

Reduced Asian monsoon influence on Mediterranean summers in a warmer climate

Corresponding Author: Professor Tianjun Zhou

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Review of Article "Impact of Asian monsoon on Mediterranean summer climate will fade away in a warming world"

by H. Yu, T. Zhou and Z. Guo

This study investigates the future evolution of the "Monsoon-Desert" mechanism based on the analysis of 40 ensemble members from CESM1. In the present climate subsidence is observed throughout the tropospheric column due to the interaction of mid-latitude westerlies with the zonally asymmetric thermal structure produced by intensive convective activity over South Asia. Steep sloping isentropes that develop over the eastern Mediterranean facilitate subsidence in the western and northern periphery of the structure which is exposed to westerlies. The authors conclude that the intensity of the mechanism will fade away in a warming world because the thermal structure will amplify and expand westward resulting in the levelling of the isentropes over the Mediterranean.

The topic is timely and relevant, and the study has the potential to make a valuable contribution to ongoing research; it is therefore suitable for publication in Nature Geosciences. However, I am confused about certain aspects of the investigation concerning the role of the mid-latitude westerlies/subtropical jet in the formation of subsidence over the Mediterranean. The authors quantify cross-contour flow (CCF) by using wind and pressure data on the isentropic surface of 325 K. During boreal summer, this surface lies at around 500 hPa but in several places in the manuscript, the authors claim that they study the role of the subtropical jet in shaping CCF. Similarly, there is widespread confusion with respect to the role of the mid-latitude westerlies. Also, although the manuscript is generally well written and the results illustrated in figures of adequate quality, the parts of the manuscript referring to moist static energy and the contribution of westerlies in CCF need to be rewritten and certain aspects of the results clarified. I recommend that the authors consider the comments and corrections listed below.

Major comments

1) "Monsoon-related" impact on the vertical velocity over the Mediterranean:

The authors present a series of plots following regression of pressure vertical velocity, precipitation etc on a standardized timeseries representing the interannual evolution of monsoon strength. If I can correctly interpret Fig. 1a, it illustrates regression coefficients that represent anomalies in pressure vertical velocity (hPa/hr) associated with a one-standard-deviation increase in the South Asian monsoon diabatic heating index. In the present climate (1950-1999), an increase in monsoon intensity by one standard deviation can cause an increase in subsidence over the Mediterranean by up to ~0.18 hPa/hr (or 0.3 Pa/min), as shown in Fig. 1a. During boreal summer, the climatologically observed pressure vertical velocity at 500 hPa is ~4.2 hPa/hr (or 7 Pa/min) showing a maximum in the vicinity of Crete, Greece (see for example Fig 1b in Gandham et al 2025). This implies that during summers of a moderately stronger monsoon by one standard deviation, the increase in subsidence over the Mediterranean reaches around 5% of the climatologically observed values.

a) In the light of the above, can we consider the impact of the monsoon at interannual timescales significant for the Mediterranean area?

b) There is convincing evidence in this study that the above-mentioned impact will fade away in an environment of a strengthening monsoon, but will this make an actual difference for the Mediterranean climate? The climatologically observed subsidence is much stronger than the projected changes.

c) Regarding the spatial pattern of the impact shown in Fig. 1a, I note that the maximum impact is found over the Levante and not over Greece, as climatologically observed (see again Fig. 1b in Gandham et al 2025). Can the authors comment on this?

2) Comparison with the subsidence calculated due to isentropic down gliding:

The monsoon-related subsidence is also assessed following the calculation of the cross-contour flow at the surface of 325 K

which represents vertical motion at around 500 hPa. In Fig. 2a, the authors do not show the monsoon-related subsidence due to isentropic gliding, for the present time as in Fig. 1a for direct comparison. But it is obvious that at least for the future period 2050-2099 the signal is 10 times stronger in Fig. 2b compared to Fig. 1b.

a) Could the authors prepare the monsoon-related signal for subsidence (calculated using CCF) for the same period 1950-1999 (Fig. 2a) for direct comparison and comment on the differences?

b) Why does the monsoon-related signal calculated with CCF appear to be an overestimation compared to the actual monsoon-related signal calculated directly from pressure vertical velocity data? What other processes could mask subsidence coming directly from isentropic gliding?

c) L82-83: Is it possible to compare the ensemble mean of vertical velocity at 500 hPa (JJA) with the ERA5 counterpart? That would be proof that the model can capture subsidence over the Mediterranean during the summer.

3) The role of the mid-latitude westerlies and the subtropical jet in shaping the zones of subsiding air over the Mediterranean:

Perhaps I am missing something, but I am confused by the role of the subtropical jet and the mid-latitude westerlies in the calculation of CCF as a proxy for subsidence.

a) L106-126: Here (e.g. L111 & 114) it is mentioned that "Here, the descending anomaly is generated by the subtropical jet that glides along the tilted isentropic surface and crosses the isobaric contours, also known as the cross-contour flows (CCF)."

Indeed, the isentropic surface 325 Kelvin is found at around 500 hPa. As a result, the calculation of CCF with wind and pressure data on 325 K cannot be representative of how air within the subtropical jet downglides along the sloping isentropes. The subtropical jet over the eastern Mediterranean is found much higher at around 200-250 hPa and not at 500 hPa.

In fact, the air sloping down the isentropic surface of 325 K is of mid-latitude origin and is not related to the subtropical jet. See for example section 3c in Rodwell and Hoskins (1996).

b) L125, 141 & 143: Do you refer here to mid-latitude westerlies or again the subtropical jet?

c) L200-210: This paragraph is very confusing. Where are on Fig. 4 the subtropical jet and the mid-latitude westerlies? It is not clear to me what is shown on Fig. 4 and where is the northward displacement over the jet (subtropical jet?) entrance over the eastern Mediterranean.

d) L204-206: The connection with ENSO is not convincing. Please remove this part or present more evidence to support the argument.

4) Calculation of CCF:

L337-359: In the formula used for the calculation of CCF the horizontal wind is used on the 325 K surface. Therefore, I do not understand why the authors insist on mentioning that "in this paradigm, the strength of vertical motion is proportional to the magnitude of the westerly wind that crosses the isobaric contours (i.e. cross-contour flows, CCF)."

Here and elsewhere in the text, the authors should make sure that they do not refer only to the westerly flow because the vertical motion is proportional to the magnitude of the horizontal wind that crosses the isobaric contours.

5) Significant northerly component of the flow related to the observed subsidence:

In continuation to the previous comment, it should be mentioned that at ~500 hPa the flow is not only westerly, but it has a significant northerly component. See for example Fig. 3b in Tyrlis et al (2013). Given that the thermal structure has a significant structure also in the meridional direction over the Mediterranean with sloping isentropes (see Fig 4 in Tyrlis et al 2013), the contribution of the northerly flow in the isentropic downgliding is also important. This northerly flow is caused by the orography over the region (see section 3b in Rodwell and Hoskins 1996) and is responsible for producing maxima of subsidence over Crete and the Aral Sea.

In this study the structure of the thermal anomaly in the meridional direction is not studied. I urge the authors to include in the discussion the role of the northerly flow and investigate how the thermal structure is expected to change in the future also in the meridional direction.

6) Diagnosis of Moist Static Energy:

L174-176: I do not understand this sentence. What does increase nearly uniformly in the vertical profile due to moist adiabatic adjustment? Please rephrase.

L182-192: Although I understand the method section, I find it difficult to follow this part of the document. Please rewrite and focus on the main results that need to be conveyed.

Minor comments

1) L8 & L27: "over Mediterranean" -> "over the Mediterranean"

2) L28: What is the meaning of "by storm track and synoptic systems"?

3) L33: What is the meaning of "counterpart of the mid-level subsidence"?

4) L34: "eastern Mediterranean" -> "over the eastern Mediterranean"

5) L34-35: How is the Etesians related to extreme climate events mentioned here? Please clarify.

6) L76: "faithful" -> "accurate"

7) L76-80: This sentence is long and confusing. Please rephrase.

8) Caption of Fig. 5: Panel c is not adequately described. In general, the authors should try to make all captions more detailed.

9) L256-257 & L280: Claiming that the fading away of the monsoon-Mediterranean link is the result of anthropogenic warming may require a more in-depth investigation of the link by employing more sophisticated attribution methods.

10) L335: "over SASM region" -> "over the SASM region".

11) L330: Could you please clarify whether you used individual monthly timeseries in the analysis or seasonal (JJA) mean

timeseries.

12) L342: This sentence is confusing. Please rephrase.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)

The present paper analyses the teleconnection between the South Asian summer monsoon (SASM) and the Central-to-Eastern Mediterranean (CEM) summer climate, and its response to climate change under the Representative Concentration Pathways (RCP) 8.5 scenario. The analysis is based on the Community Earth System Model version 1 (CESM1) large ensemble of historical+RCEP8.5 simulations (40 members, period 1920-2100). The authors show that the teleconnections significantly weakens by the end of the 21st century under the RCP8.5 and in the CESM1 large ensemble, and argue that it is related to the SASM intensified tropospheric heating, which modifies the monsoon large-scale thermal structure, and to the SASM increased interannual variability.

Though the authors' conclusions are rather well supported by the analysis, I argue in the attached document that the paper deserves further significant work to be considered for publication in Nature Geoscience.

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Second review of Article "Impact of Asian monsoon on Mediterranean summer climate will fade away in a warming world"

by H. Yu, T. Zhou and Z. Guo

The authors have made a substantial effort to address in detail all comments and issues raised by both reviewers during the first round of revisions. As a result, the quality and scientific merit of the manuscript have improved considerably. In addition, the authors have included new analyses and results, such as the decomposition of the CCF into zonal and meridional components and a discussion of the Sverdrup balance over the Mediterranean. While these additions are potentially important, their presentation and interpretation could be further clarified. I therefore recommend that the authors carefully consider the comments and suggestions listed below.

Major comments

1) "Local contribution from dynamical feedback":

L208–232: This section introduces new analysis and results; however, the presentation is somewhat unclear. I found the description difficult to follow even after multiple readings, and I believe that a general reader may struggle to grasp the main message, particularly in the second paragraph.

a) L213–215 and Fig. 4b:

The SASM–V500 signal shows a southerly flow over the core CEM region, particularly near the area of maximum climatological subsidence over Greece. I find this result difficult to interpret. Does this imply that, in the future period (2050–2099), a stronger SASM is associated with weaker northerlies at the margins of the CEM box but southerlies in its centre? The authors are encouraged to elaborate on the physical interpretation of this pattern.

b) L224–225:

The reference to 88% is unclear. Please clarify what this percentage represents and rephrase accordingly. In addition, the meaning of the symbols c^* and ω^* should be explicitly defined.

c) Fig. 4d:

It is not clear whether the two terms in the Sverdrup balance shown in the bar plot correspond specifically to the SASM-related signal. This ambiguity complicates the interpretation of the results. If the Sverdrup balance holds, one would expect the magnitudes of the two terms to be comparable. Why, then, does the discrepancy between the two bars increase in the future period?

Overall comment:

The discussion in this section requires substantial clarification. At present, the main message remains unclear. What exactly is meant by "local contribution from dynamical feedback"? My understanding is that the authors attempt to distinguish between processes acting in the

zonal direction (e.g. modification of the thermal structure and weakening of subsidence) and those acting in the meridional direction, seemingly treating them as independent. If this interpretation is correct, it should be stated more clearly; otherwise, the section would benefit from a thorough rewrite to better convey the underlying physical mechanisms.

2) Argument involving the Rossby radius of deformation:

L179–183:

I find the discussion difficult to follow, particularly the motivation for invoking the Rossby radius of deformation. In mid-latitudes, weather systems tend to have scales comparable to the Rossby radius because baroclinic instability grows most efficiently at that scale. However, it is not clear how this concept applies to the case of monsoon-related deep moist convection discussed here. The authors should clarify the relevance and physical interpretation of the Rossby radius in this context.

3) L101: The statement appears inaccurate. The SASM-related vertical motion remains positive over the western and northern parts of the CEM box. Please revise accordingly.

Minor comments

1) L57, 81 and elsewhere: it should read “timescales”

2) L108: Have the authors checked the only ensemble member that differs? It may reveal a different but yet interesting view on the SASM-Mediterranean circulation.

3) L160-162: I cannot see the relevant information on Fig. 6.

4) L179: “Why does SASM-related” -> “Why does the SASM-related”

5) L218: “Fig. 6e” -> “Fig. 7e”. Please check all references to the extended figures because there are some mistakes.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)

I reviewed the first version of the manuscript. The authors provide thorough and convincing responses to all the points I had, as well as to those of the other reviewer. In particular, I appreciate the addition of CMIP6 models' simulations, further theoretical arguments and numerical experiments based on a linear baroclinic models. They all do provide the appropriate robustness of the authors' results and enhance their physical interpretation. Besides, I find that the manuscript has been significantly clarified. Thus, following this first round of reviews, I think the manuscript is almost ready for publication, pending to the very few minor comments provided in the attached document.

(Remarks on code availability)

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I thank the authors for their careful and thorough responses to my comments in the previous rounds of review. The authors have adequately addressed all of my concerns and have made the necessary revisions. I have no further comments or suggestions. In my opinion, the manuscript is now suitable for publication in its present form.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)

The authors did answer well the comments of my second review, and I thank them for their detailed responses. I also think they did answer well to the comments of Reviewer #1. Therefore, I recommend publication of the manuscript pending to the correction of the following two very minor details:

- Extended Data Fig. 5: Qp in panel (f) should be replaced by Q1 for consistency with the rest of the manuscript
- p25, l487: I would use the plural form of area in its two occurrence.

(Remarks on code availability)

The authors wrote that the code is "available on request from the corresponding author." I haven't been able to access the code and thus did not review it.

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Title: Impact of Asian monsoon on Mediterranean summer climate will fade away in a warming world

Authors: H. Yu, T. Zhou and Z. Guo

Overview and major comments

The present paper analyses the teleconnection between the South Asian summer monsoon (SASM) and the Central-to-Eastern Mediterranean (CEM) summer climate, and its response to climate change under the Representative Concentration Pathways (RCP) 8.5 scenario. The analysis is based on the Community Earth System Model version 1 (CESM1) large ensemble of historical+RCEP8.5 simulations (40 members, period 1920-2100). The authors show that the teleconnections significantly weakens by the end of the 21st century under the RCP8.5 and in the CESM1 large ensemble, and argue that it is related to the SASM intensified tropospheric heating, which modifies the monsoon large-scale thermal structure, and to the SASM increased interannual variability.

Though the authors' conclusions are rather well supported by the analysis, I argue hereafter that the paper deserves further significant work to be considered for publication in *Nature Geoscience*. My main concerns follows:

1. The authors base their conclusion on a single model. Though CESM1 captures rather well the present-day SASM-CEM teleconnection, it does not mean that its response is certain. Considering the authors' statements and the high standard of *Nature Geoscience*, I think the study needs to assess the response of the teleconnection in a wider set of models such as the CMIP6 ensemble. This would help the authors to make a better assessment of the robustness of their results.
2. At lines 265-266, the authors mention a divergent consensus among previous studies: why previous studies are divergent? How the present study would yield a more convergent consensus? Or does it just increase the diversity of results? The authors need to more clearly position their results with respect to previous works.
3. To fully argue the importance of the SASM-CEM teleconnection response under global warming onto the CEM summer climate response

(e.g., statement at lines 270-272), it needs to be positioned with respect to the total response. E.g., how big is the teleconnection contribution to interannual variability of precipitation in the region? What are the implications of a weakened teleconnection for the CEM precipitation response (mean state and its interannual variability)?

4. The wording used by the authors is not fully appropriate. They tend to claim of cause-and-effect relationship between SASM and CEM, while they only document a teleconnection. A teleconnection is primarily a correlation between two regional climate variables or set of variables, which does not a priori imply a causal link. Of course, mechanisms can be speculated, and those mechanisms may imply a causal link. Nevertheless, because the authors' analysis uses fully synchronous correlation between the two regions, I suggest to tone down the causal relationship, and thus possibly to solely refer to the SASM-CEM teleconnection (instead of e.g., "monsoon-induced Mediterranean circulation"). Similarly, the gliding mechanism the authors invoke in their analysis is fully consistent with either a change in the monsoon thermal structure induced by the SASM amplification, or a change in the CEM circulation due to another large-scale response that would affect the monsoon thermal structure. The diagnostic thus do not obviously emphasise a causal link.
5. I have been rather confused all along the text between field anomalies and mean state and the interpretations that goes with them. I feel both aspects, i.e. mean state response to global warming and response of interannual variability, are important but need to be further documented as well as how the response of both of them contribute to the response of the SASM-CEM teleconnection. So far, I cannot find a picture emerging clearly-enough from the paper.
6. The interest of using the CESM1 large ensemble is the possible assessment of the role of internal variability in the SASM-CESM teleconnection under present-day conditions and its response under the RCP8.5 scenario. I feel this aspect is underused in the analysis.

