**egusphere-2026-2715: Response to Reviewers**

We thank both reviewers for their time reading the manuscript and positive and constructive feedback. We respond to specific comments below.

**Reviewer 1**

This study evaluates the regional and seasonal atmospheric energetic simulation in CMIP6 historical climate (good to know that the simulations resemble ERA5!) and deconstructs its NEI contributions; and then follows on to evaluate intermodel differences using EOF analysis and understanding the change from historical to SSP5-8.5 referencing the EOF space. The latter reveals groups of models with different characteristic changes, suggesting that different storylines exist in interpretation of future changes

This is a straightforward and useful paper, adequately researched and well written. This study is exploratory rather than advancing a hypothesis, so not much can go wrong here. I thought the result showing that the intermodel variation in EFP can be summarized to two EOF representing land-ocean contrast and the interhemispheric gradient to be useful. An obvious question that is not really addressed in the manuscript is in understanding why the intermodel variation in the EFP are like this; but I understand that this is probably better left to a future study.

I only have relatively minor comments, listed below.

"Major" comments

1. EOF analysis is separately applied for intermodel differences for JJA and DJF, each showing a zonal mode as EOF1 and interhemispheric mode as EOF2. The question is: are the corresponding PCs for JJA and DJF related? In other words, do models that show an eastward EPFM shift and northward EFE shift in JJA, also show an eastward EPFM shift and northward EFE shift in DJF? It would be useful to know if there is such a correlation. Similarly, is the change from historical to SSP5-8.5 in the EOF space correlated between JJA and DJF for each model?

Thank you for this suggestion. We have checked this, and find for the correlations between the JJA and DJF PCs in the historical simulation:

- For PC1 (JJA) and PC1 (DJF) a Pearson's r of 0.27 ($p=0.10$)
- For PC2 (JJA) and PC2 (DJF) a Pearson's r of 0.31 ($p=0.05$)

For the correlations between the JJA and DJF change from historical to SSP5-8.5 we find:

- For PC1 (JJA) and PC1 (DJF) a Pearson's r of 0.39 ($p=0.02$)
- For PC2 (JJA) and PC2 (DJF) a Pearson's r of -0.55 ($p=0.001$)

There does therefore seem to be some weak relationship between the seasons for the historical run, and a slightly stronger correlation for the differences. Correlations between PC1/PC2 and their changes between seasons are weak and not significant to $p<0.1$.

We will note the above correlations and their p values in the discussion of Fig. 8 in the revised manuscript.

2. Tuckman et al. 2024 examine the seasonal atmospheric energetics and propose a zonal 'Indo-Pacific monsoonal mode' and how they link to the Pacific. While not directly relevant, I think elements of the results here do connect to the Tuckman paper and

could help with putting the results in context (disclosure: I have no association to this paper).

Tuckman, P.J., Smyth, J., Lutsko, N.J. and Marshall, J., 2024. The zonal seasonal cycle of tropical precipitation: Introducing the Indo-Pacific monsoonal mode. *Journal of Climate*, *37*(14), pp.3807-3824.

Thank you for suggesting this paper, which we agree has relevance. In the revised version, we will reference this work in the discussion of Fig 2 and the interpretation of Fig. 4.

Specific comments

Figure 1 – check the labelling for SH and RAD, there's an inconsistency.

Thank you for catching this, this will be fixed in the revised paper.

Line 180 – its worth stating in the beginning that the LH and RAD contributions gives the structure to the overall EFP

Thanks for this suggestion, in the revision we will note this.

Line 186 "In DJF, the zonal structure is dominated by the latent heat component (Fig. 2f)". This is largely also true for JJA? There are quantitative differences to be sure between JJA and DJF for the zonal component between RAD and LH, but not as pronounced as what the description makes it out to be.

