they did not demonstrate the decadal variability studied here is statistically significant. Here is my assessment of the authors' response to the comments of reviewer #2 and my own evaluation of this manuscript.
Comments on the response to reviewer #2:
1. To me, a better response to the comment #1 from reviewer #2 is to test whether the relationship between AMV and KOE exists in each individual model under both PI and SSP585 conditions. If the answer is yes, the concern of review #2 is resolved. If not, it is better to examine why certain models do not produce this relationship. In addition, the location of KOE may not be the same for each model. As shown in Fig. 1a, a uniformed box may not give you the best result. It might be a good idea to define this KOE box based on each model and different mean background states.
2. For the second comment, the authors may need to do a deeper dive to figure out whether this AMV-KOE relationship is true. One way to do this is to do a lead-lag correlation between AMV and KOE for each model. If AMV indeed leads KOE in all models, it is very likely that AMV variability affects KOE variability. Then, a physical explanation is needed. In the manuscript, the authors have tried to explain this relationship but did not fully demonstrate whether this relationship exists or not. I assume this is why reviewer #2 is convinced by the argument of the authors.
3. For comment #5, it would be easy to identify which model contributes to the changes of the STD in the ensemble mean. If the authors plot the STDs for all models separately, this is an easy task to do. Once the model or models is/are identified, an explanation will not be difficult to find. It is also interesting to see that when the system is going towards a more quasi-equilibrium state, the variability reduces as the forcing after 2250 is constant in SSP585.
4. For comment #8, it is a good idea to identify whether the proposed relationship between ocean stratification and KOE

SSHa is true for each individual model under both PI and SSP585 conditions. Again, the unsignificant relationship in PI control may also be related to the KOE region which might not be the same in all models
5. The response to comments #3, #4, #6, #7, #9 is good to me.
Additional comments:
1. From my point view, the authors show increase in stds in SSP585 relative to PI control, but they did not show whether the intended decadal variability is significant or not. It is better to test where the decadal variability is significant, then explore the underlying physical processes. For example, spectral analysis can be done at each grid point to see whether the decdadal variability is significant at that grid point.
2. To define the KOE region better, it is a good idea to define it based on each model. The ensemble mean can be used, but results from each model can be provided in the online information.
3. Lines 98-99, How do you determine there are significant decadal variability in SSH? Maybe it is better to show where the decadal variability is significant in Fig. S1.
4. Line 101, Is there a reason to stop the analysis in 2014? Is it because the CMIP6 historical simulations stop in 2014? In addition, did you do the satellite derived SSH? Are they the same?
5. Line 110-111, Ideally to determine whether there is decadal variability, you need to do power spectrum analysis on each grid point and pick those points do show statistically significant decadal peaks. Then those are the grid points which you can state the decadal variability exist.
6. Line 114-115, the box seems too big which includes not only KOE, but also other things. Is it possible to narrow it to the KOE only? For example. find the ridge line of SSHa and extend 2 (or 5) degree north and 2 (or 5) degree south of the ridge.
7. Line 147, what are the regression coefficients for different modes, AMV, PDO? How much of the SSH variance near KOE can be explained by AMV or PDO?
8. Line 153, It is better to show the regressed wind stress curl anomaly which can show the Ekman convergence much better.
9. Line 174-175, are there any references to support this claim?
10. Line 183-185, is this true for each model?
11. In the manuscript, the use of “KOE” and “KOE region” seems interchangeable. As mentioned in previous comment, it is better to strictly study the KOE only.

Version 3:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Li,

Your manuscript titled "Atlantic Multidecadal Variability amplifies decadal variability in the Kuroshio-Oyashio Extension region under global warming" 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, provided that remaining reviewer concerns are met.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers, which pertain to mechanisms underlying the changes between the role of the PDO in PI control but AMV under SSP8.5. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at https://www.nature.com/documents/commsj-file-checklist.pdf .

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication. For further information about article processing charges, open access funding, and advice and support from Nature Portfolio, please visit https://www.nature.com/commsenv/open-access

At acceptance, you will be provided with instructions for completing the open access licence agreement on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC).

Please use the following link to submit the above items:
Link Redacted
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

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

Best regards,

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #4 (Remarks to the Author):

This is my second review of this manuscript, the authors, in general, have done a good job to address the comments from reviewers. From their responses, I have a few additional comments:
Comments:
1. Based on the new figure on the lead-lag correction between AMV and KOE, and between PDO and KOE, the authors may want to modify the paragraph line 62-78. In this paragraph, the authors are trying to make the relationship between AMV and KOE. However, their correlations show there is nearly no relationship between AMV and KOE. On the other hand, changes in AMV can affect the variability in the Pacific and how these effects will influence KOE is not clear.
2. It is interesting that KOE variability is dominated by PDO in PI control, but not under SSP8.5, and on the other hand, AMV becomes more important. This can be an important point for the authors to address. Why is this the case? The current analysis focuses on what has changed and how to connect these changes with AMV. It is more important to show what changes lead to the changes in the relationship between KOE and PDO, and between KOE and AMV. Here I would like to suggest the authors do a few more analyses:
2a. calculate running lead-lag correlation between KOE and AMV/PDO in the historical and SSP585 simulations. Then plot the zero-lag correlation coefficient time series. This could show how the lead-lag correlation changes over time. What happened during the transition time could be a good indicator of why the relationships change. An analysis on the variables changing at the same time could give more insights on the causes of the changing relationship.
2b. From the power spectrum analysis, it seems that there is a shift in frequency under SSP585 for KOE. Maybe the same spectrum analysis should also be done to AMV and PDO indices to see whether there is frequency shift in AMV and PDO.
2c. Do a band pass of 10 to 30 years and a lowpass 30+ years for KOE, AMV and PDO. After that, do the lead-lag correction again to see whether the relationship changes for different frequency bands. Such as does the decadal band (10-30 years) variability of KOE is still dominated by PDO in SSP585?
3. As indicated by the authors, the AMV index is derived from detrended SST. Did the same detrending method used for the PDO? Such as detrend the same way as AMV first before EOF analysis?
4. It is interesting to see in Fig. S4b. Why does the lead-lag correlation show this shape? This could be related to what I mentioned before about the frequency shift.
5. Is it possible to add AMV changes in Fig. S7?

** Visit Nature Portfolio's author and referees' website at www.nature.com/authors for information about policies, services and author benefits**

Point-by-Point Response to Reviewers (our response in **blue**)

We are grateful to the reviewers for their constructive and insightful comments, which have improved the quality and clarity of the manuscript. We have carefully revised the paper in response to all comments, as detailed below (our responses are provided in **blue**).

Response to Reviewer #1

This manuscript investigates how Kuroshio–Oyashio Extension (KOE) SSH decadal variability responds to global warming, emphasizing the strengthened role of Atlantic Multidecadal Variability (AMV). The authors propose that intensified AMV teleconnections due to a shallower oceanic mixed layer over North Atlantic contribute to enhanced and poleward-shifted KOE SSH variability under the high-emission scenario. The topic is highly relevant, and the analyses are overall thorough, combining CMIP5/CMIP6 analyses and reduced-gravity ocean model experiments. However, before the manuscript can be considered for publication, I believe a major revision is required.

We sincerely appreciate your positive feedback and the constructive comments on our manuscript. We have carefully considered all comments and revised the manuscript accordingly.

Major Comments

1. Model Bias

Model biases are not adequately addressed, particularly regarding the representation of the Kuroshio axis, which is known to overshoot in low-resolution climate model simulations (Kim et al., 2023). This overshooting bias can significantly alter upper-ocean stratification, Rossby wave dynamics, and the magnitude and spatial structure of decadal SSH variability in the KOE region. This is likely one reason why prior studies (e.g., Joh et al., 2022) employed high-resolution model simulations specifically designed to mitigate such biases. In contrast, the present manuscript relies on relatively low-resolution CMIP5/CMIP6 multi-model ensemble outputs. However, the manuscript does not evaluate how these model biases may influence the results. Although the available period is relatively short (Historical: 1950-2014, SSP585: 2015-2050), it would still be beneficial to include CMIP6 HighResMIP in the analysis.

- Kim, W. M., Yeager, S. G., Danabasoglu, G., & Chang, P. (2023). Exceptional multi-year prediction skill of the Kuroshio Extension in the CESM high-resolution decadal prediction system. npj Climate and Atmospheric Science, 6(1), 118.

- Joh, Y., Delworth, T. L., Wittenberg, A. T., Cooke, W. F., Rosati, A. J., & Zhang, L. (2022). Stronger decadal variability of the Kuroshio Extension under simulated future climate change. npj Climate and Atmospheric Science, 5(1), 63.

We agree with this important point regarding the biases of low-resolution models in representing the KOE. Our analysis focus on changes in decadal SSH variability in the KOE region, which requires simulations with sufficiently long-time spans to robustly resolve low-frequency variability. The currently available CMIP6 HighResMIP simulations are limited to relatively short periods with 65 years for the historical experiment and only about 36 years for the future scenario. These record lengths are insufficient to reliably characterize decadal variability and its response to warming.

To address this concern, we use long-term, high-resolution simulations from the Community Earth System Model in its high-resolution configuration (CESM-HR). CESM-HR is a coupled climate model based on CESM1.3 with enhanced resolution (approximately 0.25° in the atmosphere/land and 0.1° in the ocean and sea-ice components), allowing improved representation of mesoscale dynamics and reducing common low-resolution biases such as overly smoothed western boundary current structures.

To assess the impact of global warming, we analyze a 295-year pre-industrial control simulation (PiControl) and an extended RCP8.5 run covering 2006–2300. The extended RCP8.5 experiment provides a sufficiently long warming period to robustly evaluate changes in decadal SSH variability beyond the relatively short CMIP RCP8.5 interval (2006–2100). We find that SSH decadal variability in the KOE region increases by ~10.5% in the warming climate relative to PiControl (**Fig. R1-1a-c**). Consistent with this increase, the AMV-related atmospheric response over the North Pacific is strengthened in CESM-HR under global warming (**Fig. R1-1d-f**). Relative to PiControl, the RCP8.5 simulation exhibits amplified wind stress anomalies associated with AMV, which enhance surface Ekman convergence and generate stronger positive SSHa over the KOE region. These results indicate a reinforced AMV–KOE teleconnection in the high-resolution model. The consistency between the CESM-HR results and those from the lower-resolution CMIP ensembles supports our central conclusion that AMV-induced amplification of KOE decadal SSH variability under global warming is robust and not altered by model resolution–related biases.

We have added this CESM-HR analysis and a related discussion to the revised manuscript (see section of ‘**High-resolution simulation validation**’**, Lines 289-330**) to clarify the resolution dependence and to reinforce the confidence in our conclusions.

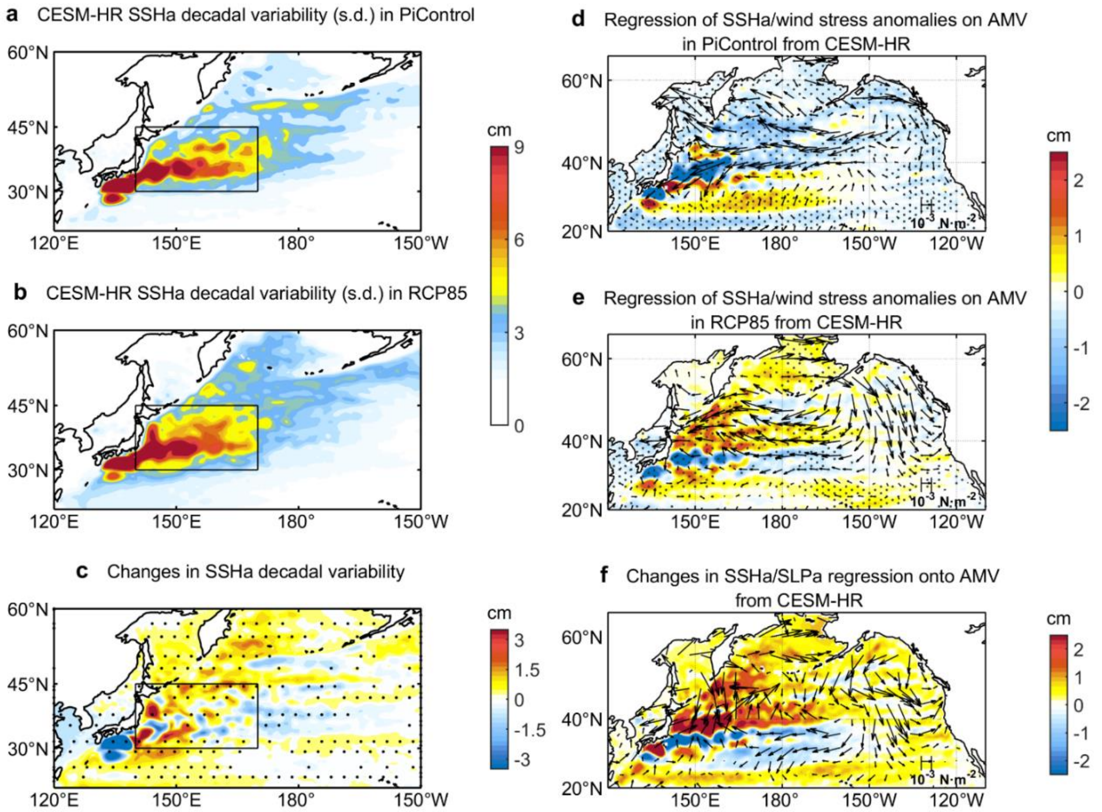

Fig. R1-1 | Intensification of decadal SSH variability in the KOE region and its response to the AMV under global warming in CESM-HR. a Spatial distribution of the standard deviation of the 11-year running-mean, quadratically detrended SSH anomalies (SSHa) at each grid point in PiControl (shading; unit: cm). **b** Same as (**a**), but for the RCP8.5 scenario. **c** Standard deviation differences of the decadal SSHa between RCP85 and PiControl (RCP8.5 minus PiControl). Black dots indicate where variance changes are significant at the 95% level based on a *F*-test. **d** Regressions of 11-yr running-mean, detrended SSHa (shading; unit: cm) and surface wind stress anomalies (arrows; unit: N·m-2) onto the normalized AMV index in PiControl. AMV-related regression patterns are derived from a multiple linear regression, with the Pacific Decadal Oscillation removed. Grey dots indicate regions where the regression coefficient is statistically significant at the 95% level based on a *t*-test. **e** Same as (**d**), but for the RCP8.5 scenario; **f** Differences between the regressions of (**d**) and (**e**) (RCP85 minus PiControl).

2. Role of Tropical Pacific Pathway

As the authors noted in the introduction (Lines 72-76), AMV can influence North Pacific atmospheric circulation patterns through two pathways: a tropical pathway and an extratropical pathway. However, the manuscript mainly focuses on the extratropical pathway (Fig. 3 and Lines 159-169). It would be helpful to discuss whether the tropical pathway also contributes to the AMV-induced strengthened North Pacific high-pressure anomalies under SSP585. In addition, a comparison of the relative roles of the two pathways would further clarify the mechanisms driving the projected circulation changes.

Thank you for this helpful comment. To disentangle the relative roles of tropical and extratropical Atlantic influences, we decompose the AMV into two regional indices: a tropical Atlantic index (20°S–20°N, 75°W–15°E) and an extratropical Atlantic index (20°N–70°N, 75°W–7°W). Both indices are calculated as area-weighted averaged SST anomalies over their respective domains and are processed using the same detrending and 11-year low-pass filtering as the original AMV index.

Our analysis indicates that the tropical Atlantic pathway contributes weakly to the projected North Pacific response under global warming. Changes in the regression patterns onto the normalized tropical Atlantic index show weak and statistically insignificant SSHa responses over the KOE region (**Fig. R1-2b**). This is likely because the amplitude of the tropical Atlantic variability does not show a significant increase under global warming (**Fig. R1-2c**), thereby limiting its ability to drive a stronger atmospheric response.

In contrast, the extratropical AMV pathway emerges as the dominant contributor to the strengthened KOE SSHa variability. The KOE SSHa response to the extratropical AMV exhibits a statistically significant increase relative to PiControl (**Fig. R1-2a**). This is consistent with the amplified extratropical AMV signal under SSP585 that drives a stronger downstream response. We have added a related discussion to the revised manuscript to clarify the relative roles of these pathways (**Lines 203-215**).