More minor comments

1. Though I am not an English-native speaker, I feel the text contains a lot of grammatical errors and inappropriate formulations. I suggest the authors' to ask a English-native speaker to carefully read and correct the paper.
2. The authors used the atmospheric diabatic heating Q_1 as an indicator of the SASM intensity. It is, expectedly, very well correlated to

the SASM precipitation. Why not using directly used precipitation? Besides, which model output frequency is used to estimate Q_p as a residual (l. 319)? If not using high-frequency data (e.g., 6-hourly or less), how reliable is the estimated Q_p ? Note also that Q_1 often refer to the heating profile in the literature. A notation such as $\overline{Q_1}$ for its vertical integral seems more appropriate to reduce confusion.

3. I think the gliding mechanism is insufficiently or inadequately illustrated. Maps of pressure on an isentropic level, together with horizontal wind speed and vertical velocity, would clearly help fully capture the mechanism, and assess how the change in mean state impacts the mechanism. In particular, I did not have really understood whether the gliding mechanism changes because of the mean state response or because of the response of the interannual variability pattern.
4. The moist static energy analysis does not seem to add much to the temperature analysis. I would suggest to remove it. Or the authors need to provide a deeper analysis that illuminates the SASM-CEM teleconnection response to global warming.
5. line 34: “As a result”: the causal relationship with what precedes is unclear.
6. line 36: “matter of urgency” (same with e.g., “critical issue” at l. 54): why is it so urgent? How would a better understanding of the CEM dynamics help better understand (or predict) extreme events? The authors must either provide more arguments for using this formulation or just avoid this kind of subjective phrasing. There is enough scientific interest to study the subject of the paper.
7. line 148: “expands increasingly westward with height”: unclear formulation.
8. line 238: “33 out 40 members”: What does it mean? Is it the number of members that simulate a decrease of the explained variance? or a significant decrease of these explained variance? A level of significance on Figure 5.d would be useful.
9. line 268: have the authors quantify the SASM-CEM teleconnection weakening onto the Etesian winds variability?
10. line 278: How sure are the authors that the SASM-CEM teleconnection has remained stable in the present day climate? What do they mean by present day? What is the internal variability of the teleconnection intensity?

11. Fig. 1: not fully clear how to quantitatively interpret it. I understand that the authors plot a regression of the 500-hPa vertical velocity on a normalized SASM interannual index based on Q_1 ? Would units in something like hPa/hr per W/m^2 provide a better quantitative analysis? What are the typical interannual variations of SASM Q_1 ? Besides, can the authors add a level of significance (e.g., 95%) on panel (d)?
12. Fig 5: how does this impact of the SASM-CEM teleconnection on precipitation compares with the total CEM precipitation interannual variability? Isn't -4 mm/month small?
13. Extended Figure 3: the plot show the period 1975-2075, while the caption indicates 1920 to 2099.
14. Extended Figure 5: unclear what is the "zonal contrast of SASM-related air temperature anomalies.
15. Extended Figure 6: I was not convinced that this figure with potential temperature anomalies add much to the same figure with temperature anomalies (Fig. 3). I would keep only the potential temperature.

Reply to Reviewers #1:

Thank you for the valuable comments and comprehensive instructions on enhancing the manuscript. We sincerely appreciate the time and effort you dedicated to reviewing our work and providing us with insightful feedback. Your comments have been instrumental in significantly improving the manuscript's quality. To ensure clarity, we have highlighted your original comments in *italic font*, and our responses are presented in normal font below each comment.

1) “Monsoon-related” impact on the vertical velocity over the Mediterranean:

The authors present a series of plots following regression of pressure vertical velocity, precipitation etc on a standardized timeseries representing the interannual evolution of monsoon strength. If I can correctly interpret Fig. 1a, it illustrates regression coefficients that represent anomalies in pressure vertical velocity (hPa/hr) associated with a one-standard-deviation increase in the South Asian monsoon diabatic heating index. In the present climate (1950-1999), an increase in monsoon intensity by one standard deviation can cause an increase in subsidence over the Mediterranean by up to ~0.18 hPa/hr (or 0.3 Pa/min), as shown in Fig. 1a. During boreal summer, the climatologically observed pressure vertical velocity at 500 hPa is ~4.2 hPa/hr (or 7 Pa/min) showing a maximum in the vicinity of Crete, Greece (see for example Fig 1b in Gandham et al 2025). This implies that during summers of a moderately stronger monsoon by one standard deviation, the increase in subsidence over the Mediterranean reaches around 5% of the climatologically observed values.

a) In the light of the above, can we consider the impact of the monsoon at interannual timescales significant for the Mediterranean area?

Response:

Thanks for your question. Fig. 1 shows the response of vertical velocity to 1-std increase in South Asian Summer Monsoon (SASM) heating on interannual timescale.

For the background of exploring the significance of monsoon's impact on Mediterranean summer climate, a number of studies demonstrated that Mediterranean summer climate itself is characterized by significant interannual variability in terms of atmospheric circulation (Cherchi et al., 2014; Rizou et al., 2015; Barcikowska et al., 2020; Gandham et al., 2025, see their Fig. 3) and precipitation (Zveryaev and Allan, 2010; Campos et al., 2025; Vincente-Serrano et al., 2025). Given the current limitation in the understanding of interannual climate variability, we hope to emphasize the role of SASM by examining the ratio of SASM-induced ω_{500} to the total ω_{500} interannual variability over CEM.

Here, to quantitatively measure the contribution of SASM, we have estimated the ratio of Central-to-Eastern Mediterranean (CEM) vertical motion variance explained by SASM to its total variance on interannual timescale (Fig. R1). The explained variance is calculated as follows:

$$R_{CEM, SASM} = \frac{Var(\omega_{CEM}) - Var(\omega_{CEM, noM})}{Var(\omega_{CEM})} \times 100\%$$

Where $Var(\omega_{CEM})$ indicates the total variance of interannual component of CEM 500hPa vertical motion and $Var(\omega_{CEM, noM})$ refers to the variance of CEM vertical motion where the impact of SASM is linearly removed.

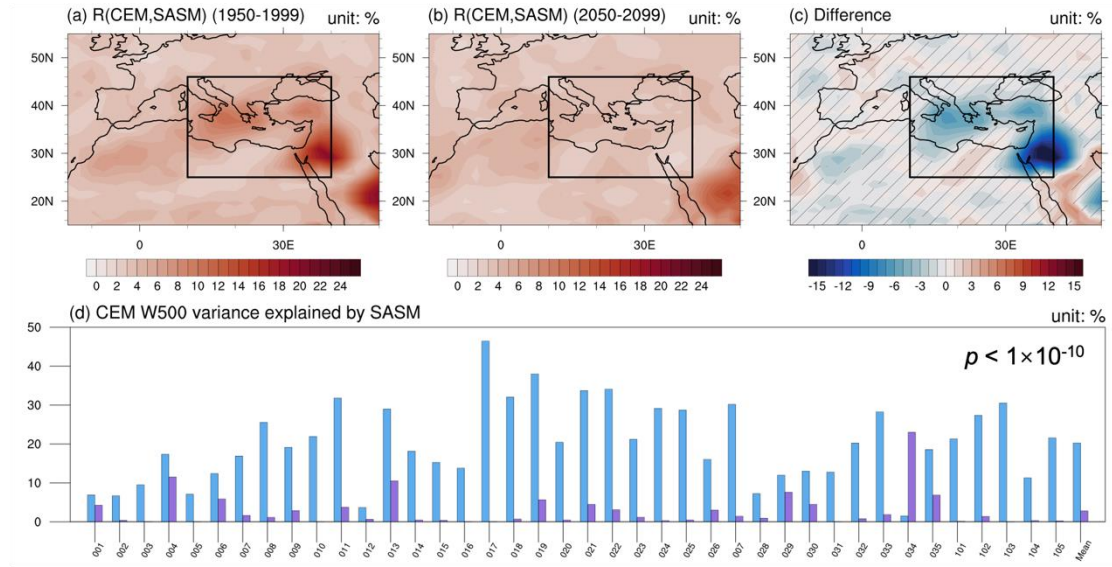


Fig. R1. Variance of CEM $\omega 500$ explained by SASM and its future change in Community Earth System Model Large Ensemble (CESM1LE). The spatial pattern of explained variance during (a) 1950-1999, (b) 2050-2099 under Representative Concentration Pathway 8.5 (RCP8.5) and (c) their difference. (d) The regional mean of explained variance over CEM is given in, with variance in the present (blue bars) and in the future (purple bars). Shadings in (c) represent area of changes not significant at 95% confidence level. The significance of change on explained variance is estimated using students' t-test.

It is evident in Fig. R1 that the variance of $\omega 500$ explained by SASM is significant during 1950-1999, with the local maximum over Levant and the vicinity of Greece (Fig. R1a). The regional mean of the variance over CEM is about 22% in terms of MME and can reach over 40% for individual members (Fig. R1d). These results indicate that the influence of SASM on Mediterranean summer tropospheric circulation is significant in present day. More importantly, the MME explained variance drops drastically to less than 3% under global warming, highlighting the vanished impact of SASM on CEM summer climate (Fig. R1c, d).

Please see **Line 104-105** and **Line 379-387** in the revised manuscript.

b) There is convincing evidence in this study that the above-mentioned impact will fade away in an environment of a strengthening monsoon, but will this make an actual difference for the Mediterranean climate? The climatologically observed subsidence is much stronger than the projected changes.

Response:

Thanks. The changes in mean state, extreme, and variability have been the research focus of climate change community. Here, we focus on the interannual climate variability. While the interannual variability cannot reshape the climate mean state, it is of great concern to society due to its large impact on water resources and ecosystem. For example, the effect of global warming on climate variability has been assessed in IPCC AR6 WGI (chapter 2 and chapter 4) and will continue to be assessed in both Chapter 3 and 7 of IPCC WGI AR7.

In our analysis, based on the variance analysis conducted to atmospheric circulation (Fig. R1) and precipitation (Fig. 5 in the revised manuscript), we found that global warming can significantly influence Mediterranean summer climate by reducing considerable portions of interannual variability explained by SASM (22% to 3% for vertical motion and 14% to 4% for precipitation). Our findings provide an example of evaluating the effect of global warming on climate variability.

c) Regarding the spatial pattern of the impact shown in Fig. 1a, I note that the maximum impact is found over the Levant and not over Greece, as climatologically observed (see again Fig. 1b in Gandham et al 2025). Can the authors comment on this?

Response:

Thanks. The mismatch between Fig. 1a in our manuscript and Fig. 1b in Gandham et al., 2025 can be explained by the difference between interannual variability and climatology. The maximum center of variability does not necessarily correspond to that of climate mean state spatially. The local maximum of climatological ω_{500} is observed in the vicinity of Crete, Greece (Fig. R2a and Fig. 1b in Gandham et al., 2025) in both ERA5 and CESM1LE, while the maximum centers of interannual variability are in Levant, Asia Minor Peninsula and the vicinity of Atlas Mountains (Fig. R2b, d).

The location of maximum climatological ω_{500} over Greece is the combined effect of adiabatic subsidence remotely induced by SASM (Rodwell and Hoskins, 1996; Tyrllis et al., 2013) and the diabatic enhancement induced by local air-sea feedback (Rodwell and Hoskins, 2001; Seager et al, 2003). Each of the two factors contribute to ~50% of the subsidence. This also explains why the climatological maximum is located above Mediterranean Sea rather than over land.

For the interannual variability, the SASM- ω_{500} connection is dominated by adiabatic subsidence (see the ratio of SASM-CCF to SASM- ω_{500} in Fig. 2e in the revised manuscript). The adiabatic response of tropospheric circulation to SASM over CEM is significantly influenced by topography (e.g. Zagros Mountain, Atlas Mountains) (Rodwell and Hoskins, 1996; Simpson et al., 2015). Thus, the locations of maximum response emerge in the vicinity of elevated mountains (Fig. R2b, d). The diabatic process only plays a minor role in the SASM-related response since the Sea Surface Temperature over Mediterranean Sea is not significantly correlated to SASM convection.

To conclude, the maximum of climatological ω_{500} located over Aegean Sea is a result of both adiabatic and diabatic process, while the center of interannual SASM- ω_{500} variability located over Levant and Asia Minor Peninsula is primarily resulted from adiabatic response. This phenomenon is consistent in ERA5 and CESM1LE simulations.

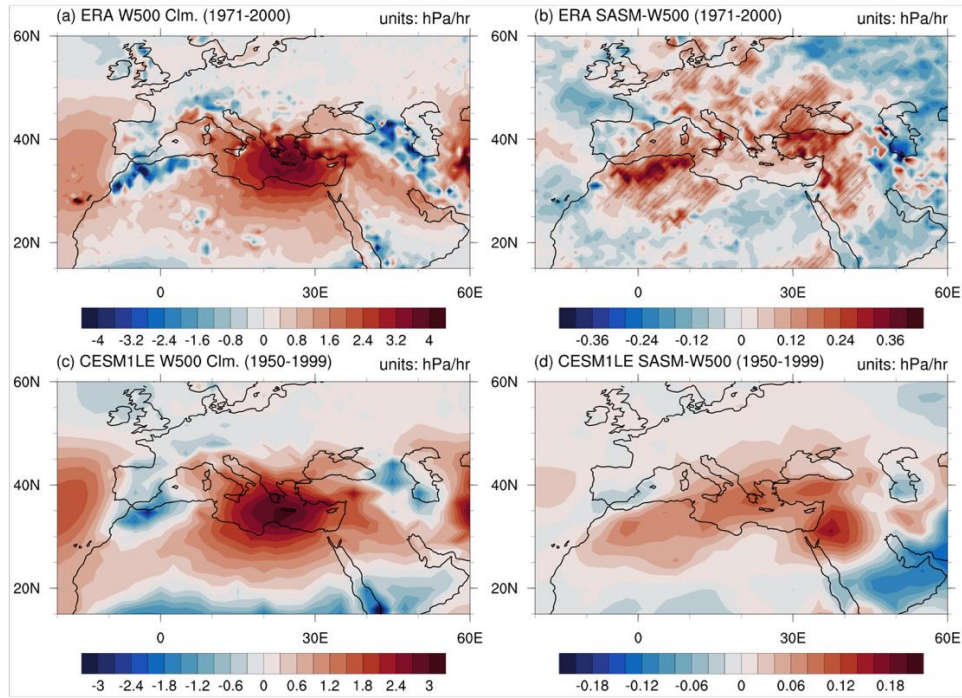


Fig. R2. JJA averaged (a) climatological ω_{500} and (b) SASM-related ω_{500} in ERA5 during 1971-2000. (c), (d): as in (a), (b), but for CESM1LE Multi-Member Ensemble Mean (MME) results during 1950-1999.

2) Comparison with the subsidence calculated due to isentropic down gliding:

The monsoon-related subsidence is also assessed following the calculation of the cross-contour flow at the surface of 325 K which represents vertical motion at around 500 hPa. In Fig. 2a, the authors do not show the monsoon-related subsidence due to isentropic gliding, for the present time as in Fig. 1a for direct comparison. But it is obvious that at least for the future period 2050-2099 the signal is 10 times stronger in Fig. 2b compared to Fig. 1b.

a) Could the authors prepare the monsoon-related signal for subsidence (calculated using CCF) for the same period 1950-1999 (Fig. 2a) for direct comparison and comment on the differences?

Response:

Thanks. As suggested, we have calculated the SASM-related Cross contour flow (CCF) during 1950-1999. Please see **Fig. 2a-c** and **Line 129-136** in the revised manuscript.

b) Why does the monsoon-related signal calculated with CCF appear to be an overestimation compared to the actual monsoon-related signal calculated directly from pressure vertical velocity data? What other processes could mask subsidence coming directly from isentropic gliding?

Response:

Thanks for your careful examination. We found that the units of CCF in the original manuscript were not marked correctly and have been corrected in the revised manuscript. We have used CCF at 330K (325K) during 2050-2099 (1950-1999) as the proxy of adiabatic subsidence to ensure that the isentropic level remains near 500hPa under global warming (The pressure on 325K isentropic surface is 550-600hPa during 2050-2099 over Mediterranean region). The results show that the change on SASM-CCF can explain about 78% of future change on SASM- ω 500 over CEM (see Fig. 2d, e in the revised manuscript).

Please see **Fig. 2d, e** in the revised manuscript for details.

c) L82-83: Is it possible to compare the ensemble mean of vertical velocity at 500 hPa (JJA) with the ERA5 counterpart? That would be proof that the model can capture subsidence over the Mediterranean during the summer.

Response:

Thank you for the suggestion. The comparison is presented in Fig. R2b and d. The spatial pattern of SASM- ω 500 matches well between CESM1LE MME and ERA5, with the maximum centers located over Levant, Southeastern Europe and Atlas Mountains. The correlation between CEM ω 500 and SASM heating is significant in both simulations and Reanalysis. The ensemble mean correlation coefficient is 0.41 ($p < 0.01$) in CESM1LE and 33 out of 40 members simulate correlation above 95% confidence level. For ERA5, the correlation coefficient is 0.43 ($p = 0.02$).

To conclude, these results indicate that CESM1LE can realistically simulate the CEM circulation response to SASM in comparison with ERA5.

3) The role of the mid-latitude westerlies and the subtropical jet in shaping the zones of subsiding air over the Mediterranean:

Perhaps I am missing something, but I am confused by the role of the subtropical jet and the mid-latitude westerlies in the calculation of CCF as a proxy for subsidence.

a) L106-126: Here (e.g. L111 & 114) it is mentioned that “Here, the descending anomaly is generated by the subtropical jet that glides along the tilted isentropic surface and crosses the isobaric contours, also known as the cross-contour flows (CCF).”