Thanks for this suggestion, having revisited the text and the figures, we agree this paragraph could be modified to recognize similarities as well as differences, e.g.:

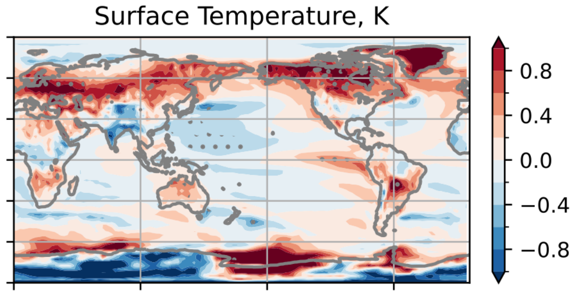
"In JJA, the structure of the latent heat component is broadly similar to that in DJF (Fig. 2e), with a minimum spanning the Indian Ocean and Pacific. In this season, the radiation-attributed component of $\chi$ (Fig. 2c) shows a regional minimum over Eurasia, linked to land-sea contrast in the net longwave surface flux (Figs. B2 and B3). This arises from weaker downward longwave surface fluxes over land where humidity is lower (Fig. B3e), particularly more arid regions, combined with stronger upward longwave surface fluxes over land (Fig. B3g), due to warmer surface temperatures relative to ocean. This radiation component of $\chi$ supports a more pronounced westward shift of the overall minimum in $\chi$ relative to that of the latent heat component than is seen in DJF."

Figure 4 and paragraph starting line 269 – I interpret the EOF1 intermodal difference as reflecting more the strength of the convection over the warm pool and maritime continent, tied to the underlying SST. The warmer SSTs in the eastern equatorial Pacific is a dynamical consequence of the reduced trades in the western and central equatorial Pacific, through thermocline adjustment. Could you comment?

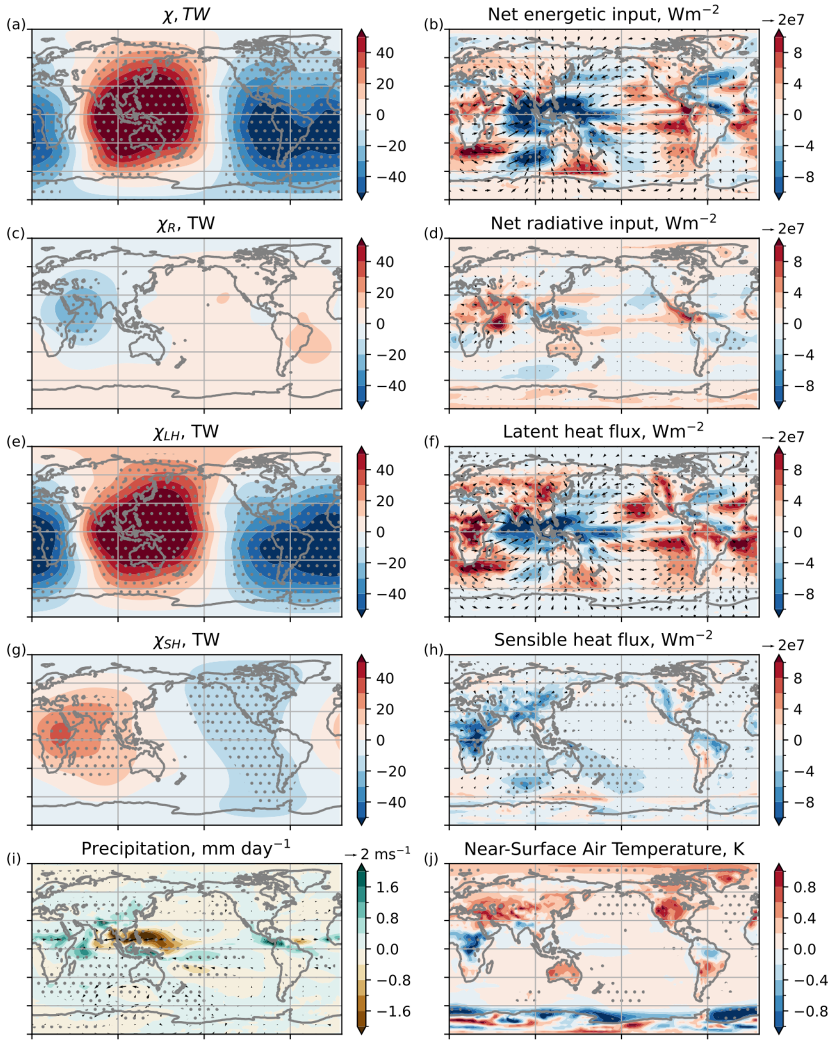
Thank you for this interpretation, which we have looked into. We agree that EOF1 reflects the strength of the convection over the warm pool and maritime continent. However, for the link to the underlying SST we note:

- Warmer JJA SSTs in this region would generally be expected to be associated with stronger, rather than weaker, trades, e.g. as seen during La Niña (e.g. Wu et al. 2010).