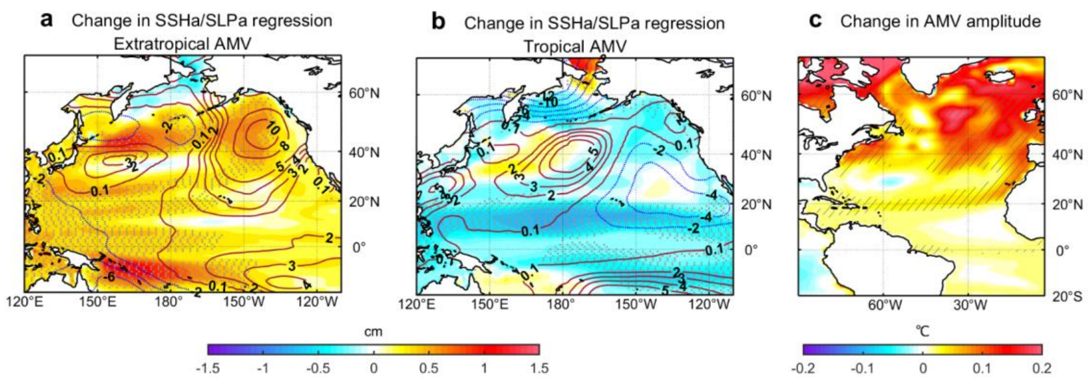

Fig. R1-2 | Projected changes in the teleconnection from tropical and extratropical components of the AMV to North Pacific under global warming. a Changes in the regressions of 11-yr running-mean and detrended SSHa (shading; unit: cm) and SLPa (contours with positive in red and negative in blue; unit: Pa) onto the normalized extratropical Atlantic index (SSP585 minus PiControl). Shown is the multi-model ensemble mean (MMEM) result. Grey dots indicate regions where the SSHa anomalies are significant at the 95% confidence level based on a bootstrap test. **b** Same as (**a**), but for regressions onto the normalized tropical Atlantic index. All regression coefficients shown in (**a**) and (**b**) are obtained using a multiple linear regression that controls for the extratropical AMV, tropical AMV, and PDO indices. **c** Projected changes in the AMV pattern (shading; unit: °C) under global warming (SSP585 minus PiControl). The AMV pattern is derived from regression of SSTa onto the normalized AMV index. Grey contours indicate regions where the changes are statistically significant at the 95% confidence level based on a bootstrap test. Shown is the MMEM result.

Specific Comments：

1. Line 99 The manuscript refers to ORAS5 as “observation-based,” but ORAS5 is an observational reanalysis. In particular, it does not directly assimilate SSH variables, so it would be more accurate to describe it as an observational reanalysis rather than an observation-based product.

We thank the reviewer for this clarification. We have revised the manuscript to describe ORAS5 as an observational reanalysis (**Lines 102, 369**).

2. The authors use a 71-year moving standard deviation in Fig. 1d, whereas an 11-year moving window is applied in other analyses. Considering the mechanisms discussed in the Introduction, such as PDO variability and Rossby wave dynamics, it would be more consistent and physically appropriate to use the 11-year window throughout the analysis rather than the 71-year window.

These two window lengths are adopted for different purposes. The 11-year running-mean filter is used to extract and diagnose decadal variability from the long simulations. The 71-year moving window is designed to illustrate whether the enhanced SSH variability under SSP585 is a persistent feature or driven by specific periods. The 71-year moving window result demonstrate that the increase in decadal variability is a robust, persistent feature over time, rather than an artifact of a single period.

To avoid confusion, we have clarified this distinction in the revised manuscript by stating the different objectives of the 11-year running-mean and 71-year moving-window and emphasizing that the physical interpretations are based on the 11-year decadal variability throughout (**Lines 95-97, 108-120**).

3. Supplementary Fig. 1a The figure caption states: "a Decadal variability intensity of SSHa at each grid point during 1901-2023, measured as its standard deviation (shading; unit: cm). The SSHa time series are quadratically detrended and smoothed with an 11-year running mean, based on ECMWF ORAS5 data for 1979-2014." This description is confusing because it is unclear which period was actually used to compute Fig. 1a. ORAS5 is only available from 1958 onward, so the caption appears inconsistent with the stated 1901-2023 period. I recommend revising the caption to clearly specify the dataset and time period used for generating Supplementary Fig. 1a to avoid confusion.

Thank you for pointing out this inconsistency. The caption of Supplementary Fig. 1a has been revised to clearly state that the decadal SSH variability is computed from ORAS5 data over 1979–2014, after quadratic detrending and applying an 11-year running mean.

4. As the ocean stratification is important for Rossby wave propagation speed, it would be helpful to include a Hovmöller diagram of the SSH anomalies from the reduced-gravity model.

Following the reviewer's suggestion, we have added longitude–time Hovmöller diagrams of SSHa from the reduced-gravity model under weak and strong stratification (**Fig. R1-3**), constructed by averaging SSHa over 35°N–50°N in the North Pacific. Under stronger stratification, the SSHa response to the same wind forcing is weaker, and the associated Rossby wave propagation is faster, thereby limiting the development of SSH variance over the KOE region. These results are consistent with our interpretation of the stratification effect on KOE SSH variability. We have included this figure in the revised manuscript (**Supplementary Fig. 9**).

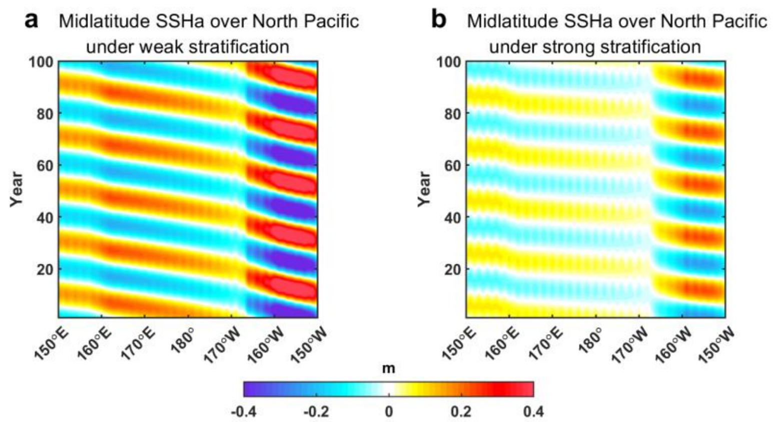

Fig. R1-3 | Longitude-time Hovmöller diagram of SSH anomalies (SSHa) at midlatitudes over North Pacific. a Hovmöller diagram of the midlatitude (averaged over 35°N–50°N) SSHa (shading; unit: m) over North Pacific under weak stratification. **b** same as (**a**), but under strong stratification.

Response to Reviewer #2

By analyzing outputs from a set of CMIP5 and CMIP6 models, this paper mainly investigates the possible reasons for the increased decadal variability of ssha in KOE region. According to this manuscript, the decadal variability of ssha in KOE is mainly affected by AMV, PDO and the ocean stratification. And through statistical analyses, the authors claim that the increased AMV variability would enhance the decadal variability of ssha in KOE region through enhanced AMV teleconnection; while impacts of PDO are reduced and much uncertain, and the stratification shows a damping effect. The thoughts and results are quite novel and interesting since the AMV associated climate impacts and their changes under global warming is always a hot topic due to their profound climate impacts. However, I would not recommend to publish this manuscript at its current stage. Because the evidences are not convincing enough, some key evidences are missing and some results are even contradicting with each other. In addition, the authors should examine the manuscript more carefully since many important definitions (for example, the MMEM, Monte-Carlo test etc.) are missing. Therefore, more calculations should be provided to make results reasonable and more explanations should be provided to make the manuscript understandable. My concerns and comments are listed as follows in detail.

We sincerely appreciate your positive feedback and the constructive comments on our manuscript. We have carefully reviewed your suggestions and addressed all issues you raised. We have made revisions to the manuscript accordingly, while ensuring that the overall structure and contents remain robust.

Major comments:

1. In this study, authors compare outputs from PiControl and SSP585/RCP85 simulations in CMIP5 and CMIP6 to address the changes of decadal variability in the present-day in the KOE region under global warming. However, the PiControl is not suitable to represent the present-day climate since it simulates states in pre-industrial periods. To represent the present-day climate, people often use the historical simulations, which are available from both CMIP5 and CMIP6.

Thank you for pointing it out. The term “present-day” is not appropriate in this context and has therefore been revised to “pre-industrial period”. Since the aim of this study is to assess the impact of greenhouse warming, the pre-industrial experiment provides a suitable baseline for comparison. This framework is consistent with previous studies that addressed similar questions using PiControl–future scenario comparison (Li et al., 2025).

Historical simulations (1850-2014) are not used here, as their limited length constrains a robust assessment of decadal variability. By contrast, the PiControl and SSP585 simulations offer multi-century outputs, enabling a more consistent evaluation of decadal variability and its response to greenhouse warming. We have clarified these methodological considerations in the revised manuscript to ensure accuracy (**Lines 102, 369**).

Reference:

Li, S., et al. Intensified Atlantic multidecadal variability in a warming climate. *Nat. Clim. Change* **15**, 293-300 (2025).

2. Authors often show the results of multiple model ensemble mean, i.e., MMEM, while with no clear statements regarding to the process of how MMEM is formed.

For each model, the indices and associated fields are detrended and filtered independently, and all analyses are performed at the individual model level prior to averaging. The multi-model ensemble mean (MMEM) is then constructed as the arithmetic mean across models with equal weighting. These procedures and clarifications have now been stated in the revised manuscript (**Lines 133-136, 375-377**).

3. Figure 4 is critical to support the authors arguments. While many clarifications should be made about figure 4. **First**, authors used equilibrium climate sensitivity in panel c and d, but with no statements explaining how it is being calculated and why it is used here. More details should be given. **Second**, results in Figure 4b and 4c seem to be replicates of those in Li et al. (2025) and no need to be displayed here again. If it is necessary to show them, please give the reasons in detail. **Third**, the relationship of ssha std and AMV std in SSP585 should also be given as scatter plots. **Fourth**, the relationship between AMV and ssha in KOE in Figure 4a seems to be dominated by ACCESS-ESM1-5, IPSL-CM6A-LR and CESM2-WACCM. However, the 3 models show insignificant relationship regarding to MLD changes vs AMV changes in Figure 4c. And in Figure 4d, the 3 models also show insignificant or negative relationship in ssha changes vs AMV changes. This doesn't support the main arguments that AMV changes enhance the ssha changes in KOE regions. In addition, this issue also occurs in Figure 5d, e.

First, equilibrium climate sensitivity (ECS) in CMIP6 is calculated as the global-mean surface air temperature increase associated with a doubling of atmospheric CO_2, and is typically estimated from each model's response to the abrupt 4×CO_2 experiment using the Gregory regression method (Meehl et al., 2020). In this study, ECS is used to account for intermodel differences in overall climate sensitivity (Li et al., 2025). By normalizing the intermodel responses by ECS, we reduce the influence of differing background warming magnitudes across models and facilitate a more meaningful comparison of model responses on a per–unit climate sensitivity basis. This approach helps isolate mechanisms that are robust across models, rather than differences arising simply from varying ECS values. The definition, source, and purpose of ECS have now been clarified in the revised manuscript (**Lines 181-185**).

Second, we agree with your comment. We have removed **Figs. 4b, c** to maintain focus on the novel aspects of our study in the main text (see **revised Fig.3, Line 675**).

Third, following the reviewer's suggestion, we have added scatter plots illustrating the relationship between AMV variability and KOE SSHa variability under SSP585 (**Fig. R2-1b**). The intermodel correlation reaches 0.86 *($p = 0.01$)*, demonstrating a robust and statistically significant association between AMV intensity and KOE SSHa variability. We have included this panel in the **revised Fig. 3 (Line 675)**.

Fourth, to assess whether the intermodel relationship is dominated by the three models (ACCESS-ESM1-5, IPSL-CM6A-LR and CESM2-WACCM), we perform a sensitivity test by excluding them from the analysis. The remaining models consistently show a tendency for larger AMV variability to be associated with enhanced KOE SSHa variability in PiControl and SSP585, although the statistical significance is reduced due to the smaller sample size (**Fig. R2-1a, b,** red lines). Furthermore, a positive intermodel relationship is still evident between changes in AMV amplitude and changes in KOE SSHa decadal variability, with a correlation coefficient of 0.45 ($p = 0.12$; **Fig. R2-1c**, red line). Thus, the intermodel relationship is not solely driven by a small subset of models, but instead reflects a more general tendency across the CMIP6 ensemble.

In addition, the climatological MLD in the North Atlantic exhibits only marginal shoaling in these three models under global warming. As a result, the AMV amplitude shows only moderate enhancement in these models, leading to relatively weak increases in KOE SSHa variability. This behavior is consistent with our proposed mechanism that greater shoaling of the North Atlantic MLD favors a larger AMV amplitude and, in turn, stronger KOE SSHa variability. Given that the relatively strong AMV amplitude in PiControl simulated by these three models may partly arise from intrinsic model biases, we do not rely on individual-model behavior. Instead, we focus on the intermodel relationship between changes in AMV and changes in KOE SSHa variability, which is designed to capture ensemble-scale tendency across a broader set of models.

Reference:

Meehl, G. A. et al. Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Sci. Adv.* **6**, eaba1981 (2020).

Li, S., et al. Intensified Atlantic multidecadal variability in a warming climate. *Nat. Clim. Change* **15**, 293-300 (2025).

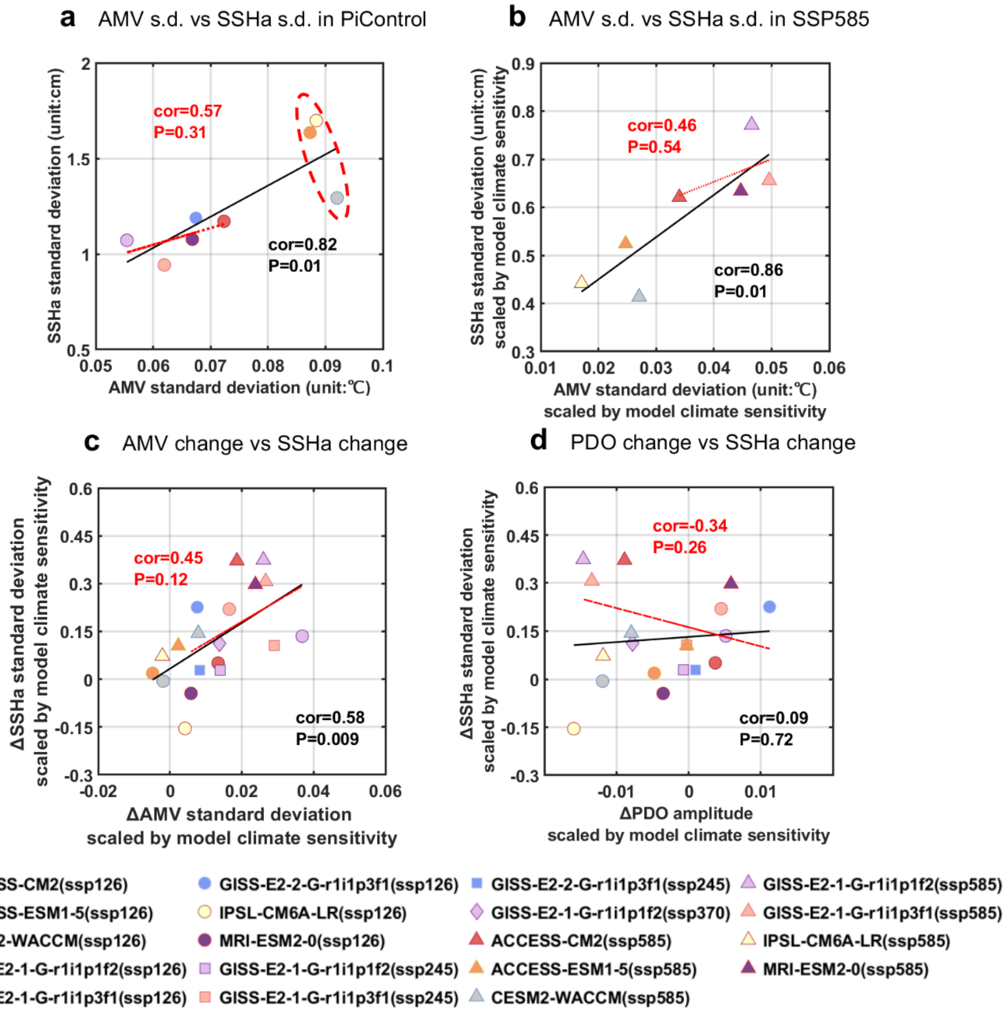

Fig. R2-1 | Intermodel relationships between AMV/PDO variability and decadal SSH variability in the KOE region under different simulations. a Intermodel correlation between the standard deviation of the AMV (unit: °C) and the area-weighted averaged SSH anomalies (SSHa; unit: cm) over the KOE (35°–50°N, 140°E–160°W) in PiControl. The black solid line shows the linear relationship across all models, whereas the red dashed line shows the relationship excluding ACCESS-ESM1-5, CESM2-WACCM, and IPSL-CM6A-LR. **b** Same as (**a**), but for SSP585, with both variables scaled by each model's equilibrium climate sensitivity (ECS) to remove intermodel differences in climate sensitivity to global warming. **c** Intermodel relationship between changes in AMV amplitude and in KOE decadal SSHa variability. Both are scaled by ECS in respective models; black and red lines as in (**a**). **d** Same as (**c**), but for the changes in PDO amplitude and in KOE decadal SSHa intensity.