Indeed, the isentropic surface 325 Kelvin is found at around 500 hPa. As a result, the calculation of CCF with wind and pressure data on 325 K cannot be representative of how air within the subtropical jet downglides along the sloping isentropes. The subtropical jet over the eastern Mediterranean is found much higher at around 200-250 hPa and not at 500 hPa.

In fact, the air sloping down the isentropic surface of 325 K is of mid-latitude origin and is not related to the subtropical jet. See for example section 3c in Rodwell and

Hoskins (1996).

Response:

Thank you for the suggestion. The terms of both “subtropical jet” and “westerly jet” have been replaced with “mid-latitude westerlies” in the revised manuscript as suggested. The CCF at 325K (330K) isentropic level in the present (future) is determined by horizontal wind and horizontal temperature gradient at around 500hPa. The CCF can be further decomposed into a zonal component and meridional component, where the magnitude of zonal component is estimated based on zonal wind and zonal temperature gradient at around 500hPa. In the original manuscript, we refer the zonal wind to “subtropical jet” but it is in fact mid-latitude westerlies at 500hPa. This has been corrected now in the revision.

b) L125, 141 & 143: Do you refer here to mid-latitude westerlies or again the subtropical jet?

Response:

Yes. Corrected as suggested.

c) L200-210: This paragraph is very confusing. Where are on Fig. 4 the subtropical jet and the mid-latitude westerlies? It is not clear to me what is shown on Fig. 4 and where is the northward displacement over the jet (subtropical jet?) entrance over the eastern Mediterranean.

Response:

Thank you for the question. We guess that your concern refers to Fig. S4 in the original manuscript rather than Fig. 4. The zonal component of CCF is determined by both zonal wind (mid-latitude westerlies) and zonal temperature gradient. In the paragraph you mentioned above, we aimed to investigate the effect of SASM-U500 on CCF change. The figure used to explain this is shown in Fig. S4 in the original manuscript.

In the revised manuscript, we present the change of SASM-U500 in Extended Data Fig. 6. To evaluate the potential influence of SASM-U500 on the zonal component of CCF, we have calculated the future change of SASM-U500 over CEM (Extended Data Fig. 6c, d in the revised manuscript) and found no inter-member consensus ($p=0.6$). Therefore, we argue that SASM-U500 has little impact on the change of zonal component of CCF under global warming.

Please see **Line 160-162** in the revised manuscript for details.

d) L204-206: The connection with ENSO is not convincing. Please remove this part or present more evidence to support the argument.

Response: Removed.

4) Calculation of CCF:

L337-359: In the formula used for the calculation of CCF the horizontal wind is used on the 325 K surface. Therefore, I do not understand why the authors insist on

mentioning that “in this paradigm, the strength of vertical motion is proportional to the magnitude of the westerly wind that crosses the isobaric contours (i.e. cross-contour flows, CCF).”

Here and elsewhere in the text, the authors should make sure that they do not refer only to the westerly flow because the vertical motion is proportional to the magnitude of the horizontal wind that crosses the isobaric contours.

Response:

Thanks for your comments. Yes, the CCF comprises both zonal and meridional components and each of them should be considered. To quantitatively evaluate their contribution to CCF and thus to vertical motion, we have examined the magnitude of these 2 terms respectively and added the results of some new analyses. For detailed explanations, please see the response to the Comment below in item #5 and **Line 143-149** in the revised manuscript.

5) Significant northerly component of the flow related to the observed subsidence:

In continuation to the previous comment, it should be mentioned that at ~500 hPa the flow is not only westerly, but it has a significant northerly component. See for example Fig. 3b in Tyrllis et al (2013). Given that the thermal structure has a significant structure also in the meridional direction over the Mediterranean with sloping isentropes (see Fig 4 in Tyrllis et al 2013), the contribution of the northerly flow in the isentropic downgliding is also important. This northerly flow is caused by the orography over the region (see section 3b in Rodwell and Hoskins 1996) and is responsible for producing maxima of subsidence over Crete and the Aral Sea.

In this study the structure of the thermal anomaly in the meridional direction is not studied. I urge the authors to include in the discussion the role of the northerly flow

and investigate how the thermal structure is expected to change in the future also in the meridional direction.

Response: This is an excellent suggestion. We have added the analysis of northerly flow as suggested and indeed found its significant contribution. The details are outlined below.

The CCF is estimated following:

$$CCF = \vec{V}_i \cdot \nabla P_i = u_i \frac{\partial P_i}{\partial x} + v_i \frac{\partial P_i}{\partial y}$$
$$CCF_x = u_i \frac{\partial P_i}{\partial x}$$
$$CCF_y = v_i \frac{\partial P_i}{\partial y}$$

Where CCF_x and CCF_y represent zonal and meridional component of CCF, respectively. The subscript “i” indicates variables interpolated onto isentropic surfaces. Detailed explanation of isentropic gliding mechanism can be found in Methods section in the revised manuscript.

To quantitatively evaluate the respective contribution of CCF_x and CCF_y to $SASM-\omega 500$, we have examined their changes under global warming. The spatial pattern of $SASM-CCF$ resembles that of $SASM-\omega 500$ markedly (Fig. R3a-c and Fig. 1 in the revised manuscript). There are 38 out of 40 members that simulate decrease in $SASM-CCF$ under global warming and correlates significantly to the change of $SASM-\omega 500$ ($r=0.79$, $p<0.001$; Fig. R3d). In terms of MME, future change of $SASM-CCF$ explains ~78% of change on $SASM-\omega 500$, indicating that CCF is a proper proxy for the evaluation on monsoon-induced circulation change. Further decomposition suggests that the zonal and meridional component contribute to 43% and 56% to the total $SASM-CCF$, respectively (Fig. R3e). In addition, we have performed same analysis on 33 coupled models from Coupled Models Intercomparison Project Phase 6 (CMIP6) and found that the ratio becomes 61% and 38% (see Extended Data Fig. 4 in the revised

manuscript). Above results indicates that both zonal and meridional component are crucial in shaping the overall change of SASM-related CCF.

To further investigate the factors that lead to changes on CCF_x and CCF_y , we have examined the variations on horizontal wind and thermal structure. The magnitude of SASM- CCF_x is determined by zonal wind and zonal temperature gradient at $\sim 500\text{hPa}$. Here, we found that the zonal gradient of SASM-T500 weakens notably during 2050-2099 (32 out of 40 members, $p < 0.001$). Moreover, the weakening of zonal temperature gradient can well explain the change on SASM- CCF_x (see Fig. 3d in the revised manuscript). For the underlying mechanism, a discussion regarding the change on SASM convection height is presented below in the response to Item#6 and Line XX-XX in the revised manuscript. The SASM-U500, on the other hand, plays a minor role in the overall change of SASM- CCF_x due to lack of inter-member consensus (see Extended Data Fig. 6d in the revised manuscript).

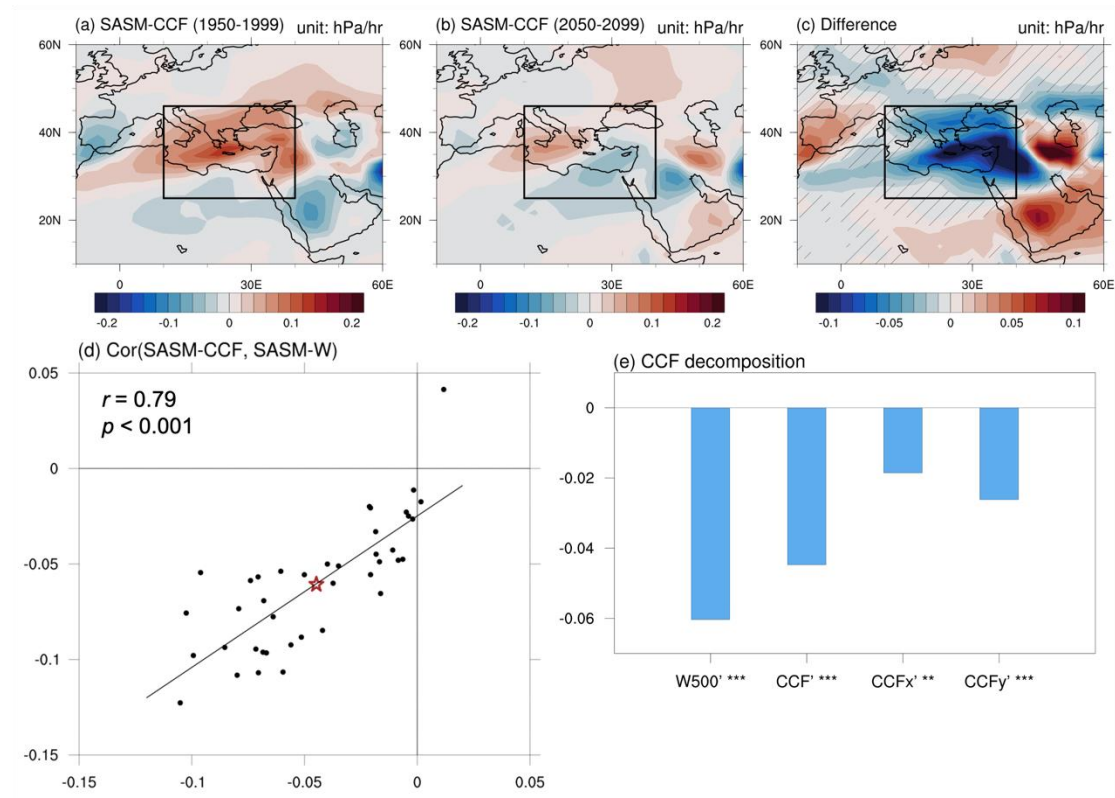


Fig. R3. SASM-related CCF (a) in 325K during 1950-1999, (b) in 330K during 2050-2099 and (c) their difference (Dashed lines represent area with change not significant at significance level

$p=0.1$). The inter-member correlation between CEM regional mean changes on SASM- $\omega 500$ and SASM-CCF is shown in (d), where each dot represents a single member and the red star refers to MME changes. X-axis (unit: hPa/hr) in (d) indicates changes on SASM-CCF and Y-axis (unit: hPa/hr), changes on SASM- $\omega 500$. (e) The decomposition of MME future change on SASM-CCF (***: $p<0.001$, **: $p<0.01$, units: hPa/hr)

On the other hand, SASM-CCF_y is determined by meridional wind and meridional temperature gradient at ~ 500 hPa. We have explored the changes on these two factors to evaluate their contributions to SASM-CCF_y changes. During 1950-1999, the CEM region is characterized by northerlies in the mid-troposphere (Fig. R4a), in line with previous studies (e.g. Cherchi et al., 2014; Tyrlis et al., 2013). The SASM-related northerlies, however, decrease considerably under global warming (Fig. R4b, c), especially over Levant and the vicinity of Greece. This weakened circulation anomaly (32 out of 40 members, $p<0.01$) significantly contribute to the decrease of SASM-CCF_y ($r=0.90$, $p<0.001$).

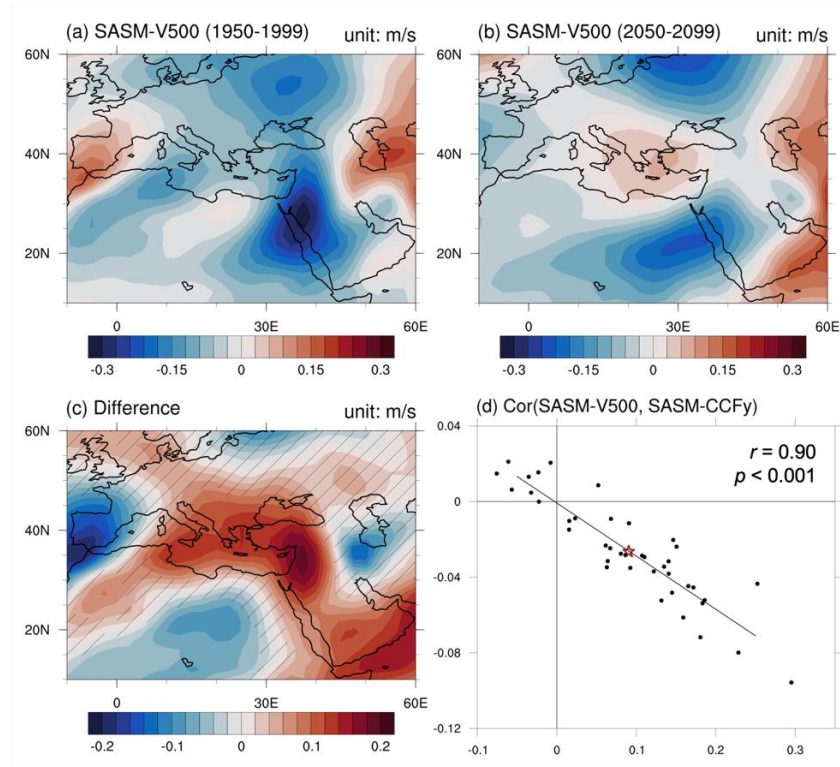


Fig. R4. SASM-related V500 during (a) 1950-1999, (b) 2050-2099 and (c) their difference

(Dashed lines represent area with change not significant at significance level $p=0.1$). The inter-member correlation between CEM regional mean changes on SASM-V500 (x-axis, units: m/s) and SASM-CCF_y (y-axis, units: hPa/hr) is shown in (d), where each black dot represents a single member and the red star refers to MME changes.

To examine why the northerly anomaly weakens substantially, we have further performed analysis based on Sverdrup balance. Due to vorticity conservation, the subsidence anomaly over CEM region should be balanced by equatorward flow (i.e. northerly wind) (Rodwell and Hoskins, 2001; Tyrlis et al., 2013):

$$f \frac{\partial \omega}{\partial p} = \beta v$$

Where f represents Coriolis parameter, β denotes the meridional gradient of f . Under global warming, the uplift of SASM convective center drives the expansion of zonal thermal structure (see response to the comment below or Line XX-XX in the revised manuscript for detailed explanations), which leads to decreases in SASM-CCF_x and thus SASM- ω 500 (Fig. R3e). The decrease of SASM- ω 500 is more prominent in 500hPa compared to lower levels, resulting in a decline of $f \frac{\partial \omega}{\partial p}$ (Fig. R5a; Note that this term is positive but decreases because its original pattern during 1950-1999 is negative, in line with the northerly anomaly). In 500hPa, the vertical gradient of subsidence term is well balanced with the meridional wind term for both spatial pattern (Fig. R5a, b; the pattern correlation coefficient is 0.52, $p<0.01$) and magnitude. These results indicate that, the change on SASM-CCF_x induces a reduction on vertical gradient of SASM-related subsidence at 500hPa, which leads to a weakening of SASM-related northerly via Sverdrup balance. The weakened northerly anomaly further reduces the SASM-related ω 500 through local dynamic feedback.

Please see **Section 3 and 4 (Line 142-246)** in the revised manuscript.

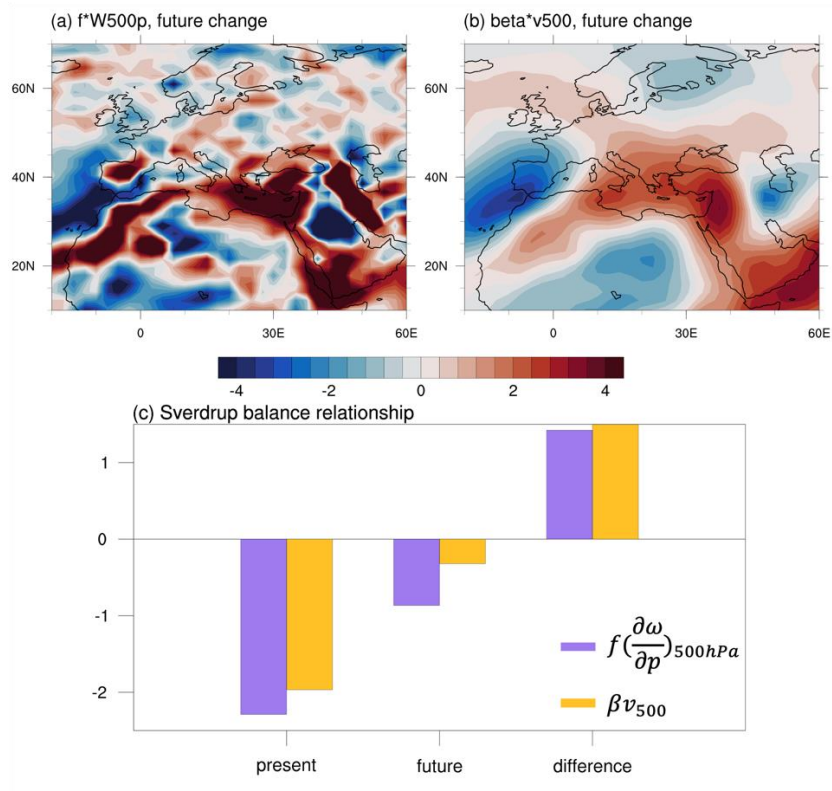


Fig. R5. Future change of (a) $f \frac{\partial \omega}{\partial p}$ and (b) βv over CEM region (unit: 10^{-12} s^{-2}). Note that the vertical motion and meridional wind in (a) and (b) are SASM-related anomalies. (c) CEM regional mean of above two terms during 1950-1999, 2050-2099 and their difference (unit: 10^{-12} s^{-2}).