- We have checked the correlation to the SST itself, and find this is weaker than that to the near-surface air temperature:




- We also find that the leading mode of intermodel difference in AMIP shows a similar pattern in agreement with the mode reflecting intermodel differences in convection over the warm pool and maritime continent, but without an oceanic mechanism at play:




We will revise the interpretation of Fig. 4 to account for the above points, as well as to discuss Tuckman et al. (2024), and modify Figs 4-7 to show surface temperature rather than 2m air temperature for clarity:

"To interpret this pattern, we look first at temperature. A positive-signed PC1 is correlated with warmer surface temperatures across much of global land, cooler temperatures over the Western North Pacific, and a warmer Pacific cold tongue (Fig. 4j). The overall picture is of enhanced thermal contrast between land and sea, and across the Pacific. This is accompanied by easterly anomalies over the western Pacific, which correspond to a weakening in magnitude of the monsoon westerlies up to the Philippines, and a strengthening of the trades over the Western Pacific. Fully determining the causal relationship between these wind anomalies, the surface temperature, and the latent heat flux is beyond the scope of this paper, but we briefly consider some plausible mechanisms here. The enhanced Pacific trade easterlies might be expected to be associated with a La Niña-like enhancement of the warm pool, but instead cooler surface temperatures are seen in this region. Tuckman et al. (2024) describe a monsoon mode whereby advection of warm, moist air by monsoon westerlies leads to warming of the ocean surface due to suppressed sea surface cooling by turbulent fluxes. Consistent with this, for negative PC1 values, from Fig. 4 we see that EOF1 would show an association of extended monsoon westerlies with weakly warmer surface temperatures. However, here this would be associated with an enhanced, rather than suppressed, turbulent latent heat flux (Fig. 4f). We find that a similarly structured EOF1 dominates the intermodel spread in $\chi$ in AMIP simulations where there is no coupled ocean (not shown), suggesting that the intermodel differences seen here may be predominantly due to differing parameterizations of turbulent heat fluxes or convection, with a particularly pronounced impact on the net energetic input over the warm pool."

Wu, B., T. Li, and T. Zhou, 2010: Asymmetry of Atmospheric Circulation Anomalies over the Western North Pacific between El Niño and La Niña. *J. Climate*, **23**, 4807–4822, https://doi.org/10.1175/2010JCLI3222.1.

Line 277 "The region of cooler near-surface air temperature (Fig. 4j) overlaps with a known region of cold bias in CMIP models in the Western North Pacific, which has persisted across CMIP generations." Since this is a regression on EOF1, presumably some models will be warmer and some will be cooler relative to the multimodel mean. Presumably it is the multimodel mean temperature that has the cold bias, but this isn't associated with EOF1 per se.

Line 313-314 "The Southern Ocean is another known region of SST bias, with CMIP models on average having a too-warm Southern Ocean". Again, unclear why this is of relevance.

Thank you for highlighting these points on multimodel mean bias. Having further considered the surface temperature regression patterns while considering our response to your previous point, we agree that the text discussing the Western North Pacific cold bias is not relevant here, and it will be removed in the revised paper.

These comments were included to make links to published work that have explored sources of model bias/intermodel differences, but we agree that the relevance here was not made clear. Although it is the multimodel mean that has the average bias, processes underlying individual model's biases will vary in size and sign between models. For example, in Fig. 8, the multimodel mean is represented by the (0,0) point. The multi-model mean sits below ERA5 in JJA and above in DJF, corresponding to an average warm Southern Ocean bias in both seasons. However, there is significant scatter both around the multi-model mean and the ERA5 cross-hairs. We feel it is helpful to acknowledge mechanisms that have previously been proposed to understand model errors when discussing these intermodel differences.

The discussion of the Southern Ocean will be clarified to state:

"The cooler Southern Ocean temperatures are associated with reduced Southern Ocean net radiative input due to weaker upward surface longwave fluxes, and reduced latent heat flux due to weaker evaporation over cooler water. Both of these effects support the overall pattern of enhanced interhemispheric contrast in NEI, and the associated EFE shifts. The Southern Ocean is a known region of SST bias, with CMIP models on average having a too-warm Southern Ocean. **Intermodel differences may relate to differing representation of the processes governing Southern Ocean SST that lead to this multi-model average too-warm bias.** In CMIP5 the warm bias was suggested to relate to errors in the Atlantic Meridional Overturning Circulation (Wang et al., 2014), or shortwave cloud radiative effects (Hyder et al. 2018). However, a more recent analysis of CMIP6 suggested a relationship to warm biases in the North Atlantic deep ocean (Luo et al., 2023)."