4. Authors often show and compare the 71-year running standard deviation and claim that the choice of 71-year is based on its ability to capture the long-term, multidecadal oscillations of oceanic processes. This seems not very consistent with the decadal variability of KOE mentioned in their title. How sensitive are the results to different length of the running window?

In all analyses, decadal variability is first isolated by removing the quadratic trend and applying an 11-year running mean, which is consistent with the decadal focus stated in the title. In contrast, the 71-year moving window is introduced for a different purpose: to assess whether the enhanced SSH variability under SSP585 represents a persistent, long-term feature or is dominated by specific time intervals.

The 71-year moving window result demonstrate that the increase in decadal SSHa variability is robust and persists throughout the simulation period. To further assess the sensitivity to window length, we repeat the analysis using alternative windows of 51, 71, and 91 years (**Fig. R2-2**). The enhanced SSHa variability in the KOE under warming remains robust across all window lengths. This demonstrates that our conclusions are not sensitive to the specific window length and do not conflict with the decadal nature of the variability emphasized in the study.

To avoid confusion, we have clarified this distinction in the revised manuscript by stating the different objectives of the 11-year running-mean and 71-year moving-window (**Lines 95-97, 109-120**).

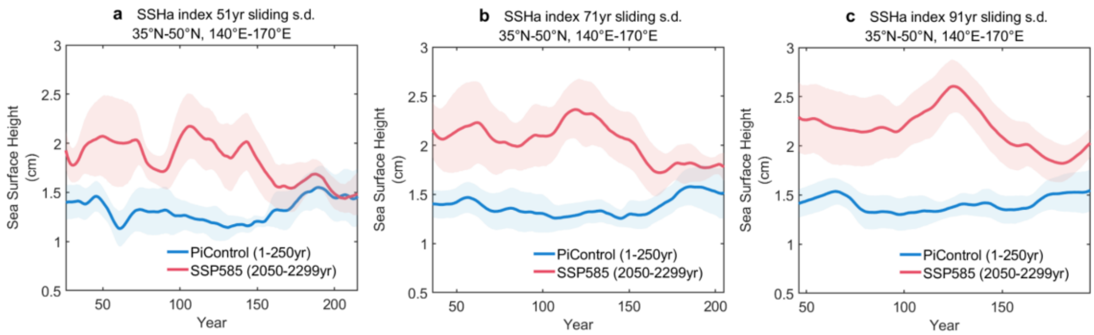

Fig. R2-2 | Sensitivity of the sliding standard deviation of North Pacific SSHa to the choice of moving window length. a Sliding standard deviation of North Pacific SSHa over the region of 35°N -50°N, 140°E–170°E using a 51-yr moving window. The PiControl and the SSP585 simulations are shown as blue and red lines, respectively. The x-axis labels denote the central year of each sliding window. Thick lines indicate the MMEM result. Shading reflects ±1 standard deviation derived from 10000 bootstrap resamples. **b, c** Same as (**a**), but using 71-year and 91-year moving windows, respectively.

Minor comments:

1. Figure 1d. In PiControl, there seems no multidecadal oscillation in the ssha index in the first 150years.

In PiControl, there is no pronounced multidecadal oscillation in the SSHa index during the first 150 years, and the amplitude of decadal variability remains relatively stable over this period. The lack of an apparent multidecadal oscillation in the first 150 years of the PiControl run does not indicate an absence of decadal variability. The key result in Fig. 1d is that the amplitude of decadal SSH variability under SSP585 consistently exceeds that in PiControl, demonstrating a robust intensification under global warming.

2. Figure 2. The while dots are hard to see clearly. Monte Carlo test should be clearly stated in section of Methods. How are the regressions obtained? Besides, statistical level of the regressions should be displayed clearly.

Thank you for this helpful comment. We have revised the manuscript accordingly.

First, as suggested, the dotted markers in the figure have been enlarged and displayed in gray for enhanced clarity (Please see revised **Fig. 2, Line 660**).

Second, the regression maps represent the multimodel ensemble mean (MMEM) of regression coefficients, obtained by first performing the regression independently for each model and then averaging the resulting regression patterns across models. We have clarified this in the revised manuscript (**Lines 376-378**).

Third, given the limited number of CMIP6 models, a bootstrap resampling approach is used to assess the robustness and statistical significance of the MMEM responses of KOE SSHa to the AMV forcing. The significance assessment serves two purposes: (1) to evaluate the intermodel consistency of the AMV-related KOE SSHa response in PiControl and SSP585, and (2) to assess whether the projected change between the two experiments exceeds intermodel uncertainty. For each experiment, seven models are randomly resampled with replacement and averaged to produce one MMEM realization. Repeating this procedure 10,000 times yields a bootstrapped distribution of MMEM estimates for each scenario. Intermodel consistency is assessed using a two-sided bootstrap test, where a MMEM response is considered robust if zero lies outside the central 80% confidence interval of the bootstrapped distribution, indicating consist response across models. The statistical significance of the change between SSP585 and PiControl is further assessed by the two bootstrapped MMEM distribution of each simulation. The MMEM change is considered significant if zero lies outside the central 95% confidence interval. We have revised the manuscript to consistently refer to this procedure as a “bootstrap test” and clarified the statistical test in the Methods and figure captions (**Lines 421-436**).

3. Figure 3. TN flux and WAF flux should be consistently used. Statistical level of the regressions should be displayed clearly.

First, we have now unified the terminology and consistently refer to the wave activity diagnostics as WAF flux throughout the text. Second, the statistical significance levels of the regressions have been clearly displayed in the corresponding figure captions (**Line 692**).

4. Figure 5. The relationship of ssha std and PDO std in SSP585 should also be given as scatter plots.

As recommended, we have included a scatter plot showing the relationship between the standard deviation of SSHa and that of the PDO in SSP585 (see revised **Fig. 5, Line 697**). The correlation between PDO variability and KOE SSHa variability is 0.49, but it does not reach statistical significance (p = 0.27), suggesting a weaker linkage compared to that in PiControl (**Fig. R2-3**).

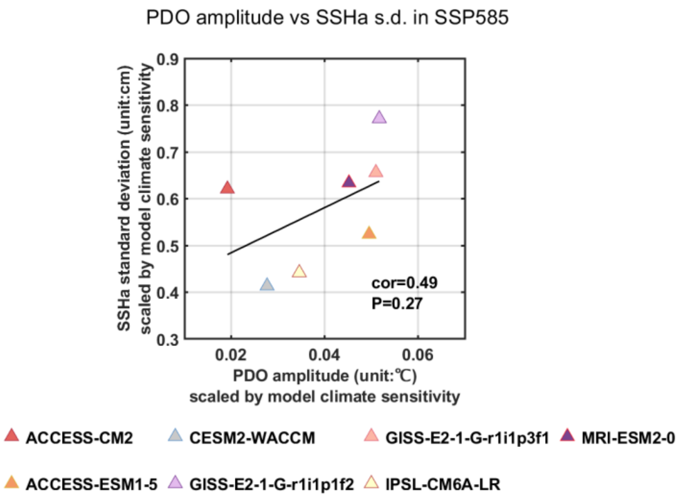

Fig. R2-3 | Intermodel relationship between PDO and decadal SSH variability in the KOE under SSP585 scenario. Intermodel correlation between the PDO amplitude (unit: °C) and the area-weighted averaged SSHa (unit: cm) over the KOE region (35°–50°N, 140°E–160°W) in SSP585. Both variables are scaled by the equilibrium climate sensitivity in each model to remove intermodel differences in climate sensitivity to global warming. The black solid line denotes the linear relationship across all models.

5. Supplementary Figure 1b. Details of how Figure 1b is generated should be clearly stated.

For each model, the SSHa time series is first quadratically detrended and smoothed using an 11-year running mean. The decadal variability intensity at each grid point is then quantified as the standard deviation of the filtered SSHa time series. All analyses are performed at the individual model level prior to averaging. The multi-model ensemble mean is then constructed as the arithmetic mean across models with equal weighting. We have clarified this in the revised manuscript (**Lines 129-136**).

6. Line 102-105: PiControl doesn't represent the present-day climate.

We replace "present-day" with "pre-industrial period" to more accurately reflect that the PiControl experiment represents an unforced baseline climate prior to anthropogenic warming, rather than the present-day climate (**Line 102**).

7. Line 115-117: Comparison between PiControl and SSP585 doesn't lead to difference of future relative to present-day.

The term "present-day" is not appropriate in this context and has therefore been revised to "pre-industrial period". Since the aim of this study is to assess the impact of global warming, the pre-industrial experiment provides a suitable baseline for comparison.

8. Line 135-137: People often refer the MMEM results in historical simulations as the forced component of AMV. A consistency between the MMEM and observation would then lead to an inappropriate conclusion, i.e., the AMV is mostly externally.

In our analysis, the MMEM derived from the historical simulations does not represent the externally forced AMV signal. Specifically, for the historical simulations we apply a quadratic detrending and an 11-year low-pass filtering to all model outputs prior to constructing the AMV index. This procedure effectively removes the long-term externally forced signals and retains the decadal variability associated with AMV. Importantly, we calculate the AMV index separately for each model and regress the corresponding SST anomalies onto the normalized AMV index to obtain the AMV-related SST pattern. The MMEM is then constructed by averaging these model-specific AMV-related patterns, rather than by first averaging the historical SST fields across models and subsequently deriving a single AMV index. This approach prevents the MMEM from being dominated by the common externally forced signal and ensures that it reflects coherent AMV-related variability across models. Therefore, the consistency between the MMEM and observations should be interpreted as robustness of the simulated AMV variability, not as evidence that AMV is predominantly externally forced. We have clarified this point in the revised manuscript to avoid potential misunderstanding (**Lines 129-136**).

9. Line 151-156: It can be understood that the increased northward Ekman heat transport an increase the local ssh mean. But why does the enhanced northward Ekman heat transport can increase the local ssha variance? In addition, authors argue that the signal (changes in mean ssh or ssha variance?) could be transferred westward to KOE region by Rossby waves. But the discussion is too vague to understand. More evidence should be provided.

The original text may have caused ambiguity. Our analysis is based on decadal anomalies and regression patterns onto the AMV index, rather than on changes in the time-mean state. The patterns shown therefore represent the atmospheric and oceanic responses associated with the positive or negative phases of AMV. Under global warming, the regression onto the AMV index reveals an enhanced anticyclonic wind stress forcing over the northeastern North Pacific during the positive AMV phase, characterized by stronger negative wind stress curl. This forcing induces surface Ekman convergence, deepens the thermocline, and leads to positive SSH anomalies through baroclinic adjustment. At the same time, the associated northward Ekman heat transport warms the upper ocean locally, further amplifying the positive SSH anomaly via thermal expansion. Importantly, during the negative AMV phase, these processes act in the opposite sense, producing negative SSH anomalies. Therefore, global warming amplifies the SSH anomalies associated with both positive and negative AMV phases, leading to a larger peak-to-trough contrast and hence an increase in local SSH variance. We have revised this description in the manuscript (**Lines 145-157**).

In addition, we perform a lagged regression of SSH anomalies onto the AMV index under SSP585 to diagnose the spatiotemporal evolution of the AMV-related SSH signals. The resulting Hovmöller diagram clearly shows a westward-propagating SSH anomaly, originating in the eastern North Pacific and extending toward the KOE region (**Fig. R2-4**). The propagation speed is consistent with that expected for first baroclinic-mode Rossby waves at mid-latitudes, providing direct dynamical evidence that the amplified AMV-related SSH anomalies under global warming can be transmitted from the eastern North Pacific to the KOE region via Rossby wave adjustment. We have added this analysis and the corresponding figure to the revised manuscript and revised the discussion accordingly to clarify the underlying physical mechanism (**Lines 157-159; Supplementary Fig. 4**).

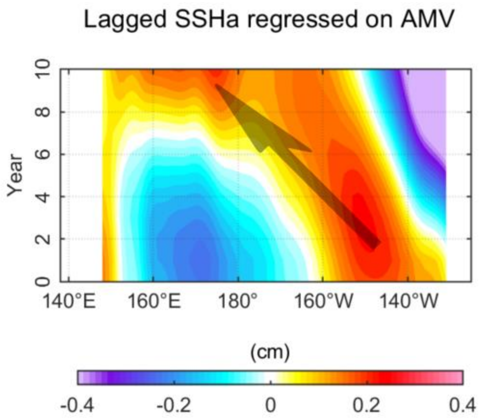

Fig. R2-4 | Evolution of westward-propagating SSH anomalies (SSHa) over North Pacific midlatitudes associated with AMV. Hovmöller diagram of SSH anomalies (SSHa, 35°-50°N; unit: cm) regression onto the normalized AMV index under SSP585 scenario. The y-axis denotes the lag years of SSHa relative to the AMV index.

10. Line 164-167: the statement is not consistent with the results shown in Figure 3a.

In the original analysis, the AMV-related geopotential height anomalies at 200hPa were partially masked by strong zonal-mean background flow. To better isolate the dynamically relevant wave signals, we present the eddy geopotential height, defined as the deviation from the zonal-mean geopotential height, which is more suitable for diagnosing Rossby wave propagation and large-scale teleconnection patterns (Takaya & Nakamura, 1997; Lee et al., 2024). In addition, we calculate the Rossby wave source and associated wave activity flux at 200hPa, which provides a direct measure of the generation of stationary Rossby waves associated with anomalous upper-tropospheric vorticity forcing.

In PiControl, the AMV-related atmospheric response exhibits a relative weak Rossby wave train originating from the North Atlantic (**Fig. R2-5**). Pronounced wave source anomalies are located over the North Atlantic sector, collocated with significant 200-hPa geopotential height anomalies, indicating active excitation of stationary Rossby waves associated with AMV variability. The wave activity flux vectors clearly point eastward and then northeastward from the North Atlantic, following the midlatitude waveguide across Eurasia and extending into the North Pacific.

In the revised analysis, we find that under SSP585 the AMV-related Atlantic warming generates a markedly stronger Rossby wave response, which leads to enhanced wind stress curl anomalies over the Northeastern Pacific. With these revisions, the AMV-related circulation anomalies and the associated wave activity flux become clearly identifiable (**Fig. R2-5**), and the revised figure is fully consistent with the statements in the text. We have clarified this point in the revised manuscript (**Lines 187-199; Fig. 4**).

Reference:

Takaya, K. & Nakamura, H. A formulation of a wave-activity flux for stationary Rossby waves on a zonally varying basic flow. *Geophys. Res. Lett.* **24**, 2985-2988 (1997).

Lee, J., Wang, SY.S., Son, SW. *et al.* Evolving winter atmospheric teleconnection patterns and their potential triggers across western North America. *npj Clim Atmos Sci* **7**, 63 (2024).