6) Diagnosis of Moist Static Energy:

L174-176: I do not understand this sentence. What does increase nearly uniformly in the vertical profile due to moist adiabatic adjustment? Please rephrase.

L182-192: Although I understand the method section, I find it difficult to follow this part of the document. Please rewrite and focus on the main results that need to be conveyed.

Response:

Thanks. We have re-examined the underlying mechanism, and presented multiple lines of evidence based on theory, simulations and numerical experiments here to demonstrate that this expansion is due to the uplift of SASM convection under global warming.

1. Theoretical basis:

Previous studies pointed out that tropical convection will become higher under global warming as a response to the elevated tropopause (Yu et al., 1998; Santer et al., 2003; Chou and Chen, 2010; Fan and Dommenges, 2023). The thermal structure in the mid-troposphere is also suggested as a westward propagating Rossby wave in response to SASM heating (e.g. Rodwell and Hoskins, 1996; Beverley et al., 2021). Under the quasi-geostrophic approximation of large-scale atmosphere motion, the horizontal scale of Rossby wave is given following the Rossby radius of deformation (Gill, 1980):

$$L_R \sim \frac{NH}{f}$$

Where N is the Brunt–Väisälä frequency, H represents the height (depth) and f denotes the Coriolis parameter. Therefore, we hypothesize that, as the tropopause and convection center shifts higher in a warming future, the horizontal extent of Rossby wave response to SASM heating will become larger, which eventually lead to the westward expansion of thermal structure.

2. Model simulations:

The westward expansion of SASM-T500 is already documented in the original manuscript, as a statistically significant phenomenon under global warming ($p < 1 \times 10^{-5}$). Here, we have calculated the SASM-related diabatic heating profile over the SASM region (Fig. R6a). It is evident that the heating rate during SASM becomes larger in the mid-to-upper troposphere while smaller in the lower troposphere. To quantify the magnitude of convection uplift, we calculated the diabatic heating-weighted convection

height following:

$$H = \frac{\int_{925\text{hPa}}^{100\text{hPa}} Q'_1(p) \cdot p \, dp}{\int_{925\text{hPa}}^{100\text{hPa}} Q'_1(p) \, dp}$$

Here, $Q'_1(p)$ is the regional average of SASM-related atmospheric heating rate at pressure level p over the SASM region. The SASM-related convection height is uplifted about 35hPa, from 452hPa to 417hPa in MME (Fig. R6a) under global warming. This is also evidenced by a high inter-member consensus (38 out of 40 members simulate uplifted convection). A significant correlation between the convection height change over SASM region and the change on zonal gradient of SASM-T500 further support our hypothesis, suggesting that higher SASM convection can lead to thermal structure with larger spatial extent (Fig. R6b).

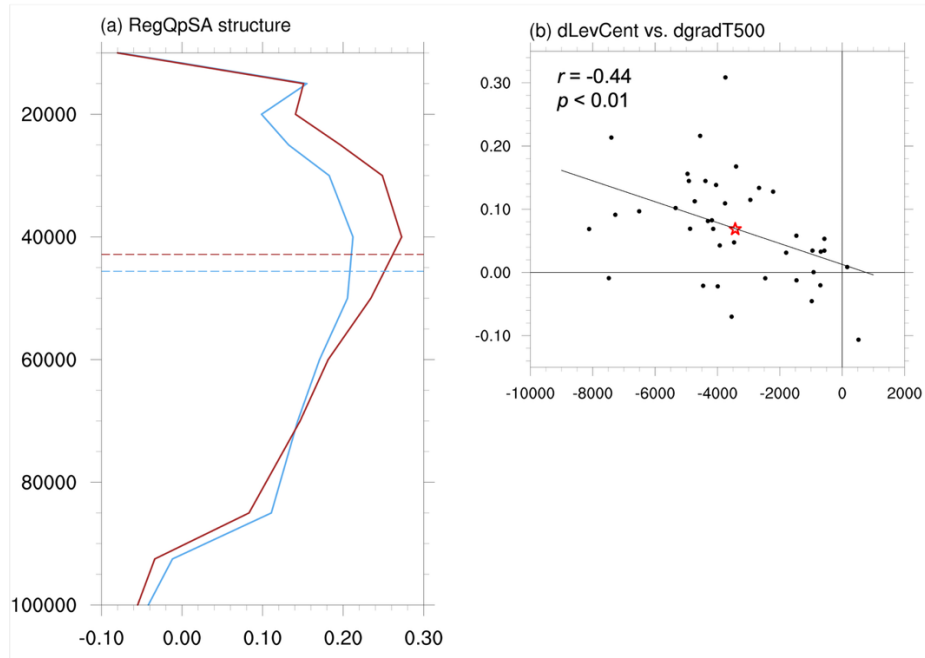


Fig. R6. (a) The heating rate profile over SASM region (x-axis: SASM- Q_1 , units: K/day; y-axis: height, units: Pa). The heating rate on each level is calculated based on Q_1 regressed onto the standardized $\langle Q_1 \rangle$ series over SASM region (see Methods in the revised manuscript). The red (blue) thick line denotes MME heating profile during 2050-2099 (1950-1999) over the SASM region. The red (blue) dashed line indicates the convection height in MME during 2050-2099

(1950-1999). (b) Scatter plot of change on convection height (x-axis, units: Pa) and change of zonal thermal structure (y-axis, units: K). Black dots indicate individual members and red star refers to MME.

3. Numerical experiments:

To further verify above conclusions, we have performed a set of numerical experiments based on Linear Baroclinic Model (LBM, Watanabe and Kimoto, 2000) to explore the circulation response to prescribed heat source. We designed two simulations using LBM: The first run (HIST) uses summer climatology during 1950-1999 in CESM1LE MME as background state and the second run (FUT) uses that of 2050-2099. The prescribed heat source is located in the same horizontal location but with different height of maximum. The maximum of heating in the HIST run is set at sigma level $\sigma=0.55$ ($\sim 500\text{hPa}$) and the FUT run, $\sigma=0.45$ ($\sim 400\text{hPa}$) (Fig. R7).

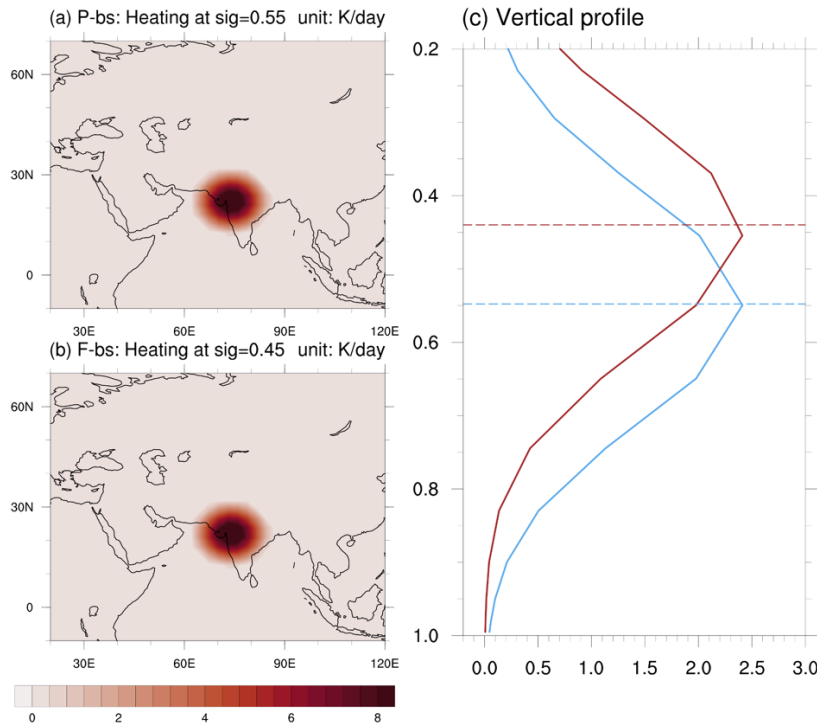


Fig. R7. Location and magnitude of the prescribed heat source over SASM region in (a) HIST run and (b) FUT run. (c) The profile of heat source in the two experiments (x-axis: heating rate, unit:

K/day; y-axis: sigma level height). The red (blue) thick line denotes heating profile in HIST (FUT) run. The dashed lines indicate the weighted height of heating calculated following formula X.

The steady atmospheric responses of the two simulations show distinct features (Fig. R8). Both LBM runs can realistically simulate the spatial pattern of the thermal structure with a positive zonal gradient over Mediterranean (Fig. R8a, c) and thus the subsidence (Fig. R8b, d). The magnitude of T500 response is larger in the FUT run and its center of maximum shifts westward, which qualitatively matches the results from coupled model simulations (Fig. R8e). As a result, the tropospheric subsidence weakens significantly over CEM (Fig. R8f), in line with Fig. 1 in the revised manuscript.

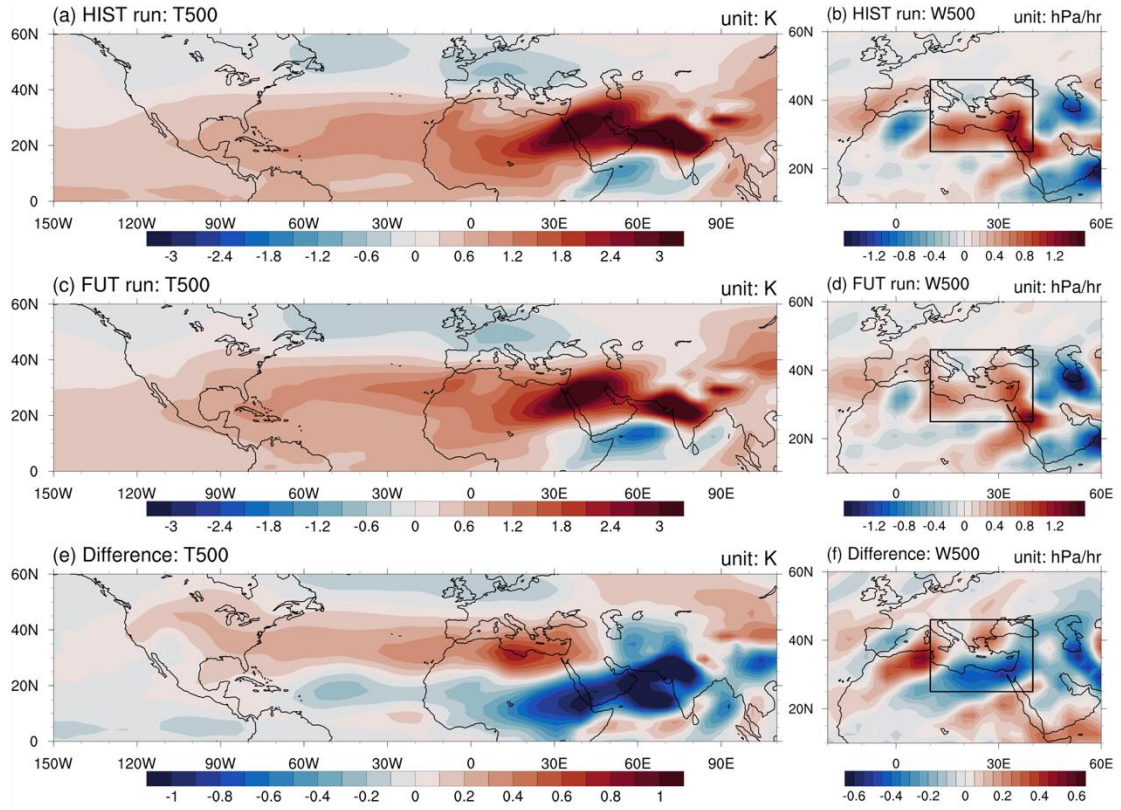


Fig. R8. Steady atmospheric response to heat source over SASM region in LBM. Temperature response at 500hPa in (a) HIST run, (b) FUT run and (c) their difference. (b), (d), (f): as in (a), (c), (e), but for vertical velocity at 500hPa.

To conclude, the weakened CEM circulation response to SASM, manifested as weaker SASM-CCF, is evidently influenced by the westward expanding SASM thermal

structure. We highlight that the change of thermal structure is induced by the uplifted deep convection over SASM region under global warming. We have supplemented these results to **Line 179-202** in the revised manuscript.

Minor comments

1) L8 & L27: “over Mediterranean” -> “over the Mediterranean”

Response: Corrected.

2) L28: What is the meaning of “by storm track and synoptic systems”?

Response:

Mediterranean climate is characterized by hot, dry summers and mild, wet winters. Previous studies suggest that winter precipitation over Mediterranean region is closely linked to storm tracks and transient eddies (e.g. Seager et al., 2014; Hoy et al., 2014). In order to focus on the summer climate concerned in this study, we have simplified the expressions. Please see **Line 27-29** in the revised manuscript.

3) L33: What is the meaning of “counterpart of the mid-level subsidence”?

Response:

Thanks. Here, we aimed to provide a comprehensive picture of Mediterranean summer circulation. In the mid-to-lower troposphere, the Mediterranean is dominated by “Etesians” in the summer, characterized by strong northerly winds. Due to Sverdrup balance, the Etesians is coupled to mid-tropospheric subsidence (Rodwell and Hoskins, 2001). Therefore, we stated that the Etesians is the counterpart of the tropospheric subsidence.

To avoid misunderstanding, in the revision, we have rephrased the statement as “The lower troposphere is dominated by strong northwesterly winds known as the ‘Etesians’, which is coupled to the mid-level subsidence and together close the Sverdrup balance over the Mediterranean.” Please see **Line 31-34** in the revised manuscript.

4) L34: “*eastern Mediterranean*” -> “*over the eastern Mediterranean*”

Response: Corrected.

5) L34-35: *How is the Etesians related to extreme climate events mentioned here? Please clarify.*

Response:

Thanks. We have supplemented explanations on how tropospheric atmospheric circulation could influence extreme events such as heatwaves and wildfires over Central-to-Eastern Mediterranean region.

Please see **Line 34-37** in the revised manuscript.

6) L76: “faithful” -> “accurate”

Response: Corrected.

7) L76-80: *This sentence is long and confusing. Please rephrase.*

Response:

We have rephrased the paragraph:

“We first assess the change of vertical motion anomalies in CESM1 large ensembles. Here, atmospheric diabatic heating ($\langle Q_1 \rangle$) is used to evaluate the convective heating released by SASM (see Methods) as demonstrated also in previous studies. The heating $\langle Q_1 \rangle$ closely resembles the monsoon precipitation in terms of both spatial pattern and temporal evolution of interannual variability (Extended Data Fig. 1a-c), confirming it is an accurate metric to depict the monsoon thermal effect. The CESM1 large ensembles reasonably represent the interannual relation of “Monsoon-Desert” teleconnection, with strong subsidence response over Central-to-Eastern Mediterranean (CEM, 25°-46°N, 10°-40°E) to SASM heating in the mid-troposphere (Fig. 1a).”

Please see also **Line 74-80** in the revised manuscript.

8) *Caption of Fig. 5: Panel c is not adequately described. In general, the authors should try to make all captions more detailed.*

Response: Thanks. The captions of Fig. 5 and other Figures in the revised manuscript are re-written.

9) L256-257 & L280: *Claiming that the fading away of the monsoon-Mediterranean link is the result of anthropogenic warming may require a more in-depth investigation of the link by employing more sophisticated attribution methods.*

Response: Thanks. Since the focus of the study is not detection and attribution of anthropogenic signals, we have replaced the phrase “anthropogenic warming” with “results of global warming”.

Please see **Line 288-290** and **Line 306-307** in the revised manuscript.

10) L335: *“over SASM region” -> “over the SASM region”.*

Response: Corrected.

11) L330: *Could you please clarify whether you used individual monthly timeseries in the analysis or seasonal (JJA) mean timeseries.*

Response: Thanks. Each variable is averaged over June-July-August in every year.

Therefore, we use the seasonal mean time series, rather than individual monthly series. This is now clarified in the Method section, please see **Line 363-364** in the revised manuscript.

12) L342: This sentence is confusing. Please rephrase.

Response: Rephrased.

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Reply to Reviewers #2:

Thank you for the valuable comments and comprehensive instructions on enhancing the manuscript. We sincerely appreciate the time and effort you dedicated to reviewing our work and providing us with insightful feedback. Your comments have been instrumental in significantly improving the manuscript's quality. To ensure clarity, we have highlighted your original comments in *italic font*, and our responses are presented in normal font below each comment.

1. The authors base their conclusion on a single model. Though CESM1 captures rather well the present-day SASM-CEM teleconnection, it does not mean that its response is certain. Considering the authors' statements and the high standard of Nature Geoscience, I think the study needs to assess the response of the teleconnection in a wider set of models such as the CMIP6 ensemble. This would help the authors to make a better assessment of the robustness of their results.