Figure 6 and paragraph starting line 323. Presumably the shift in the EFP dipole (relative to JJA) is because of the eastward shift in the mean EPFM location in DJF (relative to JJA)? Tuckman et al. 2024 is worth taking a look at here.

This is an interesting question. In DJF the EFPM shifts eastward relative to JJA, consistent with Boos and Korty (2016) and Tuckman et al. (2024). Meanwhile the EFP intermodel dipole shifts slightly westward in DJF. In both seasons the EFPM shifts away from the maximum in EFP (westward in JJA, eastward in DJF).

The longitude of the EFP dipole maximum would seem to be primarily anchored by the intermodel differences in warm pool net atmospheric energy input, the center of which doesn't appear to shift east/west significantly between JJA and DJF, although the structure changes. As discussed above, the intermodel differences seen in either season don't appear obviously connected to the monsoon mode evolution discussed by Tuckman et al. (2024), with the hypothesized relationship between the westerly advection, warm air and turbulent fluxes opposite here to that seen in the seasonal cycle.

The westward shift in the dipole in DJF vs JJA is therefore difficult to attribute, but could link to the weaker regression with radiative effect over North Africa and the Middle East in DJF vs JJA, and stronger regression with net energy input over the cold pool. In combination, these aspects lead to a weaker EFPM minimum over North Africa and stronger EFPM minimum over the Eastern Pacific.

We will provide a brief comment on these seasonal differences in the revised paper:

"Fig. 6a shows EOF1 of $\chi$ for DJF (48.2% of variance). Similar to EOF1 for JJA, the mode links to enhanced zonal energy transport across the Pacific. **The dipole shows a slight westward shift in DJF compared to JJA, with a stronger relationship with cold pool net energy input and a weaker relationship with radiative effects over North Africa and the Middle East (Fig 6b vs Fig 4b). The maximum of the dipole still appears primarily anchored to intermodel differences in warm pool net atmospheric energy input.** This EOF is associated with warmer temperatures across Africa, Asia and South America, as well as the Nino1+2 and 3 regions. This EOF broadly resembles the pattern in $\chi$ seen under ENSO in ERA-Interim reanalysis data (Boos et al. 2016) including an eastern shift in the western Pacific EFPM and a western shift in the EFPM over the Americas for warmer eastern Pacific temperatures**. Note that the difference in longitude between the climatological EFPM in JJA relative to DJF (Boos et al. 2016, Tuckman et al. 2024) yields an opposite signed shift in the EFPM between JJA and DJF for the same sign of this dipole.** Precipitation shows an enhanced double-ITCZ structure, with weakened rainfall over the equator accompanied by enhanced rain north and south of the equator over the western Pacific. There is also weakly enhanced precipitation over southern Africa."

Figure 8 caption. For readability, it would be helpful to add the physical description of the PC1 and 2 axes (as you did in the main text around line 355) to the caption.

Thanks, we will add this to the caption:

"Scatter plot showing PC1 vs PC2 for (a) JJA and (b) DJF. Symbols show the values of each for the historical simulation. Grey lines extend from each symbol to the new PCs when $\chi$ from the SSP5-8.5 simulation (where available) is projected onto the historical EOFs. Black vertical and horizontal lines indicate the PC1 and 2 values obtained when ERA5's $\chi$ is projected into this space. In both seasons a positive PC1 indicates energy import into the Western North Pacific. A positive PC2 indicates enhanced MSE transport from the summer to the winter hemisphere, i.e. a cooler (warmer) Southern Hemisphere in JJA (DJF)."

Around line 360. You add the ERA5 PCs on figure 8. Can you specify how this is done? For the model EOF, you subtract out the multimodel mean prior to the EOF. For ERA5, do you also subtract out the multimodel mean from it and then project the difference on EOF1/2?

Thanks for highlighting that this was unclear, your guess is correct, the multimodel mean is subtracted from ERA5, treating it as if it is an additional model in the analysis. A subsection will be added to the methods section explaining the projections of ERA5 and *SSP5-8.5* onto the *historical* EOFs.