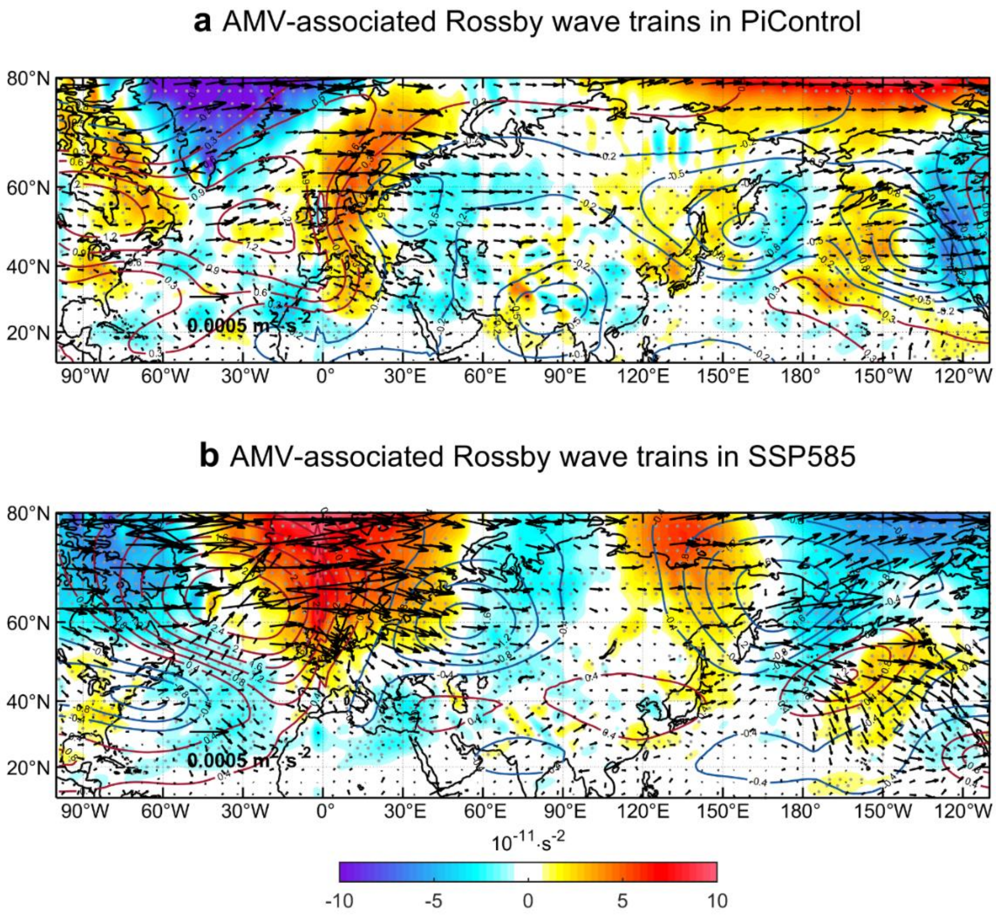

Fig. R2-5 | Atmospheric teleconnection response to AMV under global warming. **a** Regression of 200hPa geopotential height (Z200) anomalies (contours; unit: m), Rossby wave sources (RWS, shading; unit: s-2), and wave activity fluxes (WAF; vectors; unit: m2·s-2) onto the AMV index in PiControl. AMV-associated regression patterns are derived from a multiple linear regression, which removes the PDO-related component. Shown is the multi-model ensemble mean result. The grey dots indicate regions where the inter-model consistency of RWS is statistically significant at the 80% level based on a bootstrap test; **b** Same as (**a**), but for the SSP585 scenario.

11. Line 172-177: does this also hold in SSP585 and RCP85?

The intermodel relationship between AMV amplitude and KOE decadal SSH variability also holds under SSP585 scenario. Models with a larger AMV standard deviation tend to exhibit stronger decadal SSH variability in the KOE region, with a statistically significant intermodel correlation coefficient of 0.86 (**Fig. R2-1b**).

In the revised manuscript, we have removed the discussion based on CMIP5 RCP85 simulations. This is because the CMIP5 results are qualitatively similar to those from CMIP6 and are all derived from relatively low-resolution models. To better highlight the underlying physical processes, we instead include a discussion based on a high-resolution CESM simulation in the revised version. We have added the SSP585 scatterplot to the revised manuscript (see **revised Fig. 3b, Line 675**).

12. Line 178-196: this seems to explain the changes of AMV amplitude, rather than how AMV changes module decadal ssh variability in KOE regions. And most of the contents are replicates from Li et al. (2025). A reference would be enough.

We agree. Following the reviewer's suggestion, we have revised this section by removing the detailed mechanistic explanation of AMV amplitude changes and retaining only a brief summary of the key physical linkage, with a reference to Li et al. (2025). The revised text now emphasizes how changes in AMV amplitude provide a background condition that modulates the strength of the AMV-related atmospheric teleconnection and, consequently, decadal SSH variability in the KOE region (**Lines 167-218**).

13. Line 202-212: The results in Supplementary Fig.6 doesn't support the statement that the AMV-induced atmospheric teleconnection exhibits a northward shift under the SSP585 scenario since the air temperature, precipitation and wind stress shown in Supplementary Fig.6 contains contribution not only from AMV but also many other factors. The longitudinal shifts of the AMV-induced atmospheric teleconnection could easily be obtained by calculating the difference between Figure 3a and Figure 3b, which seems to be inconsistent with the results the authors claim here.

The fields shown in Supplementary Fig. 6 are intended to illustrate background-state changes under SSP585 that are relevant to atmospheric vertical motion in the mid- to high-latitudes. Under warming, the large-scale thermodynamic and dynamical conditions favoring deep convection and vertical coupling shift northward. These atmospheric background changes modulate a range of circulation processes, including the AMV-related teleconnection, rather than representing a direct AMV-induced displacement. Supplementary Fig. 6 is therefore included to provide physical context for the circulation changes under warming, not as direct evidence of an AMV-induced shift. In the revised manuscript, we have removed this discussion of a northward shift of the AMV-induced atmospheric teleconnection under SSP585. Although such a shift appears in CMIP6 lower-resolution models, it is not statistically robust in CESM-HR. We therefore focus only on the intensification of the AMV-induced response, which is consistently simulated across model resolutions.

14. Line231-233: Authors argue that the AMV is important to ssha in KOE region by discussion the secondary importance of the PDO and the damping of stratification. While here they refer it to the local ocean-atmosphere interactions. What exactly are the local ocean-atmosphere interactions? How are they related to the AMV, PDO and the stratification?

The original wording regarding "local ocean–atmosphere interactions" was not clear and could be misleading. In the revised manuscript, we emphasize that the decadal SSH change over the KOE is primarily driven by large-scale remote forcings from the AMV, rather than by intrinsic local ocean–atmosphere coupling processes over Pacific (**Lines 237-241**).

15. Line 291: The increased AMV amplitudes accounts for 34% of the increased variance of ssha in KOE. It seems that AMV is still a secondary factor to the increased variance of ssha in KOE. Can authors give more discussion in details what other factors could be?

In addition to the AMV-related wind-driven response emphasized here, other processes may also contribute to KOE decadal variability. One possible contributor is ENSO-related tropical Pacific forcing. During El Niño events, positive SST anomalies develop over the central and eastern equatorial Pacific, enhancing deep convection there. This anomalous heating induces upper-tropospheric divergence in the tropics and convergence over the subtropical North Pacific, which acts as a Rossby wave source. The resulting quasi-stationary atmospheric wave train projects onto the positive phase of the Pacific–North America (PNA) pattern, characterized by a deepened Aleutian Low. The associated anomalous cyclonic circulation strengthens surface wind stress anomalies over the midlatitude North Pacific, which in turn force westward-propagating oceanic Rossby waves, transmitting SSH anomalies from the eastern basin into the KOE region (Alexander et al., 2002; Trenberth et al., 1998; Liu and Alexander, 2007). Under global warming, ENSO-related atmospheric teleconnections are projected to intensify, reinforcing basin-scale atmospheric anomalies over the midlatitude North Pacific and enhancing the associated wind-driven Rossby wave adjustment. This mechanism is therefore expected to contribute to the amplified decadal SSH variability in the KOE under warming conditions (Joh et al., 2023).

In addition to remote atmospheric forcing, intrinsic KOE dynamics provide an internal source of low-frequency variability. Nonlinear oceanic processes, including baroclinic and barotropic instabilities, eddy–mean flow interactions, and jet–eddy–topography feedbacks, can sustain decadal KOE variability through inverse energy cascades and anomalous vorticity fluxes (Qiu and Chen, 2010; Yang et al., 2018; Zhou et al., 2021). These external and internal processes are not mutually exclusive and may interact under a warming climate, together accounting for the portion of SSHa variance not explained by the AMV alone. We have added this discussion in the revised manuscript (**Lines 347-355**).

Reference:

Alexander, M. A., Bladé, I., Newman, M., Lanzante, J. R., Lau, N.-C. & Scott, J. D. The Atmospheric Bridge: The Influence of ENSO Teleconnections on Air–Sea Interaction over the Global Oceans. *J. Clim.* **15**, 2205-2231 (2002).

Trenberth, K. E., G. W. Branstator, D. Karoly, A. Kumar, N.-C. Lau, & C. Ropelewski. Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *J. Geophys. Res.* **103**, 14291–14324 (1998).

Liu, Z., & M. Alexander. Atmospheric bridge, oceanic tunnel, and global climatic teleconnections. *Rev. Geophys.* **45**, RG2005 (2007).

Joh, Y., Delworth, T. L., Wittenberg, A. T., Cooke, W. F., Rosati, A. J. & Zhang, L. Stronger decadal variability of the Kuroshio Extension under simulated future climate change. *npj Clim. Atmos. Sci.* **5**, 63 (2022).

Qiu, B. & Chen, S. Eddy-mean flow interaction in the decadally modulating Kuroshio Extension system. *Deep Sea Res. Part II.* **57**, 1098-1110 (2010).

Yang, H. et al. Decadal Variability of Eddy Characteristics and Energetics in the Kuroshio Extension: Unstable Versus Stable States. *J. Geophys. Res.: Oceans* **123**, 6653-6669 (2018).

Zhou, G., Li, Z. & Cheng, X. Intrinsic and Wind-Driven Decadal Variability of the Kuroshio Extension in Altimeter Observations. *Front. Mar. Sci.* **8** (2021).

16. Line 338-339: To isolate the impacts of PDO or AMV, people often regressing out the PDO/AMV signal from the variables at each grid, then conduct the regression analysis.

Thank you for pointing this out. Following this procedure, we have re-conducted the analysis by first regressing out the PDO or AMV signal from the relevant variables at each grid point, and then performing the regression analysis using the residual fields. The corresponding figures have been revised accordingly in the manuscript (**Figs. 2-6 in the manuscript**). The results show minor differences compared to the original analysis, and the main features as well as the conclusions of the study remain robust and unaffected. We have added this description in **Lines 138-144**.

17. Line 342-343: why the H in EHT formula is set to be the MLD instead of Ekman layer depth?

We thank the reviewer's careful consideration of this point. The mixed layer depth (MLD) is adopted because our objective is to quantify the impact of wind forcing on the upper-ocean heat budget, rather than to represent the dynamical thickness of the Ekman layer. In the real ocean, atmospheric heat fluxes are primarily absorbed and stored within the mixed layer. Wind-driven Ekman advection redistributes this mixed-layer heat, thereby inducing upper-ocean temperature and SSHa. As a result, the mixed layer provides the physically relevant depth scale for linking wind stress forcing to heat content variability, especially on decadal time scales (Wu et al., 2018, 2020).

Reference:

Wu, B., Lin, X. & Qiu, B. Meridional shift of the Oyashio Extension front in the past 36 years. *Geophys. Res. Lett.* **45**, 9042–9048 (2018).

Wu, B., Lin, X. & Yu, L. North Pacific subtropical mode water is controlled by the Atlantic Multidecadal Variability. *Nat. Clim. Change* **10**, 238-243 (2020).

Point-by-Point Response to Reviewers (our response in **blue**)

We are grateful to the reviewers for their constructive and insightful comments. We have carefully revised the paper in response to all comments, as detailed below (our responses are provided in **blue**).

Response to Reviewer #1

I thank the authors for the additional CESM-HR analysis and the decomposition of the AMV contribution. These analyses improve the clarity of the manuscript regarding model biases and the underlying mechanisms. However, I believe that a few additional points should be addressed prior to publication.

We sincerely appreciate your positive feedback and the constructive comments on our manuscript. We have considered all comments and revised the manuscript accordingly.

Major Comments

1. CESM-HR analysis

1-1) Poleward shifted KOE decadal variability

The intensified and poleward-shifted KOE decadal variability under global warming is a key result emerging from the CMIP ensemble. In this context, the lack of explicit discussion on whether CESM-HR projects the associated meridional shift makes it difficult to assess its consistency with the CMIP results. The comparison between Fig. 1c and Fig. 7c alone may not be sufficient to fully assess whether CESM-HR reproduces the poleward-shift feature. A figure similar to Fig. 1e for CESM-HR, together with relevant discussion, would help clarify the consistency between the CMIP and CESM-HR results.

Thank you for this helpful comment. Following the reviewer's suggestion, we compare the zonally averaged SSHa variability between PiControl and RCP85 in CESM-HR, similar to Fig. 1e (**Fig. R1-1**). Two peaks of SSHa decadal variability are identified over the KOE region (30°N–45°N), located near ~35°N and ~40°N, broadly corresponding to the Kuroshio Extension (KE) and Oyashio Extension (OE) fronts. Under the RCP85 scenario, the amplitude of SSHa variability increases, particularly over ~37°–45°N. However, the latitude of the variability maxima remains largely unchanged, suggesting no clear poleward shift in CESM-HR.

These results indicate that the poleward shift of KOE decadal variability is evident in CMIP6 but is not clearly reproduced in the CESM-HR simulation. This discrepancy may arise from differences in the representation of wind-driven forcing and mesoscale ocean dynamics across models. Coarse-resolution CMIP models generally project a poleward shift and intensification of extratropical winds, together with an expansion of the Hadley Cell under greenhouse warming. These large-scale atmospheric changes can modulate the North Pacific wind-stress curl and potentially favor a northward shift of wind-forced KE variability (Yang et al., 2016; Navarra and Di Lorenzo, 2021). In contrast, eddy-resolving simulations such as CESM-HR exhibit stronger internally generated KOE variability and more active nonlinear jet–eddy interactions, which may partially reduce the externally forced meridional shifts (Nonaka et al., 2020). Furthermore, coarse-resolution models often exhibit systematic biases in the mean state of western boundary currents, such as an overly broad or displaced KE jet, potentially amplifying meridional shifts in variability patterns. Higher-resolution simulations, with sharper fronts and more realistic eddy–jet interactions, may therefore constrain the apparent poleward migration of decadal variability signals (Ma et al., 2016; An et al., 2023). We have added a brief discussion of this point in the revised manuscript (**Lines 332-349, Supplementary Fig. 8**).

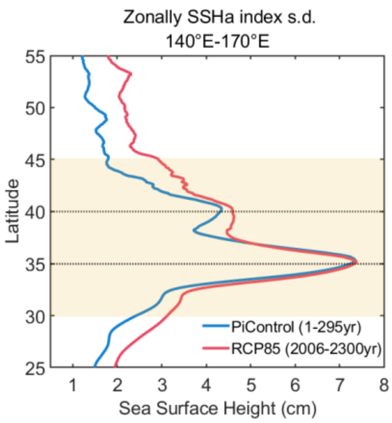

Fig. R1-1 | Comparison of the intensity and peak latitude of the zonally averaged (140°E–170°E) SSHa in KOE region between PiControl (blue) and RCP85 (red) in CESM-HR simulation. The intensity is measured by the standard deviation of SSHa.

Reference:

Yang, H., Lohmann, G., Wei, W., Dima, M., Ionita, M., & Liu, J. (2016). Intensification and poleward shift of subtropical western boundary currents in a warming climate. *Journal of Geophysical Research: Oceans*, *121*(7), 4928-4945.