Response:

Thanks. As suggested, we have analyzed the outputs of 33 models of Coupled Models Intercomparison Project Phase 6 (CMIP6). The results of CMIP6 models support our conclusions. The new evidence from CMIP6 models is outlined below:

First, we have calculated the SASM-related vertical motions at 500hPa (ω_{500}) and its future change (Note that shadings in Fig. R1a-d are all obtained by regressing different variables onto the standardized SASM $\langle Q_1 \rangle$ series) using CMIP6 models. It is evident in Fig. R1a-c that the subsidence anomaly weakens under global warming with high inter-model consistency (27 out of 33 models exhibit decrease ω_{500} over central-to-eastern Mediterranean, CEM). Future change of SASM- ω_{500} matches well with that of SASM-related cross contour flow (CCF, see Methods in the revised manuscript) over CEM, in terms of both spatial pattern (Fig. R1c, d), inter-model correlation (Fig. R1e)

and magnitude (Fig. R1f). The change of SASM-CCF anomaly explains $\sim 90\%$ of SASM- $\omega 500$ change on MME, and both zonal (CCF_x) and meridional (CCF_y) components are important in determining the change of SASM-CCF (Fig. R1f). Here, the decomposition of CCF into the zonal and meridional components is employed in the revised manuscript. For detailed explanation on the diagnosis, please see our response to your **Comment #9** below as well as **Line 143-149** in the revised manuscript.

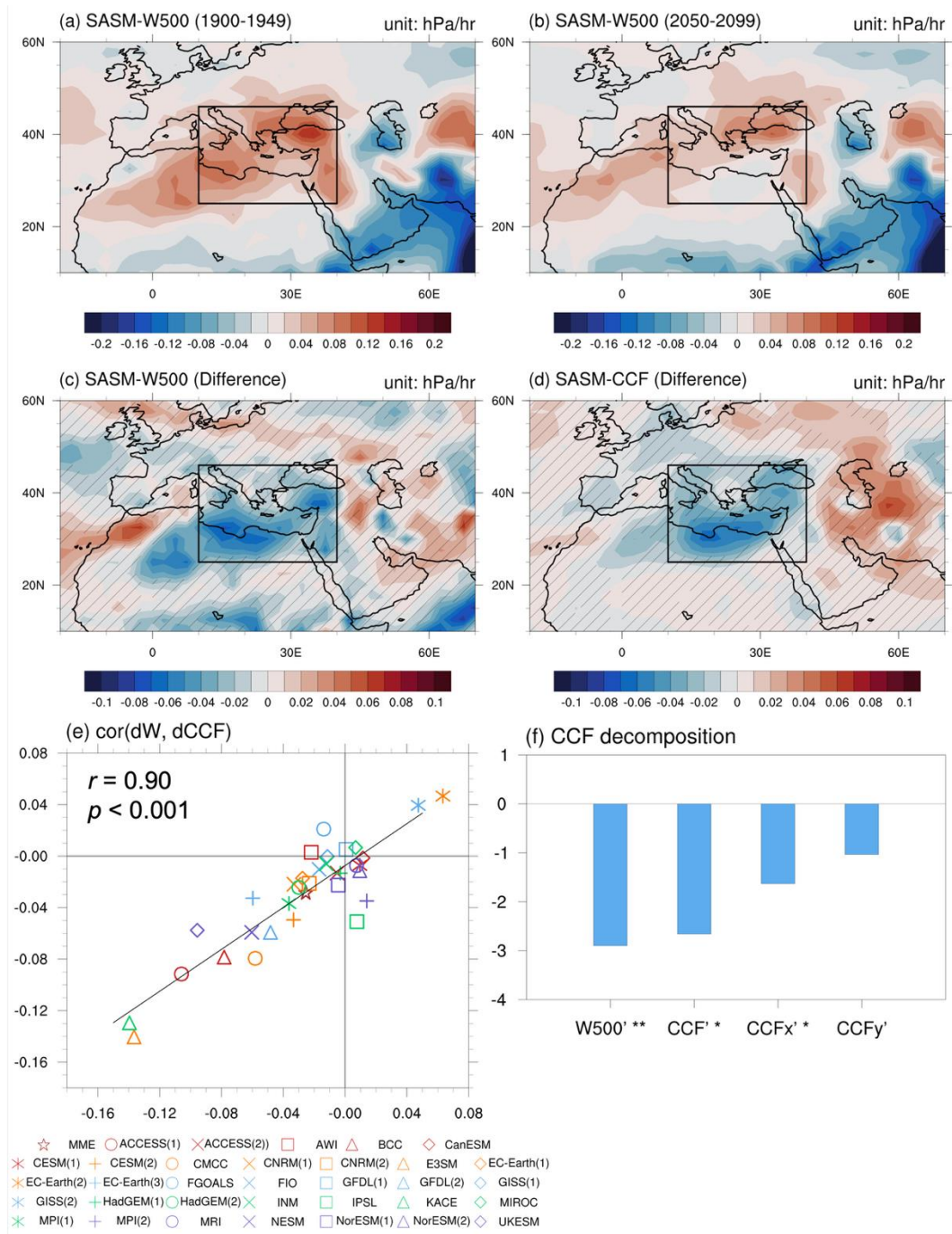


Fig. R1. Boreal summer interannual ω_{500} anomalies regressed onto the standardized diabatic heating Q_1 time series over South Asian Summer Monsoon (SASM) region in (a) 1900-1949, (b) 2050-2099 and (c) their difference. (d) as in (c), but for SASM-related CCF anomalies (see Methods for CCF calculation). (e) Inter-model correlation between CEM regional mean (25°-45°N, 10°-40°E) future change of SASM-CCF (x-axis, unit: hPa/hr) and SASM- ω_{500} (y-axis, unit: hPa/hr). (f) Decomposition results of SASM-CCF changes (bars from left to right: future change of SASM- ω_{500} , SASM-CCF, zonal component of SASM-CCF and meridional component of SASM-CCF, unit: 10^{-2} hPa/hr). Dashed lines in (c) and (d) represents area with change not significant at $p=0.1$ level.

Next, we have examined the changes in zonal thermal structure and SASM-related northerly winds, which dominate the future change of SASM-CCF_x and SASM-CCF_y, respectively. For detailed explanations on how zonal T500 gradients determine SASM-CCF_x, please see **Line 150-164** in the revised manuscript.

For more specific interpretation on how SASM-V500 can influence the SASM-CCF_y, please see **Line 209-232** in the revised manuscript. Here, we briefly present evidence that the change of these two factors matches well with that of CESM1LE in both spatial pattern and magnitude (Compare Fig. R2a, c, e with **Extended Data Fig. 5b, d** in the revised manuscript and compare Fig. R2b, d, f with **Fig. 4a, b, f** in the revised manuscript). The zonal SASM-T500 gradient over CEM weakens significantly and the SASM-related northly anomaly at 500hPa also declines markedly over the CEM.

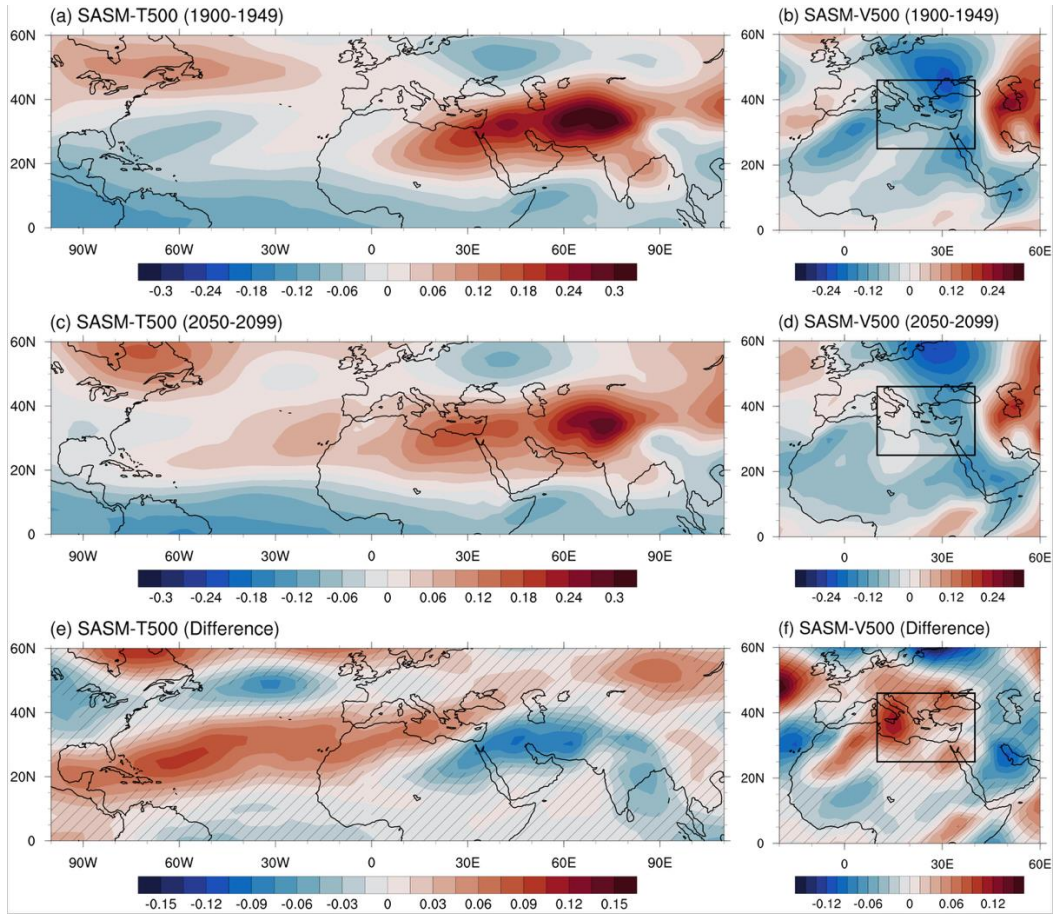


Fig. R2. SASM-related T500 anomalies during (a) 1900-1949, (c) 2050-2099 and (e) their difference. (b), (d), (f): as in (a), (c), (e), but for SASM-V500 anomalies. Dashed lines in (e) and (f) represent area with changes not significant at $p=0.1$ level.

In addition, we have estimated the response of CEM summer precipitation to SASM heating and its future change in CMIP6, as shown in Fig. R3. In present-day climate, enhancement of SASM is accompanied by strengthened CEM subsidence, thus leading to drier summer CEM (Fig. R3a and **Fig. 5a** in the revised manuscript). Under global warming, the fading away of teleconnection between SASM and CEM circulation leads to the muted response of summer Mediterranean precipitation to SASM (Fig. R3b, c and **Fig. 5b** in the revised manuscript). This is also in line with the decrease of summer precipitation variance over Mediterranean explained by SASM in both CESM1LE and CMIP6 (Fig. R3d and **Fig. 5d** in the revised manuscript).

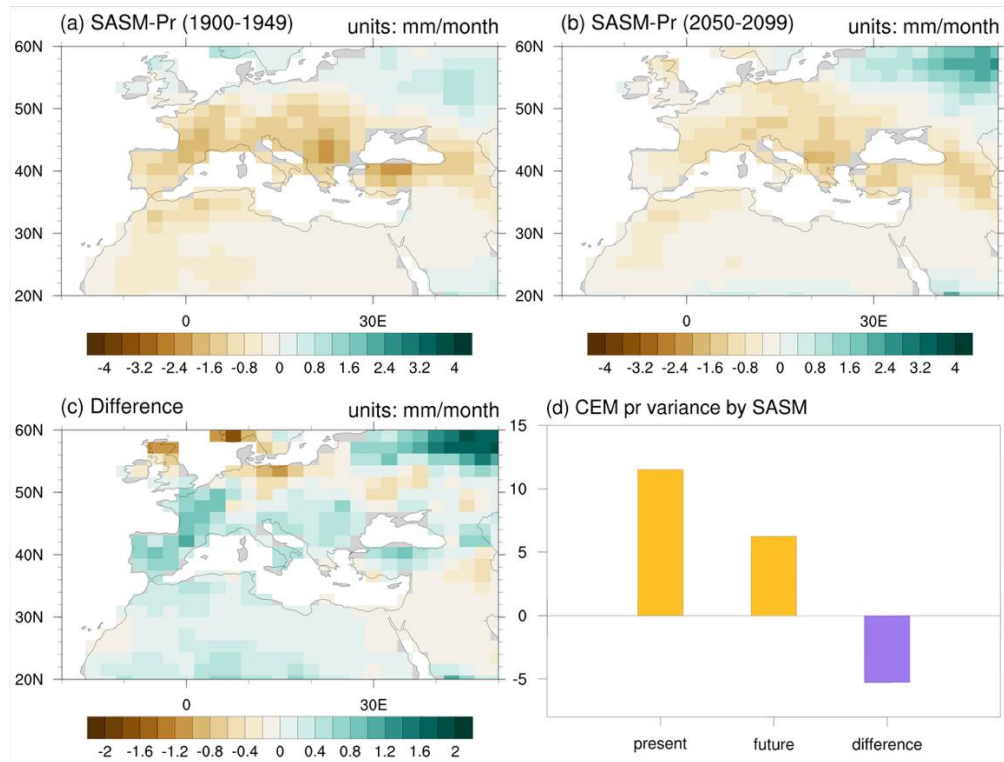


Fig. R3. SASM-related summer land precipitation over Mediterranean during (a) 1900-1949, (b) 2050-2099 and (c) their difference. (d) MME results of SASM explained Mediterranean summer land precipitation variance (unit: %). The explained variance is estimated by the ratio between term A: difference between variance of Mediterranean precipitation and the variance of Mediterranean precipitation with SASM effect linearly removed, and term B: the variance of Mediterranean precipitation.

In conclusion, the phenomenon and underlying mechanisms based on CMIP6 models are consistent that based on CESM1LE, demonstrating that the vanished impact of Asian monsoon on Mediterranean summer climate on interannual time variability under global warming is a robust signal.

2. At lines 265-266, the authors mention a divergent consensus among previous studies: why previous studies are divergent? How the present study would yield a more

convergent consensus? Or does it just increase the diversity of results? The authors need to more clearly position their results with respect to previous works.

Response:

Thanks.

First, we hope to clarify that the previous divergent consensus is on the mean state response, while our focus here is on interannual variability. Thus, our work does not increase the diversity of results.

Regarding how Mediterranean summer climate will change in the future, previous studies focus mainly on the change of mean state (e.g. tropospheric subsidence, etesian winds and precipitation) (Anagnostopoulou et al., 2014; Cherchi et al., 2016; Dafka et al., 2019). For instance, Anagnostopoulou et al. (2014) reported a weakening of future eastern Mediterranean tropospheric circulation based on regional climate model simulations, while Cherchi et al. (2016) showed evidence that the mid-level subsidence over western Mediterranean will enhance under global warming based on ScenarioMIP of CMIP5. The uncertainty partly arises from the employment of different modelling approaches.

Second, we hope to position our results with respect to previous works by highlighting our finding on interannual variability change associated with global warming. The Mediterranean summer climate is characterized by significant interannual variability in terms of both atmospheric circulation (Cherchi et al., 2014; Rizou et al., 2015; Barcikowska et al., 2020; Gandham et al., 2025) and precipitation (Zveryaev and Allan, 2010; Campos et al., 2025; Vincente-Serrano et al., 2025). However, less effort has been devoted to the future change of interannual variability of Mediterranean summer climate. Our study aims to elucidate how the effect of SASM, as a critical factor for Mediterranean summer climate in present day (Fig. 1 and 5 in the revised manuscript; see also Cherchi et al., 2014), on interannual variability of CEM climate will change under global warming. Based on large ensemble simulations, state-of-the-art coupled

model output and numerical experiments, we have provided quantitative estimation and elaborated the underlying physics to a robust decrease of the teleconnection.

Please see **Line 298-302** in the revised manuscript.

3. To fully argue the importance of the SASM-CEM teleconnection response under global warming onto the CEM summer climate response (e.g., statement at lines 270-272), it needs to be positioned with respect to the total response. E.g., how big is the teleconnection contribution to interannual variability of precipitation in the region? What are the implications of a weakened teleconnection for the CEM precipitation response (mean state and its interannual variability)?

Response:

Thanks. To quantify the change of SASM's impact on CEM summer climate, we estimated the variance of CEM atmospheric circulation ($\omega 500$) and precipitation that can be explained by SASM as follows:

$$R(k_{CEM, SASM}) = \frac{Var(k_{CEM}) - Var(k_{CEM, noM})}{Var(k_{CEM})} \times 100\%$$

Where R is the ratio of variance explained by SASM, $Var(k_{CEM})$ represents the total variance of interannual component of variable k (here, $\omega 500$ or precipitation). $Var(k_{CEM, noM})$ denotes the variance of variable k with impact of SASM linearly removed:

$$k_{CEM, noM} = k_{CEM} - reg(Q_{1, SASM}, k_{CEM}) \cdot Q_{1, SASM}$$

Where $Q_{1, SASM}$ refers to the time series of atmospheric diabatic heating over SASM region (10°-30°N, 65°-95°E) and $reg(Q_{1, SASM}, k_{CEM})$ denotes the linear regression coefficients of k_{CEM} regressed onto $Q_{1, SASM}$.