**Reviewer 2**

Geen et al. document the energy flux potential simulated by CMIP6 models and attribute it to the component caused by radiative, latent heat, and sensible heat fluxes. They provide a comprehensive diagnosis of the historical energy flux potential and its future changes under the SSP5-8.5 scenario, analyzing both model means and inter-model spreads across the JJA and DJF seasons. Through diagnostics in the PC space, the authors find that models with similar historical distributions of energy flux potential can be driven by different underlying mechanisms. When the anomalies in the SSP5-8.5 simulations are projected onto the historical EOF modes, similar energetic pathways of change emerge across different model families.

Understanding the spatial distribution of energy budget is fundamental to the energetic framework and energy-circulation coupling studies; the diagnostics provided in this study will be helpful to future research in this field. In addition, the findings that different model families can share similar energetic pathways under the SSP5-8.5 scenario provide valuable insights into future climate projections. The manuscript is well-written and properly structured. A few points are listed below, which should be addressed prior to publication.

**General comments:**

- The clarity of the methodology needs to be enhanced. For instance, the definition of 'pr-lat' in Fig. 3 could not be found.

pr-lat is defined as the latitude of the maximum zonal mean precipitation. When evaluating it, the zonal mean is first taken, and precipitation is then interpolated to a 0.01-degree resolution. We apologize for this omission. In response to your comment below, we have also now checked the precipitation centroid between 20°S and 20°N, and the precipitation asymmetry between the two hemispheres. The precipitation centroid will be added to Fig. 3, and a section explaining the precipitation latitude quantification will be added to the methods section.

Furthermore, the specific procedures and details regarding the EOF analysis are not clearly explained. I believe that the model-mean signal was subtracted prior to the EOF analysis (otherwise, EOF1 would simply capture the JJA/DJF model-mean climatology), but it is not mentioned explicitly in the text. Additionally, the procedures for projecting the SSP5-8.5 and ERA5 data onto these EOFs need to be clarified, particularly regarding whether any mean values were subtracted prior to projection. I suggest adding a subsection on the EOF procedures in the Methodology section

For the EOF analysis, we agree with the reviewer's point, and a subsection will be added to the revised manuscript explaining this.

- At times, the paragraph breaks seem a bit too frequent to me, making the text feel slightly fragmented. Consolidating these into cohesive paragraphs would enhance readability. For instance, in section 3.2, consider merging the paragraphs starting at line 186 and 191, as well as those at line 195 and 199.

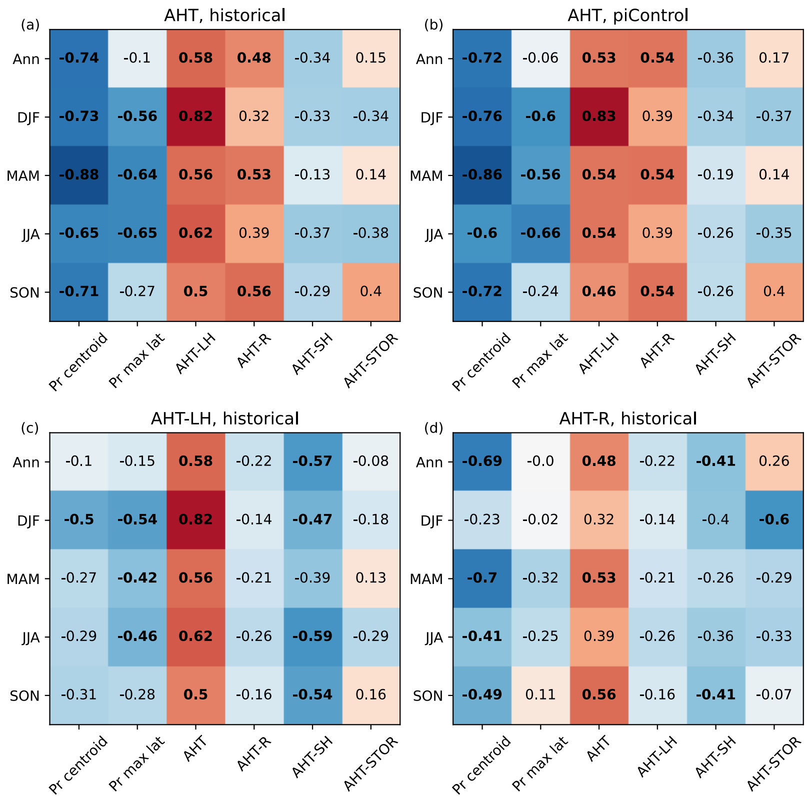
Thank you for this suggestion, we will adjust the text accordingly throughout the paper.