Navarra, G. G., & Di Lorenzo, E. (2021). Poleward shift and intensified variability of Kuroshio-Oyashio extension and North Pacific Transition Zone under climate change. *Climate Dynamics*, *56*(7), 2469-2486.

Nonaka, M., Sasaki, H., Taguchi, B., & Schneider, N. (2020). Atmospheric-driven and intrinsic interannual-to-decadal variability in the Kuroshio Extension jet and eddy activities. *Frontiers in Marine Science*, *7*, 547442.

Ma, X., Jing, Z., Chang, P., Liu, X., Montuoro, R., Small, R. J., ... & Wu, L. (2016). Western boundary currents regulated by interaction between ocean eddies and the atmosphere. *Nature*, *535*(7613), 533-537.

An, B., Yu, Y., Hewitt, H., Wu, P., Furtado, K., Liu, H., ... & Chen, K. (2023). The benefits of high-resolution models in simulating the Kuroshio Extension and its long-term changes. *Climate Dynamics*, *61*(11), 5407-5427.

1-2) Role of the model resolution

Due to data availability within HighResMIP, only one high-resolution model is analyzed in this study. In this context, it may be difficult to generalize that the results are "not altered by model resolution-related biases". Even among HighResMIP models, systematic biases can arise from differences in model physical parameterizations rather than model resolution (Sobel et al., 2023; Dhame et al., 2025). Therefore, it would be appropriate to acknowledge this limitation and clarify that the inferred robustness is based specifically on CESM-HR, rather than high-resolution models more broadly.

- Dhame, S., Olonscheck, D., & Rugenstein, M. (2025). Higher-resolution climate models do not consistently reproduce the observed tropical Pacific warming pattern. Journal of Climate, 38(13), 3131-3149.
- Sobel, A. H., Lee, C. Y., Bowen, S. G., Camargo, S. J., Cane, M. A., Clement, A., ... & Tippett, M. K. (2023). Near-term tropical cyclone risk and coupled Earth system model biases. Proceedings of the National Academy of Sciences, 120(33), e2209631120.

Thank you for this helpful suggestion. We agree that, because only one high-resolution model is analyzed in this study due to data availability within HighResMIP, the robustness of the results cannot be generalized to high-resolution models as a whole. In the revised manuscript, we have added a sentence to acknowledge this limitation and clarify that the inferred robustness is based specifically on the CESM-HR simulation rather than on high-resolution models more broadly (**Lines 368-375**). We have also cited the suggested references in the manuscript to emphasize that systematic biases can persist across high-resolution models due to differences in model physical parameterizations (**Ref. 62, 63**).

1-3) SLP regression patterns

The caption of Fig. 7f refers to "Changes in SSHa/SLPa regression onto AMV from CESM-HR"; however, the SLPa pattern does not appear to be clearly shown in the panel. Including SLP regression contours consistently in Fig. 7d-f would facilitate a more complete interpretation. For example, when comparing Fig. 2f and Fig. 7f, the atmospheric circulation pattern centered around 150°W and 50°N appears markedly different, with one exhibiting a cyclonic anomaly and the other an anticyclonic anomaly. Given that this region serves as a forcing area in the reduced-gravity model and plays a key role in baroclinic Rossby wave propagation, further discussion of the relevant mechanisms would strengthen the interpretation of the consistency between CESM-HR and CMIP results.

Thank you for this helpful comment. Following the reviewer's suggestion, we have added the SLP regression contours to **Fig. 7d-f** in the revised manuscript to facilitate comparison. With the SLP contours included, the atmospheric circulation pattern centered around 150°W and 50°N indeed shows an opposite polarity between the CMIP6 ensemble and CESM-HR (**Fig. 2c and Fig. 7f**). This difference mainly reflects a shift in the spatial structure of the warming-induced SLP response. In CESM-HR, the AMV-related atmospheric response manifests as positive SLPa mainly west of 150°W (**Fig. 7f**), whereas in the CMIP6 ensemble the positive SLPa extends more broadly across the central to eastern North Pacific (**Fig. 2c**). Consequently, the local anomaly near 150°W appears with an opposite sign between the two cases.

Despite this difference in the local SLPa structure, both simulations show an intensification of basin-scale wind stress curl forcings over the North Pacific under SSP585 relative to PiControl. The generation of baroclinic Rossby waves primarily depends on the amplitude of wind stress curl forcing. Therefore, enhanced forcing magnitude, even with anomaly centers located in the central or eastern North Pacific, can effectively excite stronger SSH variability in the KOE region. We have added a brief discussion of this point in the revised manuscript (**Lines 352-357**).

2. Decomposition of the AMV contribution

The additional analysis decomposes AMV into tropical (20°S-20°N) and extratropical (20°N-70°N) components and evaluates their respective impacts on KOE SSH variability. While this framework is useful, further justification for this separation would strengthen the analysis. In particular, providing relevant references to support this decomposition, or demonstrating its robustness using piControl simulations, would enhance confidence in the results.

Thank you for this helpful comment. A similar decomposition separating tropical and extratropical AMV components has been adopted in previous study to investigate their respective climatic impacts (e.g., Li et al., 2014). Following this approach, we separate AMV into tropical (20°S–20°N) and extratropical (20°N–70°N) components to examine how warming-induced changes in these two regions may contribute to the KOE SSH variability. The reference has been added in the revised manuscript.

Following the reviewer's suggestion, we further assess the robustness of this decomposition using the PiControl simulations. Specifically, we regress Pacific SSHa and SLPa onto the tropical (20°S–20°N) and extratropical (20°N–70°N) AMV components (**Fig. R1-2**). To isolate their respective influences, all regression coefficients are obtained using a multiple linear regression that simultaneously controls for the extratropical AMV, tropical AMV, and PDO indices.

The results show that the KOE SSHa exhibits little response to the tropical AMV component, whereas the regression onto the extratropical component produces a clear and statistically significant signal over the KOE region, with a spatial structure closely resembling that associated with the full AMV index. This comparison indicates that the KOE SSH variability is primarily linked to the extratropical AMV component. In addition, the amplitude change of the tropical AMV component under warming is relatively weak, suggesting a limited role of tropical AMV in modulating future KOE SSH variability. Together, these results provide additional support for separating AMV into tropical and extratropical components in our analysis. We have clarified this point in the revised manuscript (**Lines 219-224** and **Supplementary Fig. 5**).

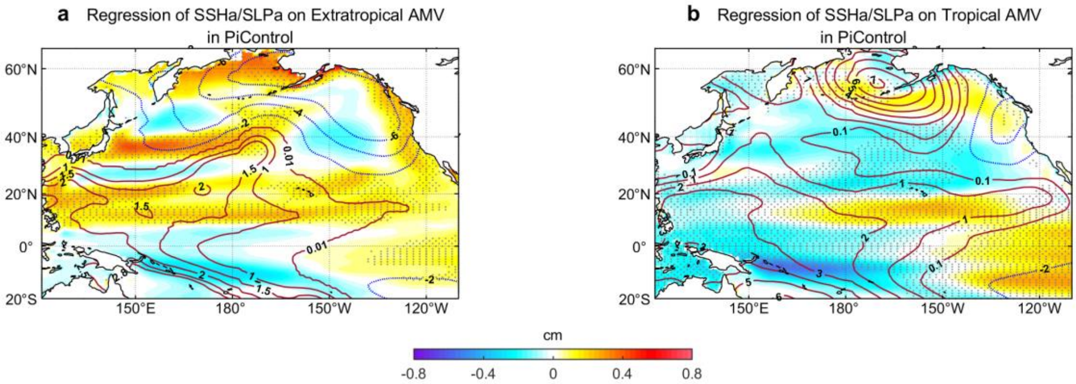

Fig. R1-2 | a Regressions of 11-yr running-mean and detrended SSHa (shading; unit: cm) and SLPa (contours with positive in red and negative in blue; unit: Pa) onto the normalized extratropical Atlantic index. Shown is the multi-model ensemble mean (MMEM) result. Grey dots indicate regions where the SSHa anomalies are significant at the 95% confidence level based on a *t*-test. **b** Same as (**a**), but for regressions onto the normalized tropical Atlantic index. All regression coefficients shown in (**a**) and (**b**) are obtained using a multiple linear regression that controls for the extratropical AMV, tropical AMV, and PDO indices.

Reference:

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), 538-542.

Specific Comments:

Line 39 in climate system > in the climate system

Revised as suggested (**Lines 38-39**). Thank you.

Line 55: trigger baroclinic Rossby waves > triggers baroclinic Rossby waves

Revised as suggested (**Lines 55**). Thank you.

Line 87: However, affects from other processes > However, effects from other processes

Revised as suggested (**Lines 90**). Thank you.

Line 329: support our central conclusion > supports our central conclusion

Revised as suggested (**Lines 368**). Thank you.

Line 330: are robust > is robust

This sentence has been removed and rewritten (**Lines 369**). Thank you.

Line 431: two scenario > two scenarios

Revised as suggested (**Lines 479**). Thank you.

Response to Reviewer #2

This manuscript is revised in many aspects. But the responses to my key concern is still not satisfying.

We sincerely appreciate your constructive comments on our manuscript. We have carefully considered all comments and revised the manuscript accordingly.

1.Specifically, in the Figure 3 in their revised manuscript (Figure 4 in their original manuscript), the relationship between AMV and ssha in KOE still seems to be dominated by ACCESSESM1-5, IPSL-CM6A-LR and CESM2-WACCM. In responses, As shown in Figure R2-1, the authors also examined this by excluding the three models and found that the relationship between AMV and ssha in KOE is not significant anymore in both PiControl and SSP585. And, the relationship between changes of AMV amplitude and changes of ssha in KOE is also not significant any more. I strongly disagree with the authors arguement that "… a tendency for larger AMV variability to be associated with enhanced KOE SSHa variability in PiControl and SSP585, although the statistical significance is reduced due to the smaller sample size …". I would interpret that, for correlations with p value as larger as 0.31, 0.54 and 0.12 (as shown in Figure R2-1), the relationship would be meaningless. Otherwise, why do we need the significant test? Similarly, in Fig.5 of the revised manuscript, if the two models of ACCESSESM1-5 and IPSL-CM6A-LR are excluded, the relationship between PDO and ssha in KOE would not be significant in piControl.

Thank you for raising this important issue. We agree that the intermodel correlations become statistically insignificant in PiControl when certain models are excluded, for both the AMV–KOE and PDO–KOE relationships. This is expected because decadal SSH variability in the KOE region likely reflects the combined influences from multiple processes, including Pacific internal variability such as PDO and remote teleconnection forcing from the Atlantic. Therefore, the relationship with any single factor may appear weak or statistically insignificant in PiControl.

Importantly, our main conclusion is not based solely on the relationship in PiControl. The key result of this study is to reveal a growing influence of AMV on KOE variability under global warming. In SSP585, the AMV–KOE relationship remains significant across models (*cor*=0.86, *p*=0.01; **Fig. 3b**). Under global warming, the intermodel relationship between the projected increase in AMV amplitude and the amplification in KOE SSH variability is also significant (*cor*=0.58, *p*=0.009; **Fig. 3c**). The models are broadly distributed around the regression line, indicating that the relationship is not dominated by a few individual models. This enhanced AMV influence on the KOE SSH variability likely arises from the amplification of AMV variability and its associated atmospheric teleconnections under global warming, together with a reduced contribution from PDO variability. Therefore, the insignificant intermodel correlations in PiControl do not contradict our conclusion, but instead reflect that the AMV influence becomes more pronounced in a warming climate. We have clarified this point in the revised manuscript (**Lines 180-192, 243-245**).

2. In their response, the authors argue that "the climatological MLD in the North Atlantic exhibits only marginal shoaling in these three models under global warming. As a result, the AMV amplitude shows only moderate enhancement in these models, leading to relatively weak increases in KOE SSHa variability". I don't agree with this since there is a weak increase in IPSL-CM6A-LR. In fact, in IPSL-CM6A-LR, the increased AMV standard deviation actually leads to a decrease standard deviation of ssha in KOE. This contradicts their main argument that increased AMV would amplify the connection between AMV and ssha in KOE.

Regarding the IPSL-CM6A-LR model, deviations from the intermodel relationship may arise from model-specific processes. In this model, the amplitude of PDO shows a pronounced reduction in SSP126 compared with PiControl (**Fig. 5f**), which may also contribute to the decrease in KOE SSH variability. As a result, although the AMV amplitude exhibits a weak increase in SSP126, the corresponding change in KOE SSHa variability does not appear to follow the general intermodel relationship (**Fig. 3c**).

Nevertheless, such individual deviation does not affect the overall conclusion of this study. The intermodel relationship shown in **Fig. 3c** reflects the overall behavior across the model ensemble rather than requiring every individual model to strictly follow the same relationship. While IPSL-CM6A-LR model may behave as an outlier, most models still exhibit a positive relationship between the projected increase in AMV amplitude and the amplification of KOE SSH variability, and the ensemble-level relationship remains statistically significant. These results suggest that stronger AMV variability tends to be associated with larger KOE SSH variability under greenhouse warming, albeit with some degree of model diversity, which is common in multimodel ensemble analyses.

3. Besides, both Figure R2-1 and Fig. 3 seem strange that the models used in panel a are different from those used in panel b. For fair comparison, the models used in panel a, b and c as well as those in panel d of Figure R2-1 should be consistent to reasonably evaluate the relationship between AMV and ssha in KOE. Why are the number of models different in these panels? For example, panel a has 8 models, panel b has 7 models, while panel c has many models… Same problem also occurs in their Figure 5. This makes me concern how other figures in the manuscript are constructed.

Thank you for this helpful comment. We agree that the different numbers of models across panels may be confusing. In this study, models are selected based on the availability of SSP simulations over 2050–2299 and corresponding PiControl runs of comparable length. As only a limited number of models meet this criterion, all eligible simulations are included to maximize the sample size and improve the robustness of the intermodel relationships (**Supplementary Table 1)**. Other figures follow the same data-availability criteria. Specifically, seven models provide suitable PiControl simulations (**Fig. 3a**). For GISS-E2-1-G model, two PiControl realizations (r1i1p1f2 and r1i1p3f1) are available, yielding eight simulations in total. Seven simulations are available for SSP585 (**Fig. 3b**). In

Fig. 3c, we additionally include all available warming scenarios (SSP126, SSP245, and SSP370) to increase the sample size.

Following the reviewer's suggestion, we have revised the figures so that the number of models used in the PiControl and SSP585 experiments use a consistent set of seven models. It is also worth noting that the primary purpose of Fig. 3 is to examine the intermodel relationship between projected changes in AMV amplitude and changes in KOE SSH variability. To obtain a more statistically robust relationship, simulations from additional warming scenarios are included to increase the sample size. The PiControl and SSP585 panels are mainly provided for reference rather than for a direct comparison of AMV–KOE correlations across scenarios. We have clarified this point in the revised manuscript (**Lines 107-109, 180-192, 423-425, revised Fig. 3**).

4. In addition, the figure caption for both Figure R2-1 and Fig. 3 in the main manuscript doesn't make sense. These two figures show results from piControl, SSP585 and their differences. While, the models used, according to their figure caption, including ssp126,245, 370 and 585. Same problem also occurs in their Figure 5.

Thank you for this helpful comment. The original captions of Fig. 3 and Fig. 5 were not sufficiently clear. In the revised manuscript, the model names used for the PiControl and SSP585 experiments are now indicated directly within the corresponding panels, and the model names associated with the change panels have also been added (**see revised Fig. 3 and Fig. 5**).

5. In Fig.1d, there std of the ssha index in the first 150years in PiControl seems doesn't change. I agree with the authors that the amplitude of decadal variability remains relatively stable over this period. But why does it increase in the last 50 years? Similarly, the std of AMV index reduced in the last 50 years of SSP585. The increase in piControl and decrease in SSP585 then actually makes the AMV std not so different in the last 50 years. According to Figure R2-2, the shorter the sliding window, the less difference would AMV std occur.

In an individual model, the sliding standard deviation may exhibit multi-decadal fluctuations, reflecting the low-frequency internal variability of the climate system. Such internal variability should, in principle, be suppressed when averaging across a sufficiently large multimodel ensemble. In the present study, however, the number of models is limited due to data availability, and the increased standard deviation in the last 50 years is therefore likely a residual of low-frequency internal variability. For the SSP585 simulations, in addition to the internal variability mentioned above, the reduction in AMV variability during the last 50 years may also be related to a slow response of the ocean to the common external forcing applied across models. A detailed investigation of this slow oceanic adjustment is beyond the scope of the present study.