For atmospheric circulation, SASM can explain ~22% of total interannual variability of ω_{500} over CEM in terms of Multi-member ensemble mean (MME) in present day, with the local maximum of explained variance over Levant and the vicinity of Greece (Fig. R4a). For individual members such as 017 and 019, the explained variance reaches 40% and even higher. In the future, however, the explained variance declines substantially to less than 3% (MME) with high inter-member consistency (decrease in 39 out of 40 members) (Fig. R4c, d). Therefore, the contribution of SASM-CEM teleconnection to the total atmospheric circulation variance over CEM decline from 22% to 3% in the future.

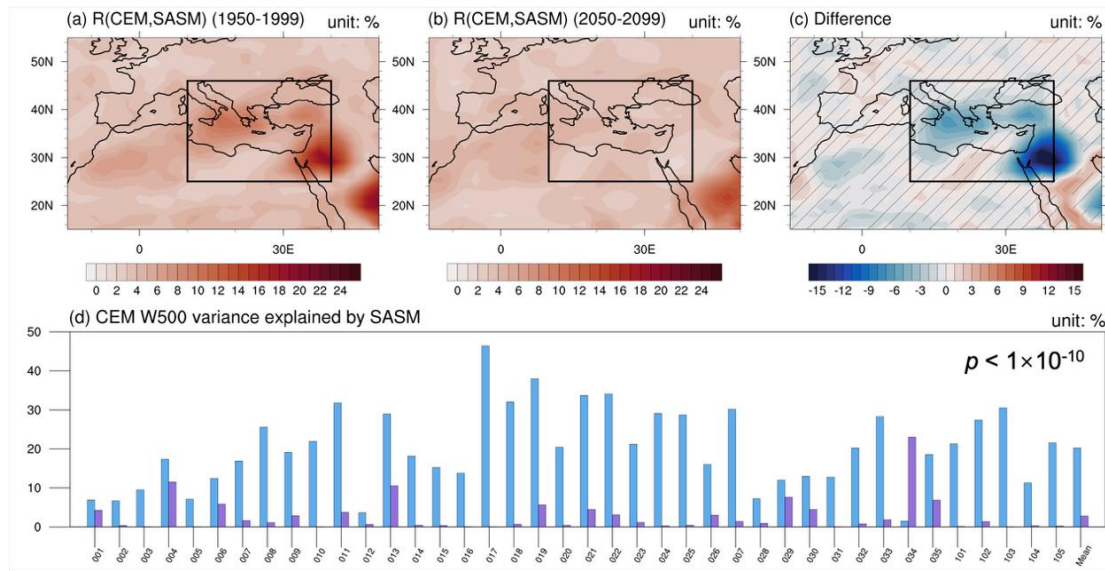


Fig. R4. Variance of CEM ω_{500} explained by SASM and its future change in CESM1LE. The spatial pattern of explained variance during (a) 1950-1999, (b) 2050-2099 under Representative Concentration Pathway 8.5 (RCP8.5) and (c) their difference. The regional mean of explained variance over CEM is given in (d), with variance in the present (blue bars) and in the future (purple bars) (x-axis: individual members in CESM1LE; y-axis: SASM-explained variance). The significance of change on explained variance is estimated using students' t-test.

For summer land precipitation, SASM explains ~15% (MME) of the total interannual precipitation variability in present day. Precipitation in regions including Asia Minor Peninsula, northern Italy and western Mediterranean are significantly influenced by SASM (**Fig. 5a** in the revised manuscript). Under global warming, this explained

variance drops evidently to ~4% (MME) with high inter-member consistency (32 out of 40 members show decline, $p < 0.01$) (Fig. 5d in the revised manuscript).

Therefore, we conclude that this teleconnection contributes 22% of total variance to CEM summer mid-level subsidence and 14% to precipitation. The explained variances diminish to less than 5% for both variables in the future. Based on these results, we highlight that global warming can significantly influence Mediterranean summer climate by reducing considerable portions of interannual variability explained by SASM. Meanwhile, our findings serve as an additional example in the context of evaluating global warming's effect on modes of variability in the climate system (IPCC AR6 WGI chapter 4).

Please see **Line 104-105** and **Line 277-279** in the revised manuscript.

4. The wording used by the authors is not fully appropriate. They tend to claim of cause-and-effect relationship between SASM and CEM, while they only document a teleconnection. A teleconnection is primarily a correlation between two regional climate variables or set of variables, which does not a priori imply a causal link. Of course, mechanisms can be speculated, and those mechanisms may imply a causal link. Nevertheless, because the authors' analysis uses fully synchronous correlation between the two regions, I suggest to tone down the causal relationship, and thus possibly to solely refer to the SASM-CEM teleconnection (instead of e.g., "monsoon-induced Mediterranean circulation"). Similarly, the gliding mechanism the authors invoke in their analysis is fully consistent with either a change in the monsoon thermal structure induced by the SASM amplification, or a change in the CEM circulation due to another large-scale response that would affect the monsoon thermal structure. The diagnostic thus does not obviously emphasize a causal link.

Response:

Thanks. While we agree that a correlation between two regional climate variables or set of variables does not necessarily imply a causal link, we have added additional evidence in our revised manuscript to demonstrate the cause-and-effect relationship between SASM and CEM at interannual time scale. Two lines of evidence are presented to support our conclusion.

1. Physical links:

The influence of SASM on Mediterranean summer climate has been well documented since Rodwell and Hoskins (1996). With regard to how SASM modulates Mediterranean climate in present day, the scientific community has reached a consensus: the diabatic heating released by SASM summer monsoon can generate a westward propagating Rossby wave, which interacts with the mid-latitude westerlies over Mediterranean and cause the mid-level subsidence. The subsidence, on the other hand, is related to mid-to-low level northerly wind called “Etesians” and also reduce precipitation by inhibiting local convection. This underlying physical link is proposed based on atmospheric dynamics theories (Rodwell and Hoskins, 1996; Rodwell and Hoskins, 2001) and testified based on diagnosis to reanalysis (Tyrlis et al., 2013) and coupled models (Cherchi et al., 2014). Di Capua et al. (2024) also validated this relation based on causal effect network. Therefore, the consensus on the theoretical basis of SASM’s impact on Mediterranean summer climate encourages us to extend the topic from mean state change to interannual variability.

2. Numerical experiments validations:

We have performed a new set of numerical experiments to validate the mechanism. We used Linear Baroclinic Model (LBM, Watanabe and Kimoto, 2000) to investigate the atmospheric response to prescribed heat source. In this simulation, we set the background state of climate to the summer (JJA) climatology obtained from CESM1LE MME during 1950-1999. Heat source is prescribed over SASM region (Fig. R5a) with maximum at ~500hPa (Fig. R5b). The steady mid-level atmospheric responses to the

heating (at day 25) coincide well with that of CESM1LE and CMIP6 (compare Fig. R5c with Fig. 1a in the revised manuscript and Fig. R1a; compare Fig. R5d with Fig. X in the revised manuscript and Fig. R2a), demonstrating the causal link between SASM heating and CEM circulation.

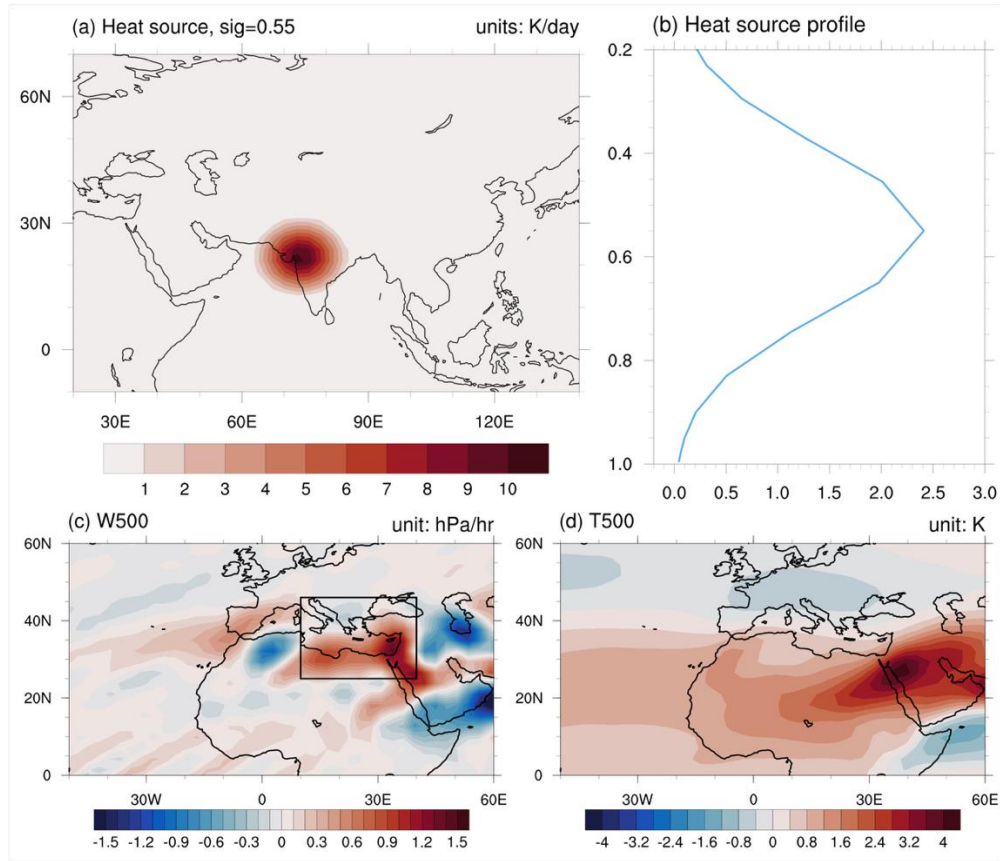


Fig. R5. (a) The horizontal distribution and (b) vertical profile of the heat source prescribed to LBM. The profile in (b) is obtained by weighted area average over 10° - 35° N, 60° - 85° E. The steady response at day 25 of (c) vertical motion at 500hPa and (d) temperature at 500hPa of LBM simulation.

In conclusion, to avoid the misleading of mere correlation analysis, we have presented evidence from both theoretical analysis and numerical experiment results to demonstrate the causal link between SASM and CEM. The LBM experiments also explain how the change in monsoon convection height affects the CEM summer circulation response. For details of discussion, please see our response to your **Comment #10** and **Line 195-202** in the revised manuscript.

5. *I have been rather confused all along the text between field anomalies and mean state and the interpretations that goes with them. I feel both aspects, i.e. mean state response to global warming and response of interannual variability, are important but need to be further documented as well as how the response of both of them contribute to the response of the SASM-CEM teleconnection. So far, I cannot find a picture emerging clearly-enough from the paper.*

Response: Thanks. First, we hope to clarify that we focus on the changes of interannual variability in this study. In our manuscript, all SASM-related variables (e.g. SASM- $\omega 500$, SASM-CCF, SASM-T500) are calculated by regressing corresponding variables onto the standardized $\langle Q_1 \rangle$ series over SASM region. The regressed field anomalies represent the response of these variables to one-standard-deviation enhancement of SASM heating. To avoid any misunderstanding, we have re-written **all figure captions** with more details in the revised manuscript.

As to how the response of interannual variability contribute to the future change of SASM-CEM teleconnection, we have quantitatively diagnosed the future change of SASM-related CCF anomalies and proposed the underlying mechanisms. We show evidence that the westward expansion of SASM-T500 is responsible for the change in SASM-CCF zonal component. The weakening of SASM-related V500 dominates the change in SASM-CCF meridional component. For detailed discussion, please see **Line 150-164** and **Line 209-219** in the revised manuscript.

6. *The interest of using the CESM1 large ensemble is the possible assessment of the role of internal variability in the SASM-CESM teleconnection under present-day*

conditions and its response under the RCP8.5 scenario. I feel this aspect is underused in the analysis.

Response:

Thanks. We fully agree that the single model initial condition large ensemble is powerful in identifying the relative contributions of internal variability and anthropogenic external forcing. In our results, the strength of SASM-CEM relation varies among ensemble members at specific time period (grey lines in Extended Data Fig. X), which signals the effect of internal variability. However, since the response of ensemble mean is markedly stronger than the spread among the ensemble members, the weakening of SASM-CEM relationship in the future is dominated by the forced response to global warming (see **Fig. 1** and red line in **Extended Data Fig. 3a** in the revised manuscript). This explains why the motivation of the study is on the interannual variability change associated with the forced warming change instead of uncertainty arising from internal noise.

In addition, CESM1LE is chosen because most of the members can realistically simulate the significant interannual relation between SASM and CEM circulation (compare **Fig. 1a** and **Extended data Fig. 2a** in the revised manuscript) during the historical period (1950-1999), with correlation coefficients significant at $p < 0.05$ level for 33 out of 40 (82.5%) members. Therefore, the analysis on future change of SASM-CEM relation is reliable and robust given its high performance on present day simulations.

We also acknowledge that how internal variability could influence the relationship between SASM and CEM is a valuable topic though it is beyond the scope of this study. We have added a brief comment on this in the Discussion session of the revised manuscript (**Line 307-309**).

7. *Though I am not an English-native speaker, I feel the text contains a lot of grammatical errors and inappropriate formulations. I suggest the authors to ask a English-native speaker to carefully read and correct the paper.*

Response:

Thanks. We have thoroughly examined the grammar mistakes and wordings to improve the language quality.

8. *The authors used the atmospheric diabatic heating Q_1 as an indicator of the SASM intensity. It is, expectedly, very well correlated to the SASM precipitation. Why not using directly used precipitation? Besides, which model output frequency is used to estimate Q_p as a residual (l. 319)? If not using high-frequency data (e.g., 6-hourly or less), how reliable is the estimated Q_p ? Note also that Q_1 often refer to the heating profile in the literature. A notation such as Q_1 for its vertical integral seems more appropriate to reduce confusion.*

Response:

Thanks. As suggested, we have performed the regression analysis between mid-level vertical motion and SASM precipitation index as shown in Fig. R6. The result is identical to the original manuscript based on Q_1 index (cf. Fig. R6 and Fig. 1 in the revised manuscript). Since the subsidence response is a result of interaction between Rossby wave and mid-latitude flow, the magnitude of ω_{500} response to SASM precipitation index is similar but slightly weaker than that of Q_1 index. The Rossby wave is generated due to convective heat releasing over SASM region associated with

monsoon precipitation. Therefore, it is more straightforward and consistent to evaluate circulation response to SASM Q_1 because it is diabatic heating rather than precipitation that directly drives the circulation changes.

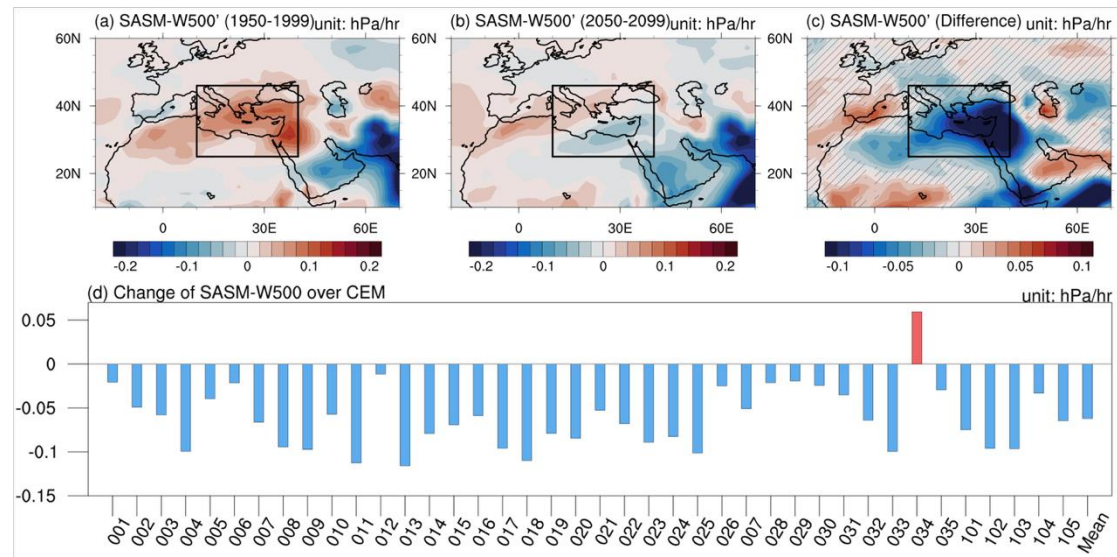


Fig. R6. Regressed field of 500hPa vertical motion onto the standardized SASM precipitation during (a) 1950-1999, (b) 2050-2099 and (c) their difference. (d) Future change of SASM- ω 500 over CEM (black rectangle in a-c). Dashed lines in (c) represents area with change not significant at $p=0.1$ level.

In addition, the model output frequency used to estimate Q_p is based on monthly data. Using monthly data to evaluate the diabatic heating over SASM region is commonly applied in previous studies (e.g. Cherchi et al., 2014; Lu et al., 2025; Song et al., 2025). In fact, the magnitude of Q_p is primarily determined by vertical advection term $C_p \omega \frac{T}{\theta} \frac{\partial \theta}{\partial p}$, rather than the time tendency term $C_p \frac{\partial T}{\partial t}$. Therefore, we suggest that using monthly model output to estimated that atmospheric diabatic heating is reasonable. With regards to the notation of Q_1 , we have changed its notation in the revised manuscript, please see **Line 354-359** in the revised manuscript.