**Specific comments:**

- **Fig. 3:**

I was surprised to find no correlation between annual-mean pr-lat and AHTeq, given that the correlations are generally high for annual-mean anomalies in response to external forcing (e.g. Donohoe et al. 2013, Schneider et al. 2014). Is this attributable to the definition of pr-lat, or does the link between pr-lat and AHTeq simply fail to explain the climatology model spread? Specifically, I wonder if the correlation would improve if alternative metrics were used instead, such as the precipitation centroid (Frierson and Hwang 2012, DOI: https://doi.org/10.1175/JCLI-D-11-00116.1) or the precipitation asymmetry (i.e., precipitation in the NH tropics minus the SH tropics).

Thank you for highlighting this point. We used the precipitation centroid during preliminary analysis of a subset of the models. We discarded this as we found a weak relationship with AHTeq compared with using precipitation maximum latitude and interpreted this as the centroid latitude being too strongly altered by remote precipitation. However, we have now checked both precipitation centroid and asymmetry for the full set of models. With the precipitation centroid, we find much stronger correlations across the year with AHTeq, alongside weaker correlation with AHTeq-LH. We have checked both latitude indicators against the zonal mean distribution of precipitation. As the two measures give different but consistent results across *historical* and *piControl*, both will be included in the revised paper and a brief discussion added, see sample figure below.




- **Line 358-359: "As would be expected, models from the same family tend to be located near to one another in the PC space in both JJA and DJF."**

Can you specifically point out how do we get this conclusion in Fig. 8? Because it is not very obvious to me.

Looking at Fig 8, we find that, in general, models from the same center appear in a similar region of the PC space, e.g. for models 11-13 from CNRM, 23, 24, 39 & 40 HadGEM/UKESM, 32 & 33 MPI-ESM1, etc. This is not always the case, but is broadly true, and intuitive given similarity between model resolutions/versions from the same center. This will be clarified in the revised paper, and this statement reworded to refer to modelling center rather than to family:

"As would be expected, models from the same **modeling center** tend to be located near to one another in the PC space in both JJA and DJF, **for example the HadGEM and UKESM models.**"

- **Line 403: “Hierarchical clustering was performed across the first 3 PCs of χ and latent heat, sensible heat and radiative input terms.”**

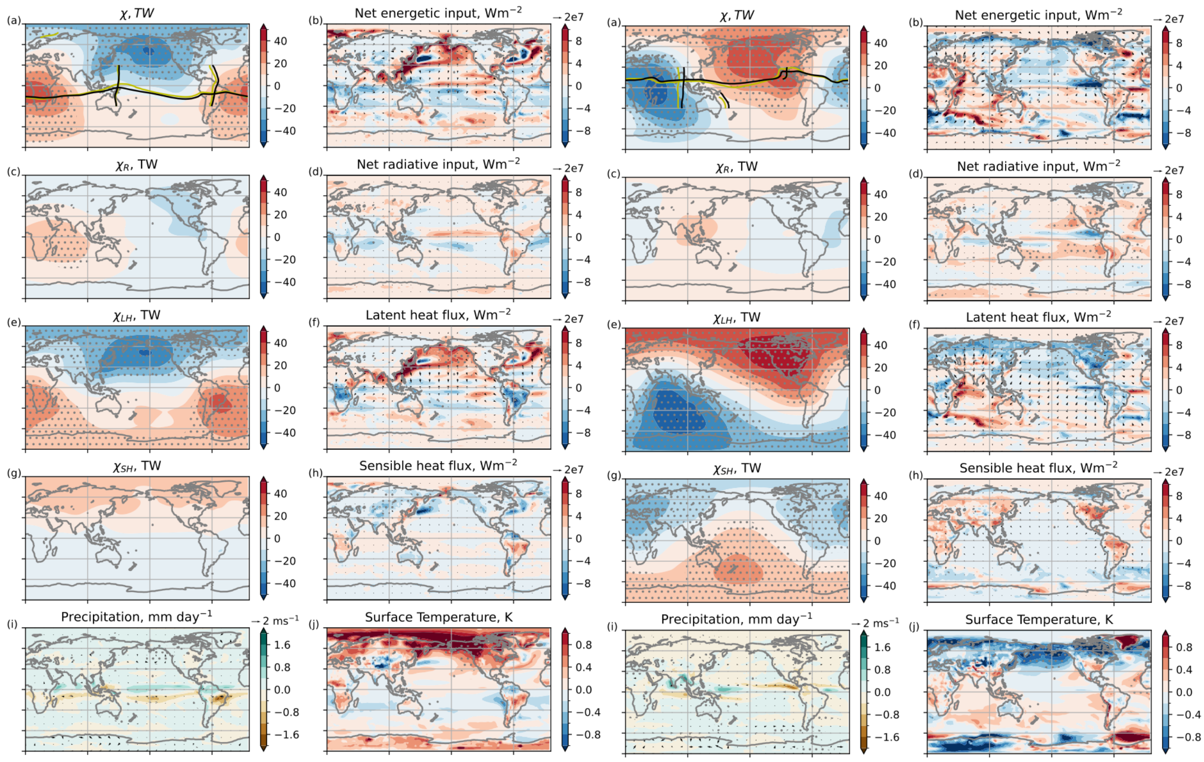
Are you applying hierarchical clustering to the projections of SSP5-8.5 anomalies onto the first 3 EOF modes? So that you are grouping models with similar impacts of climate change to the EOF modes in the historical seasonal cycle?