Nevertheless, these fluctuations do not affect our main conclusion. Across the entire analysis period, the decadal variability of SSHa in SSP585 remains consistently larger than that in PiControl, indicating an enhancement of KOE SSH variability under global warming.

6. In Fig2, there is a short vertical black line at the top at around longitude of 180 in each panel. What is that for?

The short vertical black line along 180° longitude was an artifact generated by the MATLAB mapping routine. We have adjusted the plotting settings and removed it in the revised **Fig. 2**.

7. In Fig2 and Fig5a,b,c, the y axis is better on the left to be consistent with other figures.

Thank you for this helpful suggestion. We have adjusted the y-axis to the left in the revised **Fig. 2** and **Fig. 5a-c** for consistency with other figures.

8. In Fig. 6b, the models used should be clearly stated. Besides, the relationship between ocean stratification and ssha in piControl is also not significant.

Thank you for this helpful comment. Based on the CMIP6 PiControl simulations, we find a negative correlation between the upper-ocean stratification and the amplitude of KOE SSH variability (*cor*=−0.61), but the relationship is not statistically significant (*p*=0.15). Thus, the PiControl simulations alone do not provide convincing evidence to support our argument. To better isolate the role of stratification, we conduct a set of reduced-gravity model experiments to directly examine how changes in ocean stratification influence the intensity of KOE decadal SSH variability.

In the revised manuscript, we now acknowledge the lack of statistical significance in the PiControl relationship and move this result to the **Supplementary Fig. 8** (**Lines 275-278**). The revised **Fig. 6** instead presents the reduced-gravity model results, which illustrate the intensity of decadal SSH variability under different oceanic stratification conditions.

9. In Fig.7, the y-axis better be consistent.

Thank you for this helpful suggestion. We have adjusted the latitude range in the Pacific to ensure that the y-axes are consistent across all panels (**see revised Fig. 7)**.

Point-by-Point Response to Reviewers (our response in **blue**)

We are grateful to the reviewers for their constructive and insightful comments. We have carefully revised the paper in response to all comments, as detailed below (our responses are provided in **blue**).

Response to Reviewer #1

I thank the authors for the additional analysis and revisions in response to my previous comment. While I believe most of my previous questions have been addressed, I would appreciate clarification regarding the following point related to my earlier question before publication.

Thank you very much for your constructive comments. We appreciate the opportunity to further clarify this point.

Comments

Mismatch in wind stress curl forcing for oceanic Rossby wave generation among CMIP6, CESM-HR, and the reduced-gravity ocean model
In lines 354-357, the authors state that the strength of basin-scale wind stress curl forcing, rather than its local structure, is important for enhancing local surface Ekman convergence and generating stronger positive SSH anomalies over the KOE region. Nevertheless, in the specific region associated with baroclinic Rossby wave generation, the sign of the wind stress curl forcing appears to be opposite between CMIP6 and CESM-HR. Specifically, the reduced-gravity ocean model presented in Fig. 6 prescribes wind stress forcing at 150°W, 50°N based on the results shown in Fig. 2f from CMIP6, corresponding to an anticyclonic wind stress curl. In addition, the authors stated (lines 156-157) that this anticyclonic wind forcing induces surface Ekman convergence, deepens the thermocline, and generates and propagates positive SSH anomalies westward. However, Fig. 7f from CESM-HR shows a cyclonic wind stress curl forcing at the same location (150°W, 50°N). Given this discrepancy, a more consistent explanation is needed to reconcile the results from CMIP6, CESM-HR, and the reduced-gravity ocean model.

The opposite wind stress anomaly at 150°W, 50°N between CMIP6 and CESM-HR primarily reflects a westward shift of the North Pacific high-pressure center in CESM-HR, rather than a fundamental dynamical inconsistency (**Fig.2f and Fig.7f**). This westward shift is also evident in the AMV-associated 500 hPa geopotential height changes. Although the overall Rossby wave train structure remains similar between CMIP6 and CESM-HR, the North Pacific high-pressure anomaly in CESM-HR is shifted westward, consistent with the displacement observed in the corresponding surface high-pressure field (**Figure R1c, d**).

The westward shift in CESM-HR likely arises from differences in the background westerly jet, which is weaker and located farther west over North Pacific compared to CMIP6 (**Figure R1a, b**). According to stationary wave theory (Hoskins & Karoly, 1981), the background zonal wind largely controls the propagation pathways and preferred locations of stationary Rossby waves. In particular, the zonally asymmetric climatological flow modulates the efficiency of eddy–mean flow energy conversion (Simmons et al., 1983), favoring enhanced barotropic growth and maintenance of anomalies in regions of strong shear. These factors collectively contribute to the westward-shifted atmospheric response in CESM-HR.

In the reduced-gravity model experiments, wind stress forcing is prescribed according to CMIP6-derived anomalies at this location, and is therefore consistent with the CMIP6. The forcing is applied as a time-varying sinusoidal perturbation with a 20-year periodicity. Under such forcing, anticyclonic (cyclonic) wind stress curls generate positive (negative) SSH anomalies, with the KOE SSHa amplitude (estimated as standard deviation) primarily determined by the forcing amplitude, instead of whether the forcing is cyclonic or anticyclonic. We have clarified the wind forcing discrepancy between CMIP6 and CESM-HR (**Lines 360-372, Supplementary Fig. 10**).

Reference:

Hoskins, B. J., & Karoly, D. J. (1981). The steady linear response of a spherical atmosphere to thermal and orographic forcing. *Journal of Atmospheric Sciences*, *38*(6), 1179-1196.

Simmons, A. J., Wallace, J., & Branstator, G. W. (1983). Barotropic wave propagation and instability, and atmospheric teleconnection patterns. *Journal of Atmospheric Sciences*, *40*(6), 1363-1392.

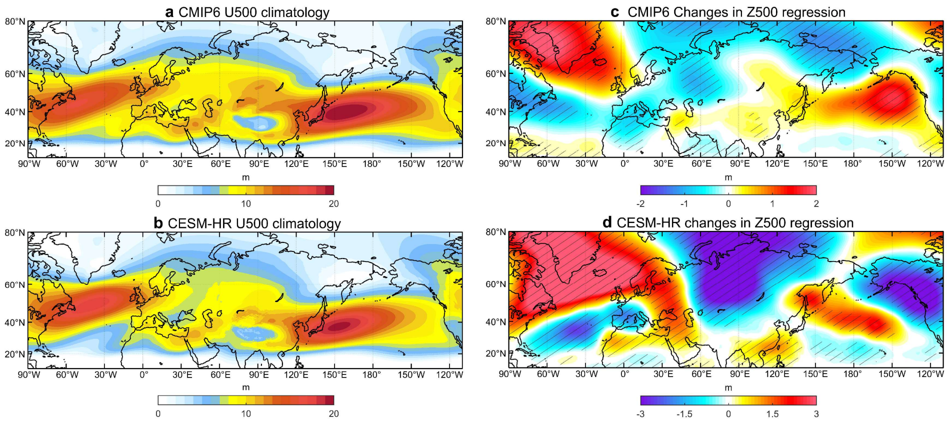

Figure R1. **Climatological zonal mean flow and AMV-related 500 hPa geopotential height (Z500) anomalies in CMIP6 models and CESM-HR**. **a**, Climatological zonal wind at 500 hPa (U500) under SSP585, averaged across CMIP6 models. **b**, Same as **a**, but for the CESM-HR under RCP85. **c**, Regression of Z500 anomalies onto the AMV index, showing the difference between SSP585 and PiControl in CMIP6 models. Hatched areas indicate regions where changes under global warming are significant at the 90% confidence level. **d**, Same as **c**, but for the CESM-HR.

Response to Reviewer #4

In this manuscript, the authors study the influence of AMV on KOE SSHa variability using CMIP6 models under PI and SSP585 conditions. They show a northward movement of KOE under a warmer state and intensified decadal variability of KOE ssha. They have attributed this intensification to the increased variability of AMV. The overall results are interesting, but they did not demonstrate the decadal variability studied here is statistically significant. Here is my assessment of the authors' response to the comments of reviewer #2 and my own evaluation of this manuscript.

Thank you very much for the careful evaluation of our manuscript and for the constructive comments. To improve clarity and provide a structured response, we organize the main concerns into four key issues: **(1)** the definition of model-specific KOE regions, **(2)** the statistical significance of decadal variability in the KOE region, **(3)** the robustness of the AMV–KOE relationship, and **(4)** the relationship between ocean stratification and KOE SSH anomalies. We respond to each of these points in detail below. In addition, we address the remaining comments individually in the subsequent sections.

1. The model-specific KOE regions

Related comments:

1) In addition, the location of KOE may not be the same for each model. As shown in Fig. 1a, a uniformed box may not give you the best result. It might be a good idea to define this KOE box based on each model and different mean background states.
2) To define the KOE region better, it is a good idea to define it based on each model. The ensemble mean can be used, but results from each model can be provided in the online information.
3) Line 114-115, the box seems too big which includes not only KOE, but also other things. Is it possible to narrow it to the KOE only? For example. find the ridge line of SSHa and extend 2 (or 5) degree north and 2 (or 5) degree south of the ridge.

Thank you for this helpful comment. Instead of using a fixed box, we now define the KOE region separately for each model and experiment based on their mean-state frontal structures. The Kuroshio extension is identified by the latitude of maximum meridional SSH gradient (shading), and the Oyashio Extension by the latitude of maximum meridional SST gradient (contours), following previous studies (Qiu et al., 2017; Thompson & Kwon, 2010). The KOE region is then constructed by extending 5° north and south from these dynamically identified fronts (red boxes in **Figure R2**).

Using this model-specific definition, we calculate a KOE index as the area-averaged decadal SSHa for each model and experiment. Based on this updated index, we confirm that **(1)** the AMV–KOE relationship remains robust within individual models (see detailed responses in Part 3 of our reply, **Figure R6**), and **(2)** the intermodel relationship between AMV variability and KOE variability is largely unchanged. This suggests that models with stronger AMV variability still tend to exhibit a more pronounced enhancement of KOE decadal variability under global warming (**Figure R3**).

Importantly, we find that our results are not sensitive to the exact definition of the KOE region. Both the AMV–KOE relationship within individual models and the intermodel relationship remain qualitatively consistent whether using a broad, fixed KOE box or the refined, model-specific regions. This further supports the robustness of our conclusions. The manuscript and all related figures have been revised accordingly (**Lines 142–153**; **Fig. 3**; **Fig. 5d-f**; **Supplementary Fig. 3**).

Reference:

Qiu, B., Chen, S., & Schneider, N. (2017). Dynamical links between the decadal variability of the Oyashio and Kuroshio Extensions. *Journal of Climate*, *30*(23), 9591-9605.

Thompson, L. A., & Kwon, Y. O. (2010). An enhancement of low-frequency variability in the Kuroshio–Oyashio extension in CCSM3 owing to ocean model biases. *Journal of climate*, *23*(23), 6221-6233.

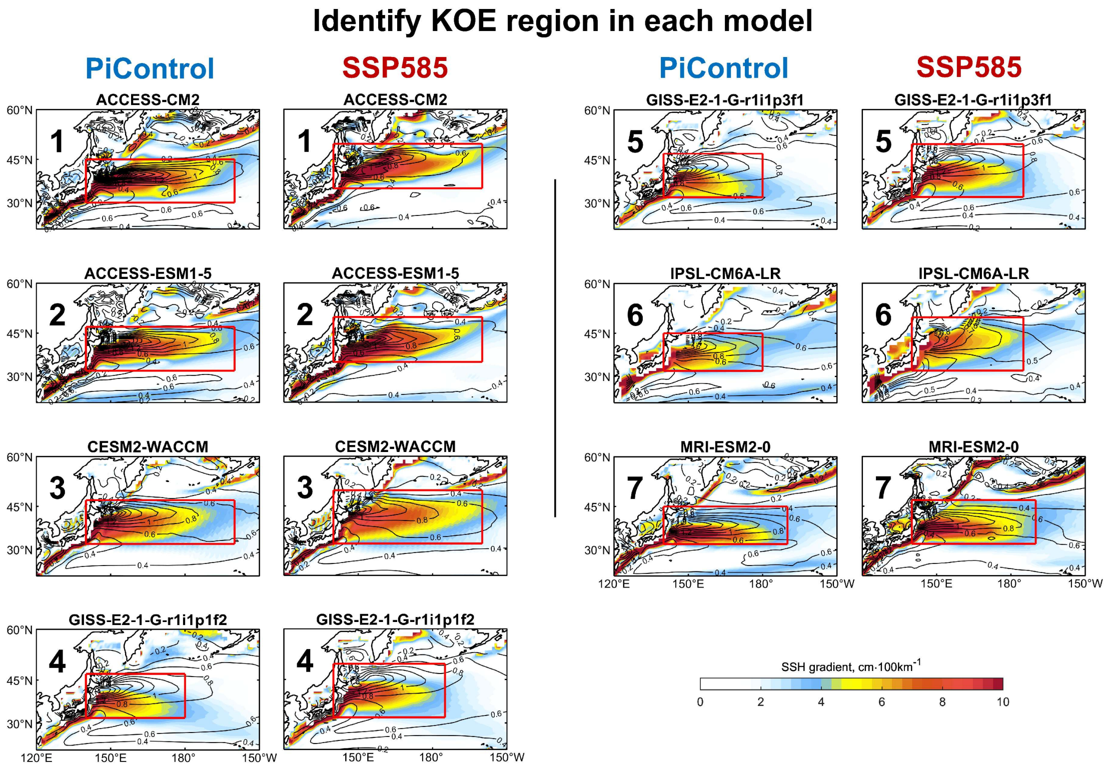

Figure R2. Climatology of meridional SSH and SST gradients in the Kuroshio–Oyashio Extension (KOE) region across individual CMIP6 models under PiControl and SSP585. Mean meridional SSH gradients (shading; cm·100 km^{-1}) and SST gradients (contours; °C·100 km^{-1}) are shown for seven CMIP6 models (model identifiers are indicated in the upper-left corner of each panel). The red box highlights the KOE region in each model.

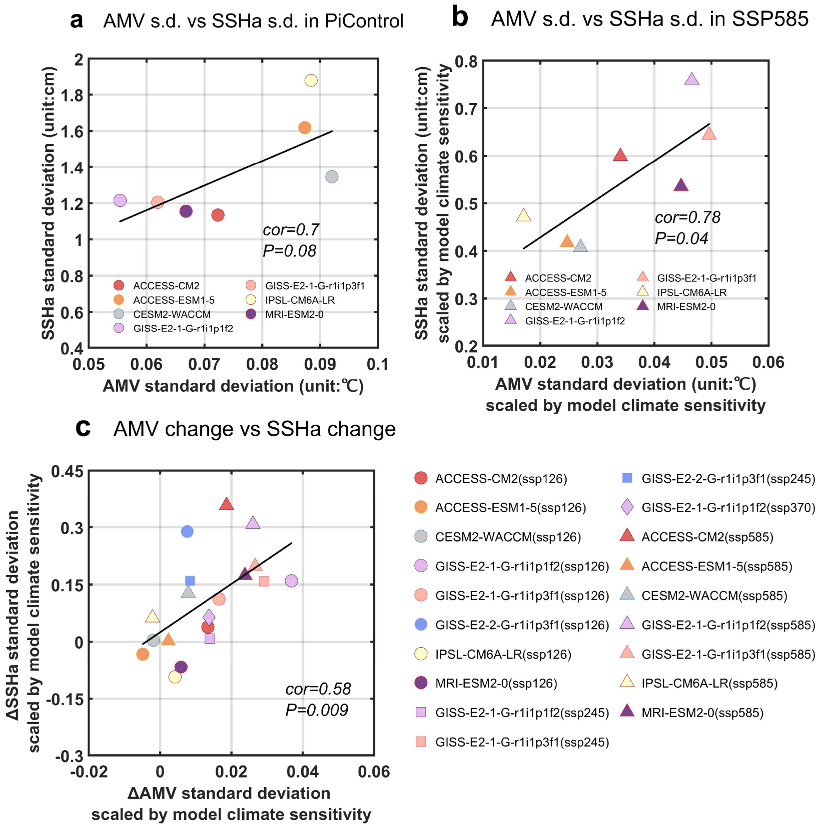

Figure R3. Intermodel relationship between amplitude of AMV and amplitude of KOE decadal variability using model-specific KOE regions. a Intermodel correlation between the standard deviation in AMV index (unit: °C) and in the sea surface height anomalies (SSHa; unit: cm) over the KOE region (red box in Fig. R3) in PiControl. **b** Same as (**a**), but for the SSP585 scenario, with both variables scaled by each model's equilibrium climate sensitivity (ECS) to remove intermodel differences in climate sensitivity to global warming. **c** A statistically significant intermodel relationship between standard deviation changes in the AMV index and in the decadal SSHa variability over the KOE. Both are scaled by ECS in respective models. Correlation coefficient and *p*-value are also indicated.