9. I think the gliding mechanism is insufficiently or inadequately illustrated. Maps of

pressure on an isentropic level, together with horizontal wind speed and vertical velocity, would clearly help fully capture the mechanism, and assess how the change in mean state impacts the mechanism. In particular, I did not have really understood whether the gliding mechanism changes because of the mean state response or because of the response of the interannual variability pattern.

Response:

Thanks. First, we hope to clarify that future change of SASM-related cross-contour flow (CCF) anomaly has resulted from SASM-related field (i.e. interannual variability pattern) rather than mean state change.

Second, to illustrate the thermal gliding mechanism more sufficiently, we conducted a series of quantitative diagnosis and provided more details. The calculation of CCF is estimated by:

$$CCF = \vec{V}_i \cdot \nabla P_i = u_i \frac{\partial P_i}{\partial x} + v_i \frac{\partial P_i}{\partial y}$$

$$CCF_x = u_i \frac{\partial P_i}{\partial x}$$

$$CCF_y = v_i \frac{\partial P_i}{\partial y}$$

Where CCF denotes the total cross-contour flow, CCF_x and CCF_y represent zonal and meridional component of CCF, respectively. The subscript “i” indicates variables interpolated onto isentropic surfaces. To quantitatively evaluate the respective contribution of CCF_x and CCF_y to SASM- ω 500, we examined their changes under global warming. Note that we selected SASM-related CCF at 325K isentropic surface in the present and 330K for future. This is because we focus on the change of SASM-related subsidence at 500hPa. Under global warming, tropospheric temperature increases significantly that 330K becomes closer to 500hPa compared to 325K.

The spatial pattern of SASM-CCF resembles that of SASM- ω 500 markedly (cf. Fig. R7a-c and Fig. 1 in the revised manuscript). There are totally 38 out of 40 members

simulate decrease in SASM-CCF under global warming and correlates significantly to the change of SASM- ω 500 ($r=0.79$, $p<0.001$). In terms of MME, future change of SASM-CCF explains $\sim 76\%$ of change on SASM- ω 500, indicating that CCF is a proper proxy for the evaluation on monsoon-induced circulation change. Further decomposition suggests that the zonal and meridional component contribute to 43% and 56% to the total SASM-CCF, respectively (Fig. R7e).

To improve the robustness of the analysis, we have also performed the same diagnosis by using 33 CMIP6 models as you recommended in your Comment #1. We found that the ratios derived from CMIP6 models are 61% and 38%, respectively (Fig. R1f). These results indicates that both zonal and meridional component are important.

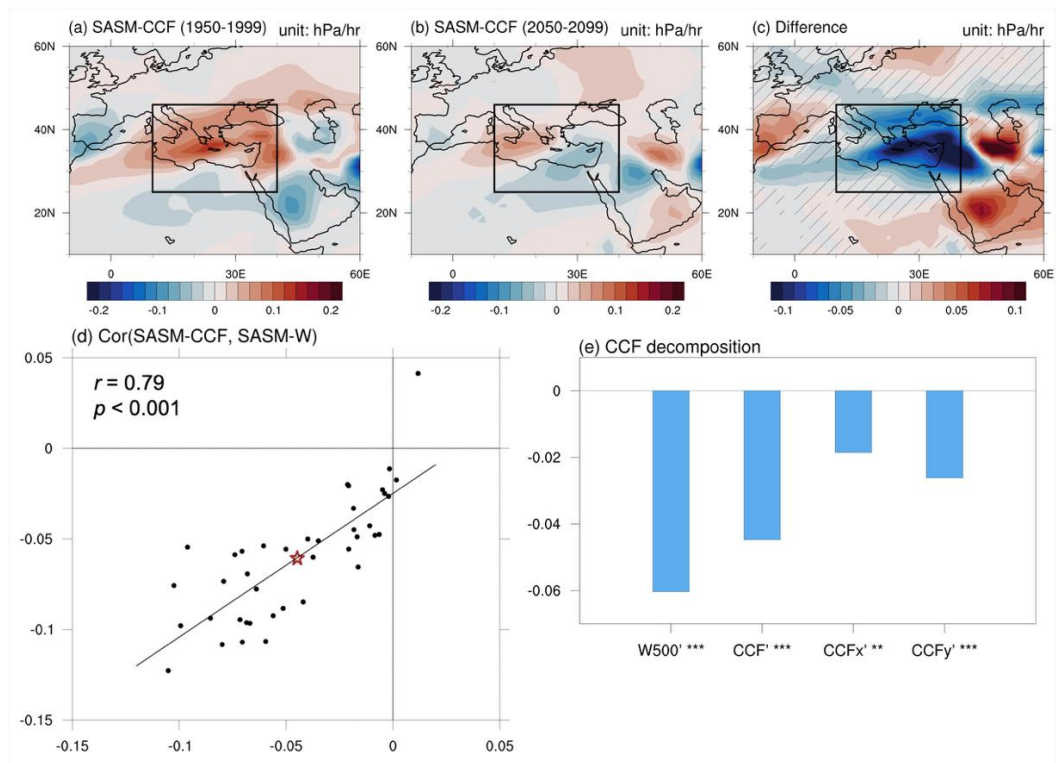


Fig. R7. SASM-related CCF anomalies based on CESM1LE (a) at 325K isentropic surface during 1950-1999, (b) at 330K isentropic surface during 2050-2099 and (c) their difference (Slashes represent area with change not significant at significance level $p=0.1$). Different isentropic level is selected here because of greenhouse-warming-driven increase on tropospheric potential temperature. During 2050-2099, 330K isentropic surface is closer to 500hPa pressure level. The inter-member correlation between CEM regional mean changes on SASM- ω 500 and SASM-CCF

is shown in (d), where each dot represents a single member and the red star refers to MME changes. X-axis (units: hPa/hr) in (d) indicates changes on SASM-CCF and Y-axis (units: hPa/hr), changes on SASM- ω 500. (e) The decomposition of MME future change on SASM-CCF (***:

$$p<0.001, **: p<0.01, \text{ units: hPa/hr})$$

Next, we further examined the processes that determine the change of SASM-CCF_x and SASM-CCF_y. According to the equation (4) and (5), CCF_x (CCF_y) is determined by zonal (meridional) wind and zonal (meridional) pressure gradient on isentropic surface, which is equivalent to zonal (meridional) temperature gradient on isobaric level. Hence, we further investigated their change, respectively. For SASM-CCF_x, we found an evident weakening of zonal gradient of SASM-T500 over CEM (31 out of 40 members), which correlates significantly with future change of SASM-CCF_x (Fig. R8a). This suggests that, the SASM-related isentropic surface change will become more flat in the future, thus inhibiting adiabatic subsidence. The SASM-U500, on the contrary, shows no significant change by 2100 (Fig. R8c). Therefore, change on SASM-CCF_x is mainly caused by change of SASM-related zonal thermal structure.

For SASM-CCF_y, we note a substantial decline on SASM-V500 (32 out of 40 members) and can well explain the future change of SASM-CCF_y (Fig. R8b). As a contrast, the meridional thermal structure induced by SASM change little under global warming (Fig. R8d), suggesting its trivial role on shaping the decrease of SASM-CCF_y.

We have also conducted identical analysis using CMIP6 models and obtain similar conclusions (Fig. R9).

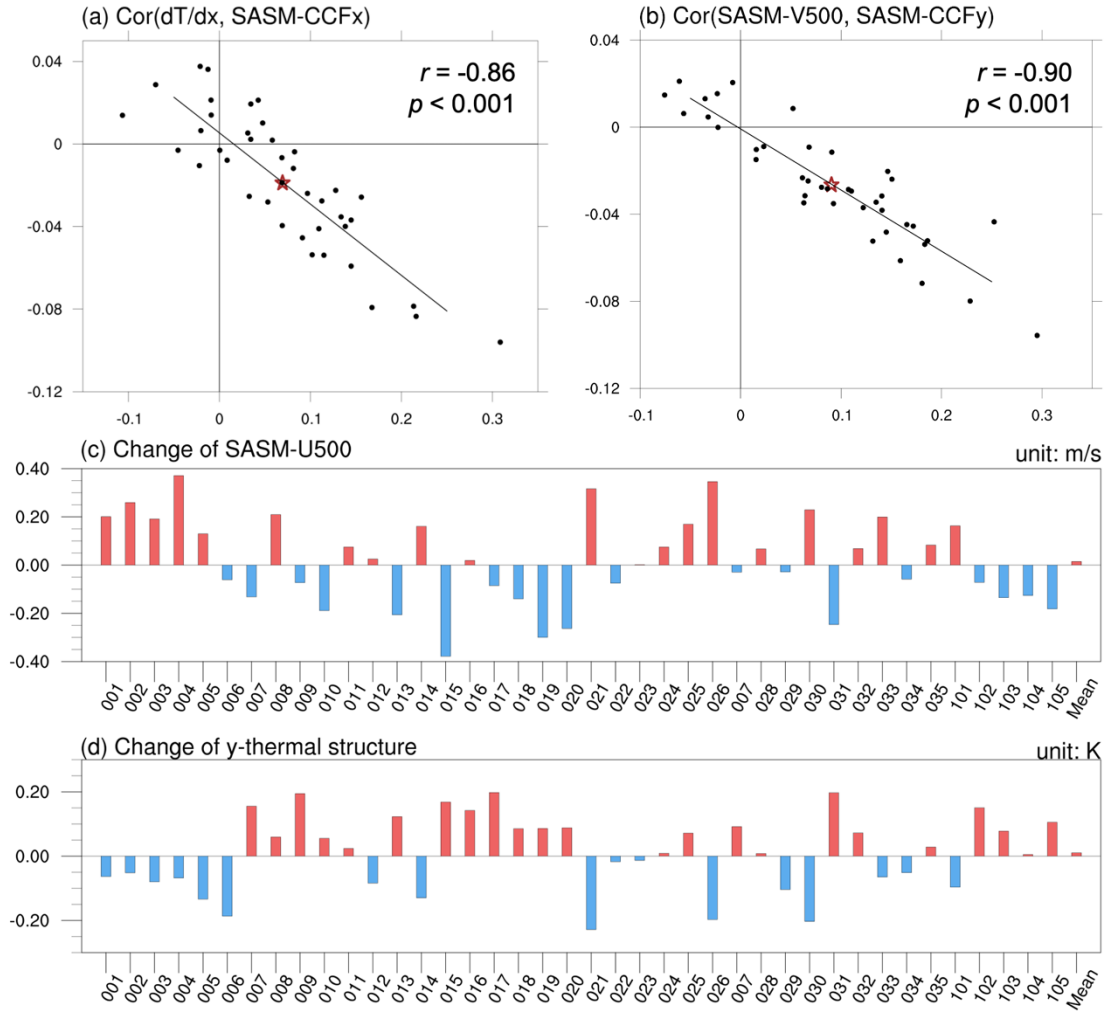


Fig. R8. (a) Scatter plot of future change (2050-2099 minus 1950-1999) on zonal thermal structure induced by SASM and SASM-CCF_x (x-axis: change on zonal thermal structure, unit: K; y-axis: change on SASM-CCF_x, unit: hPa/hr) (b) Same as (a), but for future change on SASM-V500 and SASM-CCF_y (x-axis: change on SASM-V500, unit: m/s; y-axis: change on SASM-CCF_y, unit: hPa/hr). (c) Future change of SASM-U500 for CESM1LE individual members and MME. (d) Same as (c), but for change on meridional thermal structure induced by SASM. The zonal thermal structure induced by SASM is estimated by the difference between meridionally (25°-45°N) weighted averaged SASM-T500 at 10°E and that of 40°E. The meridional thermal structure induced by SASM is calculated by the difference between zonally (10°-40°E) averaged SASM-T500 at 45°N and that of 25°N. Black dots in (a) and (b) represent individual members and the red star denotes MME results.

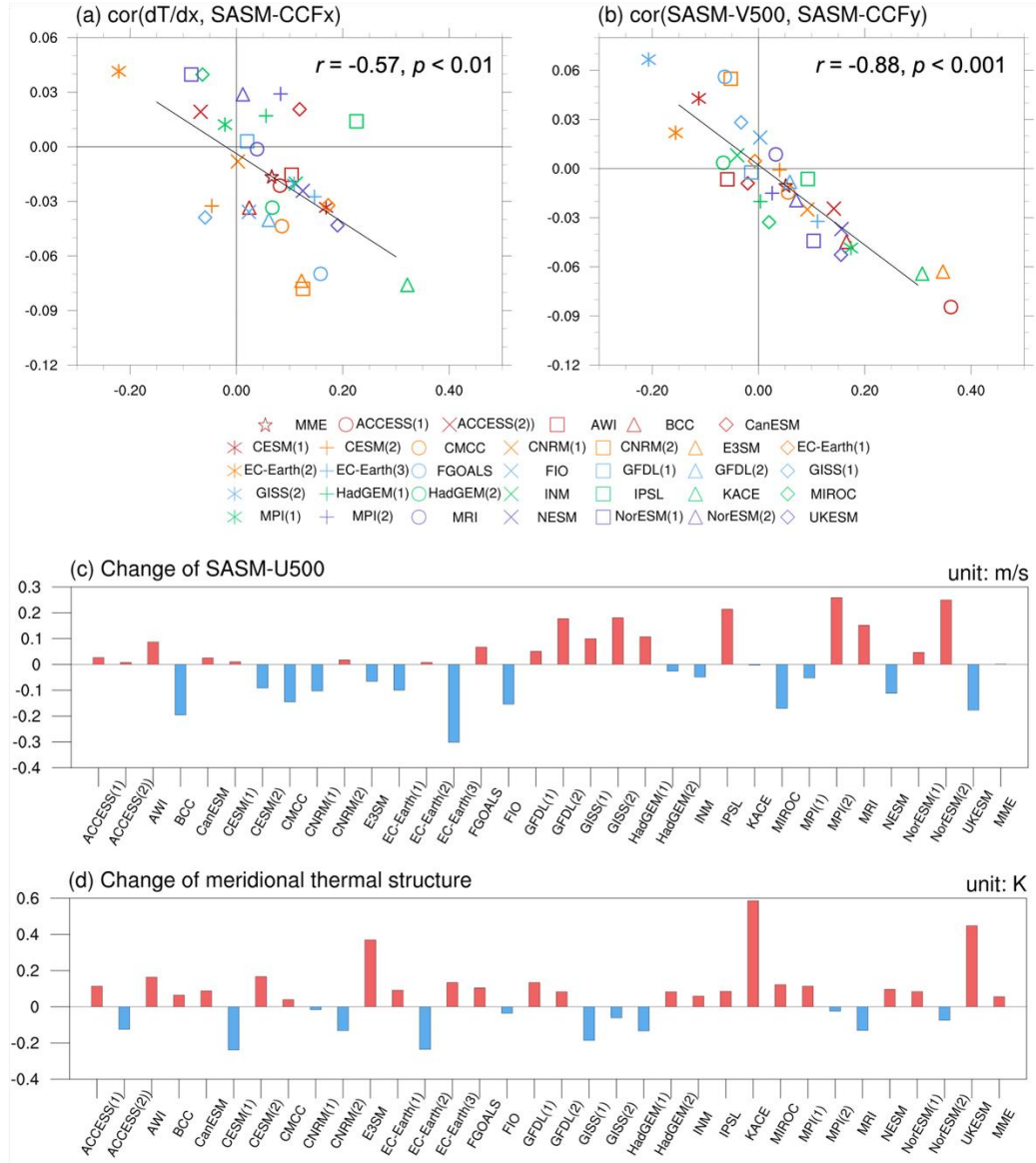


Fig. R9. Same as Fig. R8, but for results from 33 CMIP6 models.

To summarize, we have further decomposed the SASM-CCF into zonal and meridional components. We found that both components significantly weakened under global warming, where weakening of zonal thermal structure induced by SASM led to decline of SASM-CCF_x and diminished SASM-V500 caused a weaker SASM-CCF_y . Please see **session 3 and 4** in the revised manuscript for revision of detailed analysis of the physical mechanisms.

10. The moist static energy analysis does not seem to add much to the temperature analysis. I would suggest to remove it. Or the authors need to provide a deeper analysis that illuminates the SASM-CEM teleconnection response to global warming.

Response:

Thanks. The original moist static energy diagnosis is removed in the revision. We have re-examined the underlying mechanism, and present multiple lines of evidence based on theory, simulations and numerical experiments to demonstrate that the westward expansion of the SASM related thermal structure is due to the uplift of SASM convection under global warming.

1) Theoretical basis:

Previous studies pointed out that tropical convection will become higher under global warming as a response to the elevated tropopause (Yu et al., 1998; Santer et al., 2003; Chou and Chen, 2010; Fan and Dommenges, 2023). The thermal structure in the mid-troposphere is also suggested as a westward propagating Rossby wave in response to SASM heating (e.g. Rodwell and Hoskins, 1996; Beverley et al., 2021). Under the quasi-geostrophic approximation of large-scale atmosphere motion, the horizontal scale of Rossby wave is given following the Rossby radius of deformation (Gill, 1980):

$$L_R \sim \frac{NH}{f}$$

Where N is the Brunt–Väisälä frequency, H represents the height (depth) and f denotes the Coriolis parameter. Therefore, we hypothesize that, as the tropopause and convection center shifts higher in a warming future, the horizontal extent of Rossby wave response to SASM heating will become larger, which eventually lead to the westward expansion of thermal structure.