That is correct, this will be clarified in the revised paper:

“In order to group together models with similar changes in both $\chi$ and the relevant fluxes, we apply hierarchical clustering using 12 values as features: the first 3 PCs of total $\chi$, and the first 3 pseudo-PCs of the breakdown of $\chi$ by latent heat, sensible heat and radiative input (see Fig. B9 for JJA's PC3).”

Also, what is the pattern of the third EOF mode? It should at least be demonstrated in Supplementary if this is important for the results of hierarchical clustering.

The third EOF mode is shown below for DJF (left) and JJA (right), and will be added to the Appendix. PC3 acts as a dipole between the North Pacific and southern Atlantic, with centers offset from both PC1 and PC2. This is linked to 16.4% and 10.6% of variance in JJA and DJF respectively, these values will be noted in the figure captions.




- **Fig. 12**

I feel the methodology of projecting the anomalies in SSP5-8.5 onto the EOF modes requires careful interpretation, as it may mislead readers into thinking that the model spread in climate change responses can be largely explained by the strengthening or weakening of seasonal EOFs; this requires thorough clarification.

The first two EOF modes represent the north-south asymmetry and east-west dipole, respectively, and I suspect that the third EOF simply represents another east-west dipole with a 90-degree phase shift compared to EOF2. In this case, these EOF modes collectively provide a spatial basis that can describe any wavenumber-1 structure. As the energy flux potential usually exhibits a spatial structure of wavenumber 1 or 2, it is not surprising that the first three EOF modes can adequately describe its overall pattern and thus be used for model selection in hierarchical clustering. However, replacing these three EOF modes with any arbitrary spatial basis that captures a wavenumber-1 structure might yield similar results. Therefore, this mathematical alignment does not necessarily support a physical linkage between the seasonal model spread and future climate change responses.

Thanks for raising this important point. Our intention was to use this basis to give a reduced dimension interpretation of how the models EFP changes under SSP585, and to use this space to help visualize how different components of the NEI change in each model, rather than to indicate a physical linkage between the seasonal model spread and future change. However, we can see that this could easily confuse readers. We will highlight this in the revised version, noting that this basis is used as a low dimensional representation of the model changes, and to illustrate the decomposition, rather than implying a physical linkage:

"Note also that we do not mean to imply a physical linkage between the historical JJA intermodel spread and future climate change responses, but only to use this as a low-dimensional basis to visualize the different model responses."