2. The statistical significance of decadal variability in the KOE region

Related comments:

1) From my point view, the authors show increase in stds in SSP585 relative to PI control, but they did not show whether the intended decadal variability is significant or not. It is better to test where the decadal variability is significant, then explore the underlying physical processes. For example, spectral analysis can be done at each grid point to see whether the decadal variability is significant at that grid point.
2) Lines 98-99, How do you determine there are significant decadal variability in SSH? Maybe it is better to show where the decadal variability is significant in Fig. S1.
3) Line 110-111, Ideally to determine whether there is decadal variability, you need to do power spectrum analysis on each grid point and pick those points do show statistically significant decadal peaks. Then those are the grid points which you can state the decadal variability exist.

Following the reviewer's suggestion, we construct a KOE index for each model and each experiment by averaging SSHa over the model-specific KOE region. The resulting 250-year time series are detrended and subjected to power spectral analysis without additional filtering. All models exhibit statistically significant spectral peaks on decadal timescales under both PiControl (blue) and SSP585 (red) simulations, with higher spectral power under SSP585, indicating enhanced decadal variability under global warming (**Figure R4b-h**). This result is qualitatively unchanged when using a fixed, broad KOE box, suggesting that the detection of decadal variability is not sensitive to the exact regional definition. A consistent feature is also found in the ORAS5 reanalysis (**Figure R4a**), which shows significant variability in the 10–30-year band despite the relatively short observational record (1958–2025).

To further address spatial significance, we perform grid-point-based spectral analysis and identify regions exhibiting statistically significant peaks in the decadal band (hatched regions in **Figure R5**). The results show that the core KOE region consistently displays significant decadal variability under both PiControl and SSP585 simulations. This finding is consistent with previous studies that identify the KOE as a key center of decadal variability and a major action center of the PDO pattern (e.g. Ref. 3, 14, 20, 22, 26). Therefore, the existence of decadal variability in the KOE region is supported both spectrally and spatially, and is not an artifact of internal noise or region selection. These spectral analyses have been added into the revised manuscript (**Lines 103-104, 739-741, 826-828; Fig. 1a-b; Fig. 7a-b; Supplementary Fig. 1**).

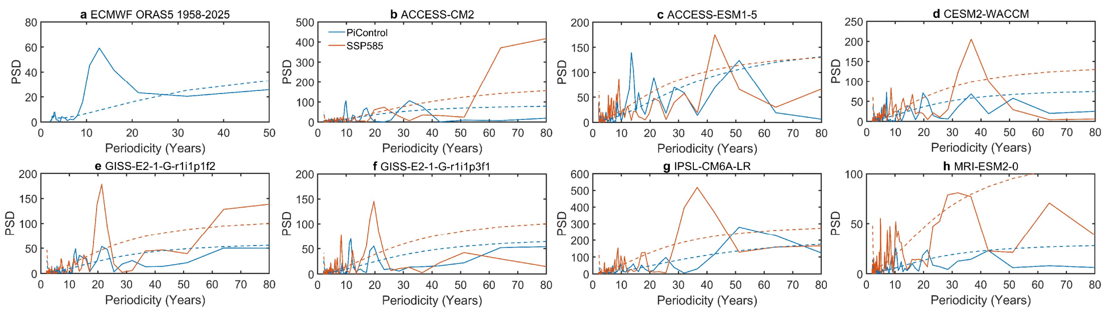

Figure R4. Spectral analysis of unfiltered KOE SSH index for ORA-S5 reanalysis data (a) and CMIP6 models (b-h). For each model and each experiment, the KOE index is defined by averaging SSHa over the model-specific KOE region. The resulting time series are quadratically detrended and analyzed without temporal filtering. The power spectrum in PiControl (SSP585) experiments is signified by blue (red) solid line. The 95% confidence level is signified by dashed line based on a red noise null hypothesis. Spectral peaks in the decadal band that rise above the confidence level are interpreted as evidence of statistically significant decadal variability.

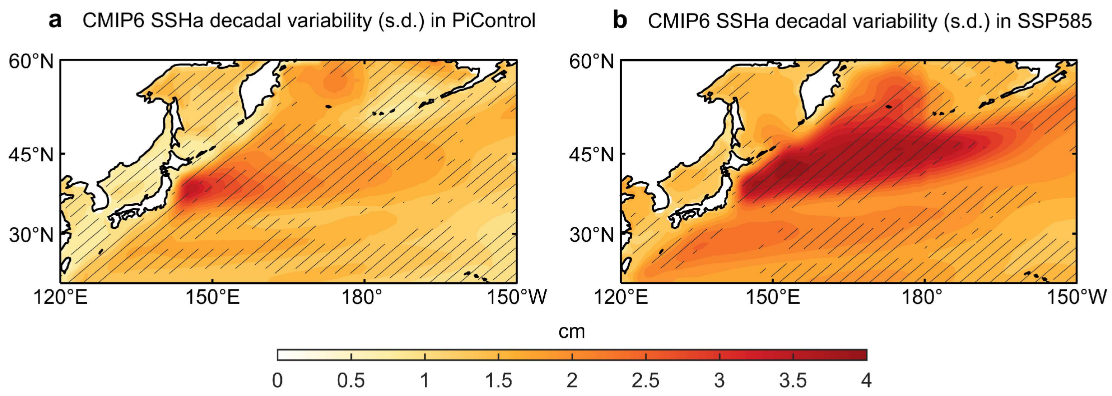

Figure R5. Comparison of SSH decadal variability in the KOE region under PiControl and SSP585 simulations. a Spatial distribution of the standard deviation of the 11-year running-mean, quadratically detrended SSH anomalies at each grid point in PiControl (shading; unit: cm). Shown is the multi-model ensemble mean. **b** Same as (**a**), but for the SSP585 scenario. The statistical significance of decadal variability is assessed at each grid point separately for each model and each experiment using spectral analysis of the corresponding SSH time series (quadratically detrended, without temporal filtering), with significance evaluated based on a red-noise null hypothesis at the 95% confidence level. Hatching indicates regions where all models consistently exhibit significant decadal variability.

3. The robustness of the AMV–KOE relationship

Related comments:

1) To me, a better response to the comment #1 from reviewer #2 is to test whether the relationship between AMV and KOE exists in each individual model under both PI and SSP585 conditions. If the answer is yes, the concern of review #2 is resolved. If not, it is better to examine why certain models do not produce this relationship. As shown in Fig. 1a, a uniformed box may not give you the best result. It might be a good idea to define this KOE box based on each model and different mean background states.
2) For the second comment, the authors may need to do a deeper dive to figure out whether this AMV-KOE relationship is true. One way to do this is to do a lead-lag correlation between AMV and KOE for each model. If AMV indeed leads KOE in all models, it is very likely that AMV variability affects KOE variability. Then, a physical explanation is needed. In the manuscript, the authors have tried to explain this relationship but did not fully demonstrate whether this relationship exists or not. I assume this is why reviewer #2 is convinced by the argument of the authors.

Following this comment, we examine the AMV–KOE and PDO–KOE relationships by computing their lead–lag correlations in each model under both PiControl and SSP585 (**Figure R6**). In PiControl, KOE decadal variability is consistently more strongly correlated with PDO than with AMV across models, with statistically significant multi-model agreement (**Figure R6a, c**). This is physically expected, as in the unforced climate the KOE region is primarily influenced by intrinsic North Pacific variability and local air–sea coupling processes associated with the PDO, which tend to dominate over weaker remote Atlantic signals.

However, under SSP585, a robust AMV–KOE relationship emerges in all models (**Figure R6b, d**). Correlations become significantly stronger over a wide range of lead–lag times, with clear signals when AMV leads KOE as well as at near-zero lag. This behavior likely arises from the combined effects of slow oceanic adjustment (e.g., Rossby wave propagation and ocean memory) and fast atmospheric bridge processes, which distribute the KOE response to AMV forcing over a range of timescales. The presence of a leading AMV signal provides direct support for a dynamical influence of AMV on KOE variability. Therefore, the AMV–KOE linkage is weak in PiControl yet becomes systematically strengthened under greenhouse warming. This behavior is fully consistent with our proposed mechanism of an enhanced AMV influence on KOE variability in a warmer climate.

In addition, the original manuscript already provided supporting evidence for the AMV–KOE relationship through the regression of North Pacific decadal SSH anomalies onto the AMV index (**Fig. 2**). Although shown as the multi-model ensemble mean, the stippling highlights regions with consistent responses across models, suggesting a coherent KOE SSH response to AMV forcing. Overall, these results consistently support our central conclusion that KOE variability is primarily governed by Pacific internal variability (PDO) in the unforced climate, but becomes increasingly modulated by AMV through enhanced teleconnections under global warming.

In the revised manuscript, we have added lead–lag analysis to more directly illustrating the temporal relationship within individual models (**Lines 142-153; Supplementary Fig. 4**).

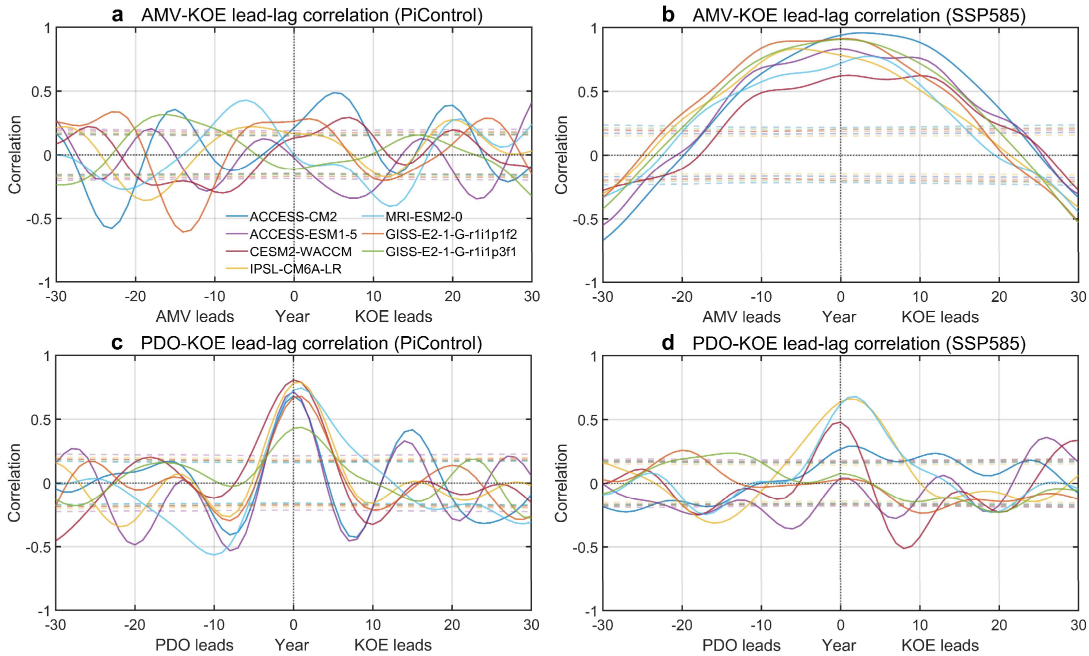

Figure R6. Lead–lag correlations of AMV–KOE and PDO–KOE in each model and simulation. (a, b) Lead–lag correlation between AMV index and KOE SSH index under PiControl **(a)** and SSP585 **(b)** simulations. **(c, d)** Lead–lag correlation between PDO index and KOE SSH index under PiControl **(c)** and SSP585 **(d)** simulations. Colored lines represent individual models. Horizontal dashed lines indicate significance thresholds for each model at the 95% confidence level.

4. The significant relationship between ocean stratification and KOE SSHa

For comment #8, it is a good idea to identify whether the proposed relationship between ocean stratification and KOE SSHa is true for each individual model under both PI and SSP585 conditions. Again, the unsignificant relationship in PI control may also be related to the KOE region which might not be the same in all models.

Following this comment, we adopt model-specific KOE definitions and find that the intermodel relationship between stratification and KOE SSH variability still remains statistically insignificant in the PiControl simulations (**Figure R7**). Physically, ocean stratification acts as a key intermediary in this pathway, fundamentally influencing Rossby wave characteristics by regulating their propagation speed and vertical structure. However, in the CMIP6 models, KOE variability arises from multiple competing processes, including remote atmospheric forcing (e.g. AMV) and internal ocean dynamics (e.g. PDO), which makes it difficult to isolate the specific contribution of stratification from intermodel comparisons alone.

To isolate this effect, we further design a pair of reduced-gravity model experiments in which only the background stratification differs (strong vs. weak), while all other parameters and forcings are held identical. The results show that enhanced stratification leads to a reduction in decadal SSH variability in the KOE, indicating that stronger stratification is not favorable for amplifying KOE variability. It supports our main conclusion that the intensified KOE variability is primarily driven by the strengthened remote forcing associated with AMV.

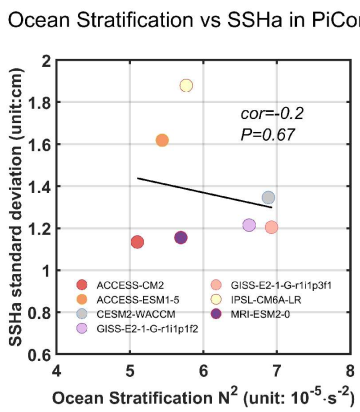

Figure R7. Intermodel correlation between the ocean stratification, calculated as area-weighted mean of squared Brunt-Väisälä frequency (N^2; unit: s^{-2}) and the standard deviation in the SSH anomalies (SSHa; unit: cm) over the KOE region in PiControl based on CMIP6.

Other comments

5. For comment #5, it would be easy to identify which model contributes to the changes of the STD in the ensemble mean. If the authors plot the STDs for all models separately, this is an easy task to do. Once the model or models is/are identified, an explanation will not be difficult to find. It is also interesting to see that when the system is going towards a more quasi-equilibrium state, the variability reduces as the forcing after 2250 is constant in SSP585.

Following your suggestion, we analyze the evolution of the 71-year running STD for each model. This reveals that the late-stage change in the ensemble-mean STD is primarily driven by ACCESS-ESM1-5 (**Figure R8**). Overall, the KOE variability is stronger under warming conditions, with a mean running STD of 2.57 in SSP585 compared to 1.83 in PiControl, indicating an enhanced decadal variability in the KOE region in a warmer climate. Superimposed on this mean-state difference, a reduction of KOE variability is observed during the last ~50 years of the SSP585 simulations. To explore the possible drivers of this behavior, we examine its relationship with major climate modes. We find that the temporal evolution of the AMV index shows a similar tendency to the running STD of KOE variability during this period, suggesting a potential linkage between AMV and KOE.

It is possible that the reduced SSH variability after 2250 reflects a transition of the climate system from a transient response to increasing CO_2 forcing toward a quasi-equilibrium state, as the radiative forcing becomes constant after 2250. However, confirming this hypothesis would require a clear separation between the forced response and internal variability, which relies on a sufficiently large multi-model ensemble. Given data availability, the present analysis, based on only seven CMIP6 models, is insufficient to robustly address this issue.

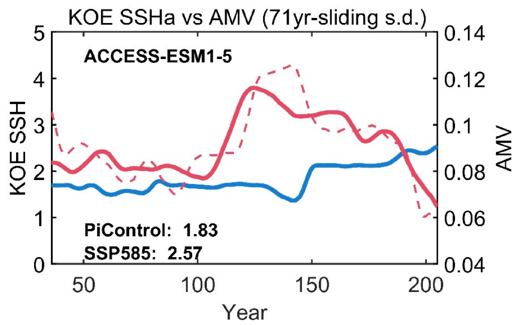

Figure R8. Evolution of the 71-year running standard deviation of the KOE SSHa and AMV indices in the ACCESS-ESM1-5 model. The 71-year sliding standard deviation of the KOE SSHa indices (35°N -50°N, 140°E–170°E) under PiControl and SSP585 simulations are shown by the blue and red solid lines, respectively. The x-axis denotes the central year of sliding window. The red dashed line denotes the running standard deviation of the AMV index. The mean KOE SSHa variability over the analyzed period is 1.83 for PiControl and 2.57 for SSP585.

6. Line 101, Is there a reason to stop the analysis in 2014? Is it because the CMIP6 historical simulations stop in 2014? In addition, did you do the satellite derived SSH? Are they the same?

Yes. We stop analysis in 2014 to maintain consistency with the CMIP6 historical simulations, which end in that year. To ensure that time coverage choice does not affect our results, we repeat the analysis using the full available ORAS5 record (1958–2025). The spatial pattern of SSH decadal variability remains highly similar, with pronounced amplitudes in the KOE region compared to the rest of the North Pacific. We further examined satellite-derived SSH from AVISO (1993–2022), which shows very consistent variability characteristics and spatial patterns (**Figure R9**). All datasets exhibit enhanced decadal variability in the KOE region. The statistical significance of decadal variability is assessed at each grid point using power spectral analysis, with hatched regions indicating significant decadal signals. The updated results have now been incorporated into the revised manuscript (**Lines 103-105, Supplementary Fig. S1**).

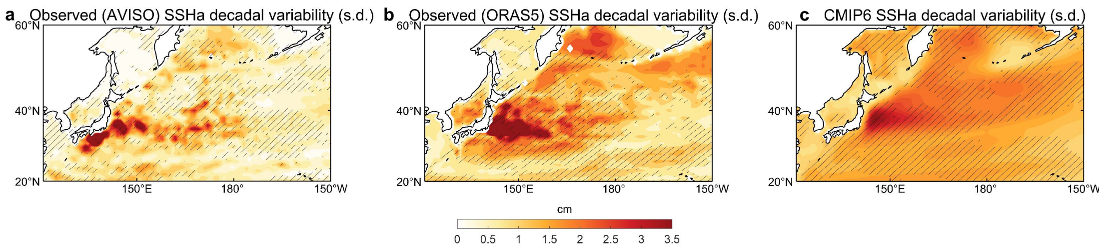

Figure R9. Observed and simulated decadal variability of Pacific SSH. The intensity of SSH decadal variability is quantified as the standard deviation at each grid point (shading; unit: cm). **a** Decadal variability intensity of SSH anomalies (SSHa), quantified as the standard deviation at each grid point (shading; unit: cm). The SSHa time series is quadratically detrended and smoothed with an 11-year running, based on the AVISO for 1993–2022. **b** same as **a**, but for ECMWF ORAS5 during 1958-2025. **c** The multi-model ensemble mean results in historical simulations from CMIP6. The statistical significance of decadal variability is assessed at each grid point using power spectral analysis, with hatched regions indicating signals statistically significant at the 95% confidence level.

7. Line 147, what are the regression coefficients for different modes, AMV, PDO? How much of the SSH variance near KOE can be explained by AMV or PDO?

The regression coefficients for AMV and PDO are shown in **Fig. 2** and **Fig. 5a–c**, respectively. They are derived from a multiple linear regression in which AMV and PDO indices are included simultaneously, so that each coefficient represents the SSH response to one mode after removing the influence of the other. Thus, these regression patterns reflect the independent contribution of AMV and PDO, respectively.

To quantify the relative contributions of AMV and PDO, we compute the fraction of KOE SSH variance explained by each mode across individual models (**Figure R10**). In PiControl, PDO dominates the variability, explaining a large fraction of the variance across models, with a multi-model ensemble mean (MMEM) of ~49%, whereas AMV contributes only marginally (MMEM ~3%). In contrast, under the SSP585 scenario, a clear shift emerges. The explained variance associated with AMV increases across all models (MMEM ~64%), while the contribution from PDO is markedly reduced (MMEM ~13%). These results provide quantitative support for our central conclusion that AMV exerts a growing influence on KOE variability in a warming climate.

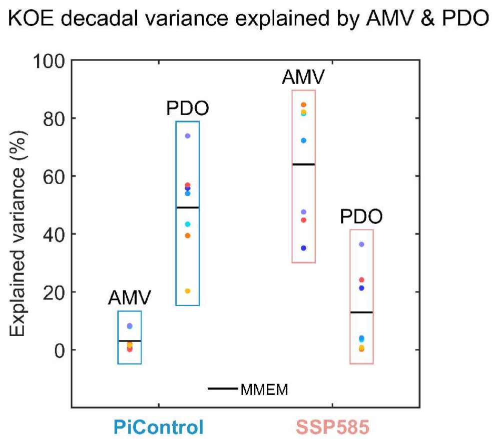

Figure R10. Explained variance of decadal KOE SSH associated with AMV and PDO in PiControl and SSP585 simulations. Values are derived from multiple linear regression and represent the partial contribution of each mode. Dots show seven individual models, and black lines in boxes denote the multimodel ensemble mean result.

8. Line 153, It is better to show the regressed wind stress curl anomaly which can show the Ekman convergence much better.

Thanks for your suggestion. When we attempted to replace wind stress with wind stress curl in the same figure, however, the curl field exhibits more noisy structures (**Figure R11**), which reduces the visual clarity of the large-scale signal and makes the figure less effective for illustrating the key mechanism in the KOE region. For this reason, we retain wind stress in the main figure for clearer presentation.

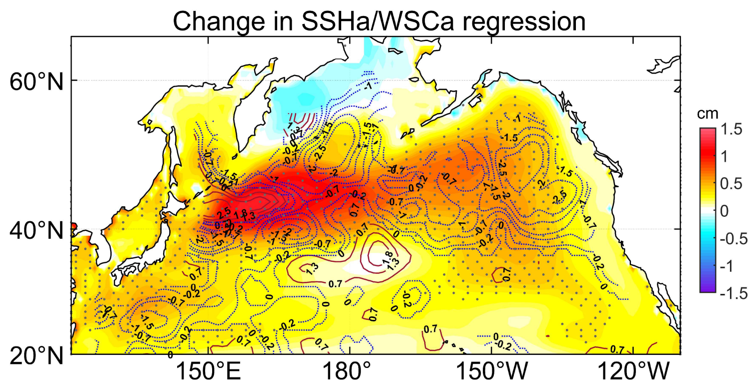

Figure R11. Regressions of 11-yr running-mean, quadratically detrended SSHa (shading; unit: cm) and wind stress curl anomalies (contours with positive in red and negative in blue) onto the normalized AMV index. Shown are the regression differences between SSP585 and PiControl.

9. Line 174-175, are there any references to support this claim?

Yes, Ref.46 is the reference to support this. We have cited in the revised manuscript (**Lines 185**).

10. Line 183-185, is this true for each model?

The result shown in Fig. 3 reflects an intermodel relationship between AMV and KOE variability. We examine whether models with larger AMV amplitude also tend to exhibit stronger decadal KOE SSH variability. This relationship is inherently defined across models, rather than within each individual model, since each model provides only a single estimate of AMV variability and KOE SSH variability. Therefore, the analysis cannot be conducted at the single-model level. Instead, the emergent intermodel relationship across the model ensemble indicates a consistent tendency for models with stronger AMV variability to simulate enhanced KOE variability, supporting the robustness of the AMV–KOE linkage.

11. In the manuscript, the use of "KOE" and "KOE region" seems interchangeable. As mentioned in previous comment, it is better to strictly study the KOE only.

Thank you for this helpful comment. In the revised manuscript, we have followed your suggestion and now define the KOE region separately for each model and experiment based on their mean-state frontal structures. With this model-specific definition, the terms "KOE" and "KOE region" are used interchangeably to refer to the same dynamically relevant area. In some contexts, we retain the expression "KOE region" to emphasize the location or spatial patterns. We have carefully revised the manuscript to ensure that the usage is consistent and contextually appropriate throughout.

This manuscript is revised in many aspects. But the responses to my key concern is still not satisfying.

Specifically, in the Figure 3 in their revised manuscript (Figure 4 in their original manuscript), the relationship between AMV and ssha in KOE still seems to be dominated by ACCESS-ESM1-5, IPSL-CM6A-LR and CESM2-WACCM. In responses, As shown in Figure R2-1, the authors also examined this by excluding the three models and found that the relationship between AMV and ssha in KOE is not significant anymore in both PiControl and SSP585. And, the relationship between changes of AMV amplitude and changes of ssha in KOE is also not significant any more. I strongly disagree with the authors arguement that "…a tendency for larger AMV variability to be associated with enhanced KOE SSHa variability in PiControl and SSP585, although the statistical significance is reduced due to the smaller sample size …". I would interpret that, for correlations with *p* value as larger as 0.31, 0.54 and 0.12 (as shown in Figure R2-1), the relationship would be meaningless. Otherwise, why do we need the significant test? Similarly, in Fig.5 of the revised manuscript, if the two models of ACCESS-ESM1-5 and IPSL-CM6A-LR are excluded, the relationship between PDO and ssha in KOE would not be significant in piControl.

In their response, the authors argue that "the climatological MLD in the North Atlantic exhibits only marginal shoaling in these three models under global warming. As a result, the AMV amplitude shows only moderate enhancement in these models, leading to relatively weak increases in KOE SSHa variability". I don't agree with this since there is a weak increase in IPSL-CM6A-LR. In fact, in IPSL-CM6A-LR, the increased AMV standard deviation actually leads to a decrease standard deviation of ssha in KOE. This contradicts their main argument that increased AMV would amplify the connection between AMV and ssha in KOE.

Besides, both Figure R2-1 and Fig. 3 seem strange that the models used in panel **a** are different from those used in panel **b**. For fair comparison, the models used in panel **a, b** and **c** as well as those in panel d of Figure R2-1 should be consistent to reasonably evaluate the relationship between AMV and ssha in KOE. Why are the number of models different in these panels? For example, panel a has 8 models, panel b has 7 models, while panel c has many models… Same problem also occurs in their Figure 5. This makes me concern how other figures in the manuscript are constructed.

In addition, the figure caption for both Figure R2-1 and Fig. 3 in the main manuscript doesn't make sense. These two figures show results from piControl, SSP585 and their differences. While, the models used, according to their figure caption, including ssp126,245, 370 and 585. Same problem also occurs in their Figure 5.

In Fig.1d, there std of the ssha index in the first 150years in PiControl seems doesn't change. I agree with the authors that the amplitude of decadal variability remains relatively stable over this period. But why does it increase in the last 50 years? Similarly, the std of AMV index reduced in the last 50 years of SSP585. The increase in piControl and decrease in SSP585 then actually makes the AMV std not so different in the last 50 years. According to Figure R2-2, the shorter the sliding window, the less difference would AMV std occur.

In Fig2, there is a short vertical black line at the top at around longitude of 180 in each panel. What is that for?

In Fig2 and Fig5a,b,c, the y axis is better on the left to be consistent with other figures.

In Fig. 6b, the models used should be clearly stated. Besides, the relationship between ocean stratification and ssha in piControl is also not significant.

In Fig.7, the y-axis better be consistent.

Paper: **Atlantic Multidecadal Variability amplifies decadal variability in the Kuroshio-Oyashio Extension region under global warming**

This manuscript presents a novel study on the influence of Atlantic Multidecadal Variability (AMV) on decadal variability of the Kuroshio–Oyashio Extension (KOE) in a warming climate. The authors show that an intensified AMV strengthens atmospheric teleconnections, producing negative wind stress curl anomalies over the northeastern North Pacific. These anomalies drive surface Ekman convergence, deepen the thermocline, and enhance northward Ekman heat transport, increasing local sea surface height (SSH). The resulting SSH anomalies propagate westward as baroclinic Rossby waves, amplifying decadal variability in the KOE and shifting its maximum intensity northward.

The study demonstrates that, in comparison, the PDO and local stratification play a reduced role in modulating KOE variability, highlighting the dominant influence of the AMV and the importance of Atlantic–Pacific teleconnections. The manuscript is clear, well-written, and scientifically robust. I recommend it for publication, with only minor revisions to further improve clarity.

Figure captions: The final lines of all figure captions, including those in the Supplementary Material, provide interpretative statements. In my experience, figure captions should primarily describe the figure rather than interpret the results. That said, these interpretations are clearly written, easy to follow, and add value to the manuscript. For this reason, whether to move this interpretative text to the main text or retain it in the captions ***is a decision I leave to the editor***.

Lines 86–90: I understand that the Kuroshio Extension (KE) and the Kuroshio–Oyashio Extension (KOE) are distinct and not synonymous. However, the current wording may give the impression that these terms are interchangeable, which could lead to misinterpretation. For example, Joh et al. (2022) discuss strengthened atmospheric teleconnection effects acting on the KE, rather than explicitly on the KOE, as implied here. In addition, neither this teleconnection effect nor the other processes mentioned—such as AMV influence, Rossby wave propagation, and local atmospheric forcing—are yet well established specifically for the KOE, which is the primary focus of this study. I therefore suggest revising these sentences to clearly distinguish between KE and KOE and to avoid ambiguity.

Line 120: For clarity, it would be helpful to introduce the multi-model ensemble mean (MMEM) at the beginning of the Results section, where it is first defined (lines 96–106).

Figure 2: The white dots indicating statistically significant anomalies are difficult to discern and are only faintly visible at high zoom levels (~200%) in the digital version. Consider changing their color (e.g., from white to grey) to improve legibility.

Figures 3: The abbreviation "TN" is only defined in the Methods section (line 347) as WAF (TN flux). I suggest either defining it in the main text (e.g., around line 162) or, if you prefer to leave the main text and Methods unchanged, changing the figure titles from "TN flux" to "WAF" to avoid confusion.

Line 174: Was the SSHa detrended? If so, please indicate this in the text and in the Figure 4 caption, consistent with how it is reported for the previous figures.

Line 195: Are you talking about meridional oceanic advection? Please clarify.

Figure 4: Up to this point, the manuscript gives the impression that only the SSP585 scenario is being used. Although other scenarios are listed in Supplementary Table 1 and mentioned in the Methods (lines 315–317), it is not clear in the main text that additional future scenarios (SSP126, SSP245, and SSP370) are included when discussing Figures 4c and 4d (lines 181–186). Clarifying this in the main text, and briefly explaining the reason for including these additional future scenarios in the analysis shown in Figure 4 (and later in Figure 5), would help avoid potential confusion and improve readability.

Line 209: "Northward displacement" of what? Please clarify to avoid confusion.

Supplementary Figure 6: The last sentence of the caption refers to information that is not directly depicted in the figure. The figure shows only the poleward-shifting teleconnections and atmospheric stratification and anomalies. Please rephrase the sentence so that the caption accurately reflects the figure's content.

Lines 269–272: This sentence appears to refer to **Figure 6c** rather than **Figure 6b**. In addition, the figure indicates a **negative**, rather than positive, correlation. Clarifying this point and specifying the statistical significance based on the Monte Carlo test—as done for the other figures in the manuscript—would improve consistency and clarity (the significance appears to be ~87% based on the figure).

Line 291: The 34% value is not mentioned in the main text. To improve clarity and consistency, it would be helpful to include this percentage in the main text when discussing the figure from which it is derived, so that the summary reflects information already presented.

Lines 338–339: Could you please briefly clarify how the PDO and AMV signals are isolated from each other in the respective indices? A short explanation would help readers better understand the methodology.

Code availability: The manuscript states that all analysis codes are available upon request from the corresponding author. While this is appreciated, making the code publicly available (e.g., via GitHub or a similar repository) would substantially enhance the transparency, reproducibility, and long-term accessibility of the results. Public code availability would also facilitate reuse by the community and align with current best practices in open and reproducible science. I therefore encourage the authors to consider publishing the analysis code in a public repository.