**Comments to figures:**

- **Figs. 9, 11:**

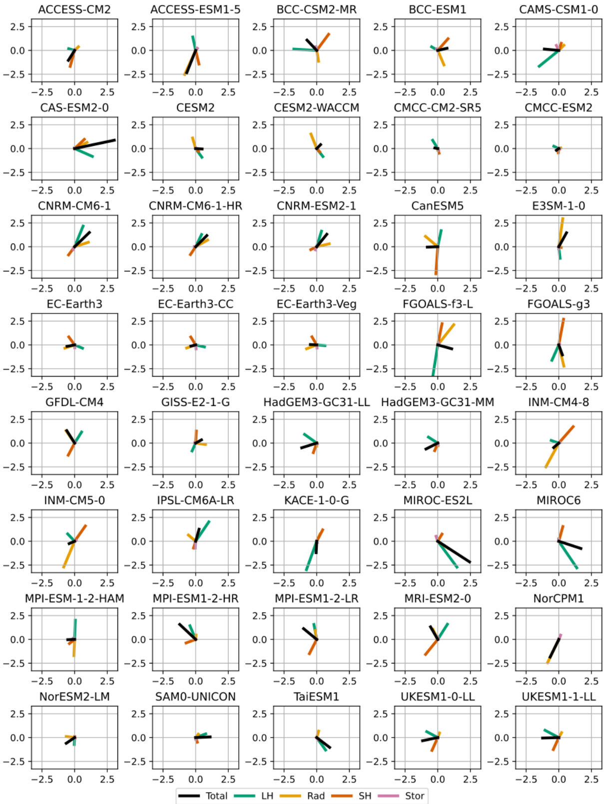
The red, orange, and magenta lines are hard to distinguish. Please consider change the colors, and also make the lines thicker so that the readers can recognize each line easily.

The colors and shapes of the symbols are a bit distracting. As the model name is already on the top of each panel, a black dot should be enough.

Consider add a legend below the figure, showing the corresponding components of each line.

We have made the above adjustments and show samples of the revised figures that will be used in the updated manuscript below.

We hope that the thicker lines and change to yellow, red and lilac helps in distinguishing these lines better. Additionally, here, and in a revision to Fig. 1, colors have now been selected from the Okabe Ito palette, to enhance accessibility.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BCC-ESM1
CAMS-CSM1-0
CAS-ESM2-0
CESM2
CESM2-WACCM
CMCC-CM2-SR5
CMCC-ESM2
CNRM-CM6-1
CNRM-CM6-1-HR
CNRM-ESM2-1
CanESM5
E3SM-1-0
EC-Earth3
EC-Earth3-CC
EC-Earth3-Veg
FGOALS-f3-L
FGOALS-g3
GFDL-CM4
GISS-E2-1-G
HadGEM3-GC31-LL
HadGEM3-GC31-MM
INM-CM4-8
INM-CM5-0
IPSL-CM6A-LR
KACE-1-0-G
MIROC-ES2L
MIROC6
MPI-ESM-1-2-HAM
MPI-ESM1-2-HR
MPI-ESM1-2-LR
MRI-ESM2-0
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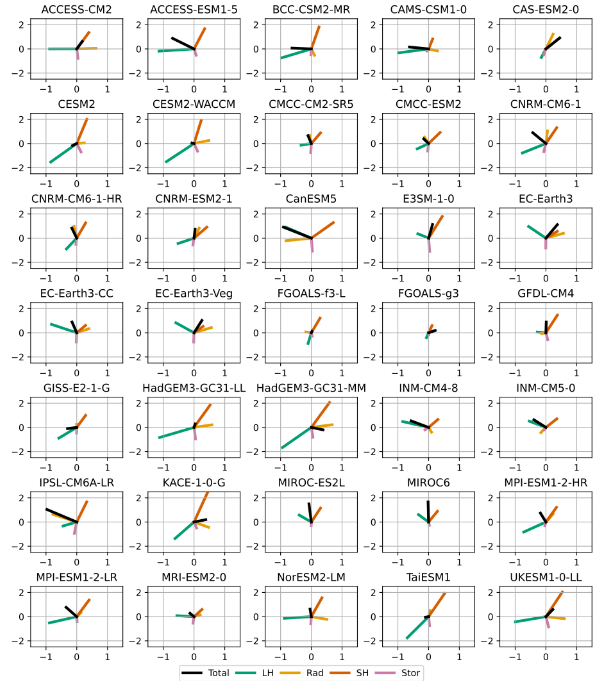
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CAS-ESM2-0
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CESM2-WACCM
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CMCC-ESM2
CNRM-CM6-1
CNRM-CM6-1-HR
CNRM-ESM2-1
CanESM5
E3SM-1-0
EC-Earth3
EC-Earth3-CC
EC-Earth3-Veg
FGOALS-f3-L
FGOALS-g3
GFDL-CM4
GISS-E2-1-G
HadGEM3-GC31-LL
HadGEM3-GC31-MM
INM-CM4-8
INM-CM5-0
IPSL-CM6A-LR
KACE-1-0-G
MIROC-ES2L
MIROC6
MPI-ESM1-2-HR
MPI-ESM1-2-LR
MRI-ESM2-0
NorESM2-LM
TaiESM1
UKESM1-0-LL
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