2) Model simulations:

The westward expansion of SASM-T500 is already documented in the original

manuscript, as a statistically significant phenomenon under global warming ($p < 1 \times 10^{-5}$). Here, we also calculated the diabatic heating profile over the SASM region (Fig. R6a). It is evident that the heating rate during SASM becomes larger in the mid-to-upper troposphere while smaller in the lower troposphere. To quantify the magnitude of convection uplift, we calculated the level-weighted average convection height following:

$$H = \frac{\int_{925hPa}^{100hPa} Q'_p(p) \cdot p dp}{\int_{925hPa}^{100hPa} Q'_p(p) dp}$$

Here, $Q'_1(p)$ is the regional average of SASM-related atmospheric heating rate at pressure level p over the SASM region. The SASM-related convection height is uplifted about 35hPa, from 452hPa to 417hPa in MME (Fig. R6a). This is also evidenced by a high inter-member consensus (38 out of 40 members simulate uplifted convection). A significant correlation between the convection height change over SASM region and the change on zonal gradient of SASM-T500 further support our hypothesis, suggesting that higher SASM convection can lead to thermal structure with larger spatial extent (Fig. R6b).

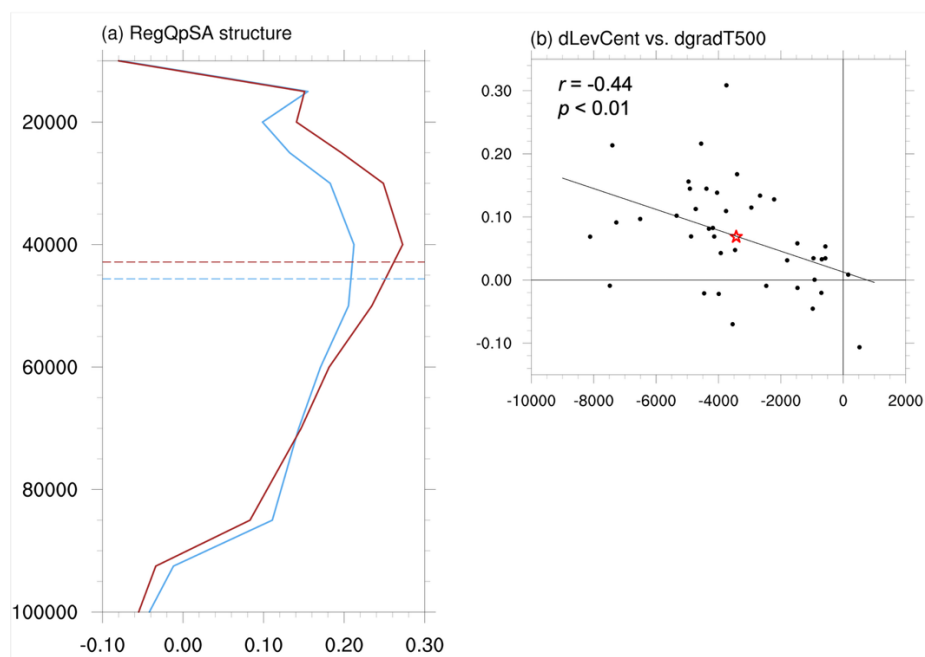


Fig. R10. (a) The heating rate profile over SASM region (x-axis: SASM-Qp, units: K/day; y-axis: height, units: Pa). The heating rate on each level is calculated based on Qp (see Methods in the

revised manuscript) anomalies regressed onto the standardized Q1 series over SASM region. The red (blue) thick line denotes MME heating profile during 2050-2099 (1950-1999). The red (blue) dashed line indicates the convection height in MME during 2050-2099 (1950-1999). (b) Scatter plot of change on convection height (x-axis, units: Pa) and change of zonal thermal structure (y-axis, units: K). Black dots indicate individual members and red star refers to MME.

3) Numerical experiments:

To further verify above conclusions, we have performed a set of numerical experiments based on LBM to explore the circulation response to prescribed heat source. We designed two simulations using LBM: The first run (HIST) uses summer climatology during 1950-1999 in CESM1LE MME as background state and the second run (FUT) uses that of 2050-2099. The prescribed heat source is located in the same horizontal location but with different height of maximum. The maximum of heating in the HIST run is set at sigma level $\sigma=0.55$ and the FUT run, $\sigma=0.45$ (Fig. R7).

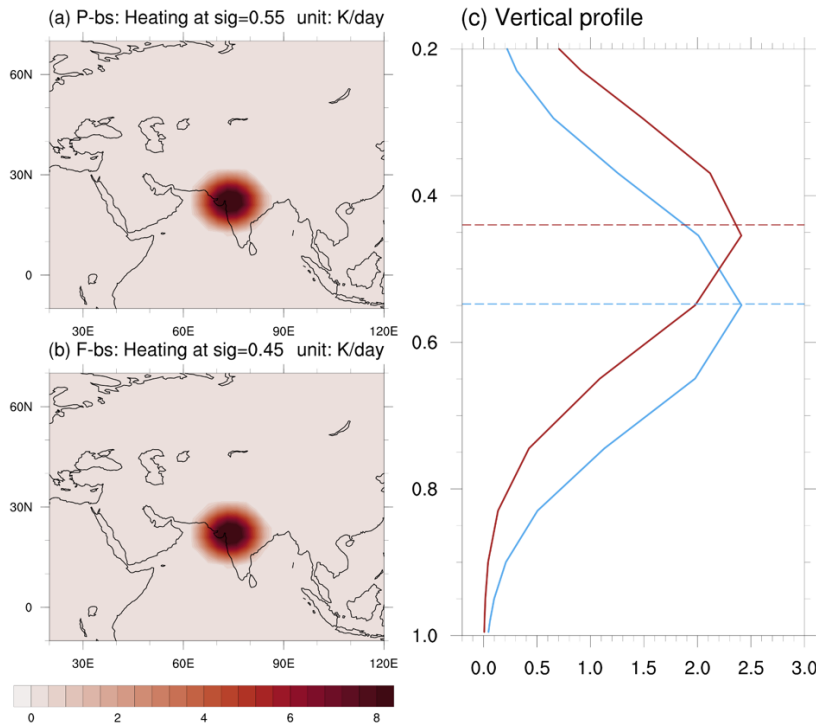


Fig. R11. Location and magnitude of the prescribed heat source over SASM region in (a) HIST run and (b) FUT run. (c) The profile of heat source in the two experiments (x-axis: heating rate, unit: K/day; y-axis: sigma level height). The red (blue) thick line denotes heating profile in HIST

(FUT) run. The dashed lines indicate the weighted height of heating.

The steady atmospheric responses of the two simulations show distinct features (Fig. R8). Both LBM runs can realistically simulate the spatial pattern of the thermal structure with a positive zonal gradient over Mediterranean (Fig. R8a, c) and thus the subsidence (Fig. R8b, d). Nevertheless, the magnitude of T500 response is larger in the FUT run and its center of maximum shifts westward, which qualitatively matches the results from coupled model simulations (Fig. R8e). As a result, the tropospheric subsidence weakens significantly over CEM (Fig. R8f), in line with Fig. 1 in the revised manuscript.

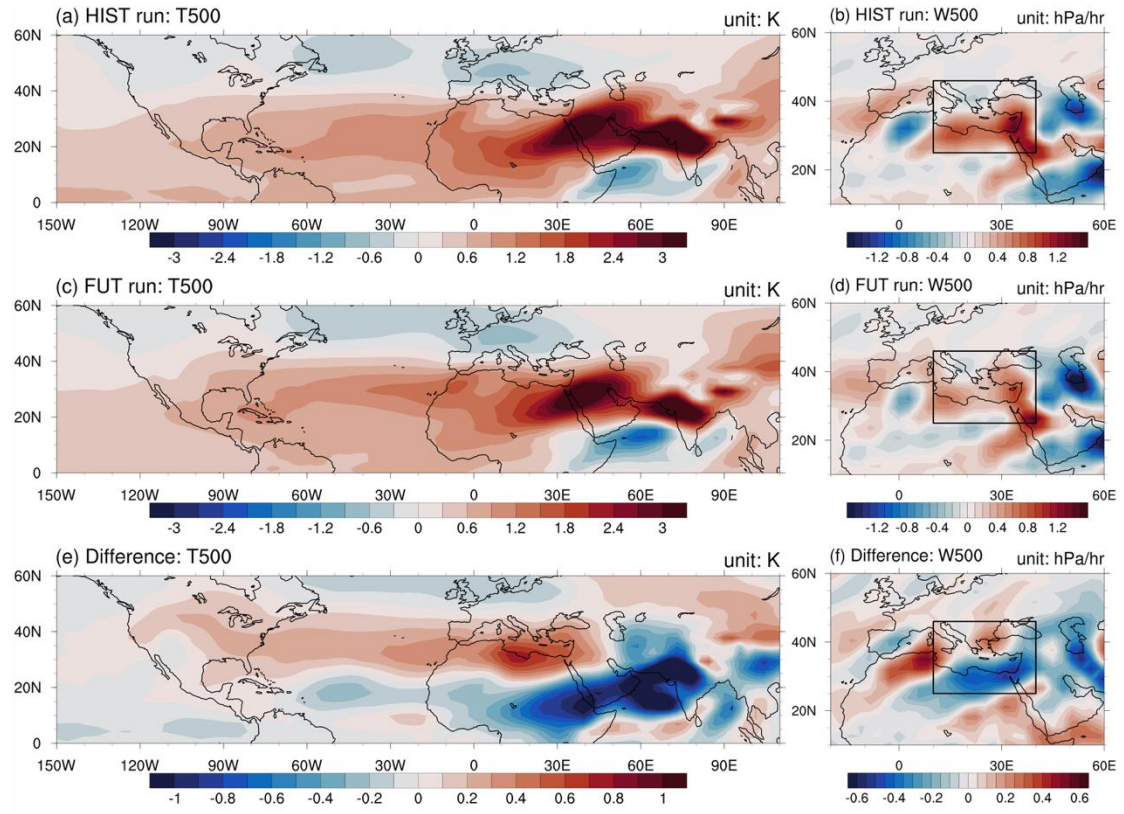


Fig. R12. Steady atmospheric response to heat source over SASM region in LBM. Temperature response at 500hPa in (a) HIST run, (b) FUT run and (c) their difference. (b), (d), (f): as in (a), (c), (e), but for vertical velocity at 500hPa.

To conclude, the weakened CEM circulation response to SASM, manifested as weaker SASM-CCF, is evidently influenced by the westward expansion of SASM thermal structure. We highlight that the change of thermal structure is induced by the uplifted

deep convection over SASM region under global warming. For details of the updated mechanism analysis, please see **Line 179-202** of the revised manuscript.

11. line 34: *“As a result”*: the causal relationship with what precedes is unclear.

Response:

Thanks. Rephrased. Please see **Line 31-38** in the revised manuscript.

12. line 36: *“matter of urgency”* (same with e.g., *“critical issue”* at l. 54): why is it so urgent? How would a better understanding of the CEM dynamics help better understand (or predict) extreme events? The authors must either provide more arguments for using this formulation or just avoid this kind of subjective phrasing. There is enough scientific interest to study the subject of the paper.

Response:

Thanks. We have avoided similar expressions in the revised manuscript. Please see **Line 37-38** for detail.

13. line 148: *“expands increasingly westward with height”*: unclear formulation.

Response: Rephrased.

14. line 238: “33 out 40 members”: What does it mean? Is it the number of members that simulate a decrease of the explained variance? or a significant decrease of these explained variance? A level of significance on Figure 5.d would be useful.

Response:

Thanks. Among the 40 CESM1LE members, 33 members show a decrease in SASM-explained variance for Mediterranean summer land precipitation. The decrease on variance is at $p < 0.001$ level of significance based on students' t-test. We have supplemented this information in **Fig. 5d** in the revised manuscript.

15. line 268: have the authors quantify the SASM-CEM teleconnection weakening onto the Etesian winds variability?

Response:

Thanks. We have evaluated the change of SASM-related V850 over Aegean Sea. The Etesian wind is commonly defined as the strength of summer low-level meridional wind over Aegean Sea (e.g. Tyrlis and Lelieveld, 2013; Di Capua et al., 2024). Here, we estimate the Etesian winds using V850 over 30°-42°N, 20°-28°N (Black rectangle in Fig. R13a-c). Our results show that V850 over Aegean Sea exhibits northerly anomaly in response to SASM in the present (Fig. R13a), which coincides with previous studies (Di Capua et al., 2024). Under global warming, the strength of SASM-related northerlies significantly weakens (Fig. R13c). We have calculated the change of Etesian wind variance explained by SASM (see formula X) and found a significant decrease

(from ~10% to less than 3%) as shown in Fig. R13d. These results provide new evidence that the influence of SASM on CEM climate will vanish under global warming.

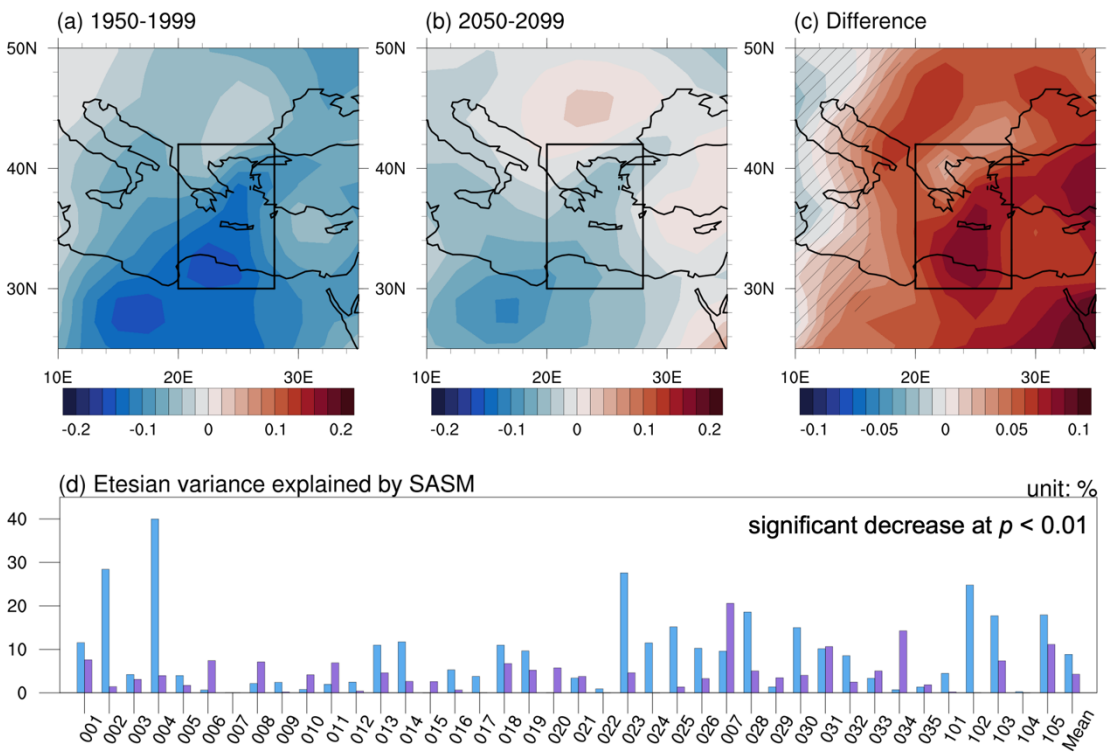


Fig. R13. SASM-related V850 during (a) 1950-1999, (b) 2050-2099 and (c) their difference. (d) Etesian wind variance explained by SASM of individual members in CESM1LE. Black rectangle in (a)-(c) represent area used to calculate strength of Etesian wind. Dashed lines in (c) denote area with change not significant at $p=0.1$. Blue (Purple) bars in (d) refers to Etesian wind variance explained by SASM during 1950-1999 (2050-2099).

16. line 278: *How sure are the authors that the SASM-CEM teleconnection has remained stable in the present day climate? What do they mean by present day? What is the internal variability of the teleconnection intensity?*

Response:

Thanks. In our study, we refer “present day” to the time period 1950-1999. CESM1LE can realistically simulate the significant interannual relation between SASM and CEM ω_{500} during 1950-1999. To be specific, the correlation coefficient (CC) between CEM ω_{500} and SASM diabatic heating is 0.41 in terms of MME. Among the large ensemble members, 34 out of 40 members (85%) simulate CC higher than 0.304, which represents the threshold of significance level $p=0.05$. 26 out of 40 members (65%) reproduce CC higher than 0.393, representing the threshold of $p=0.01$. The high performance of CESM1LE gives us confidence to state that SASM-CEM teleconnection is significant and stable in the present-day climate. Moreover, this relationship is also evident in ERA5 during 1971-2000 (see Extended Data Fig. 2 in the revised manuscript).

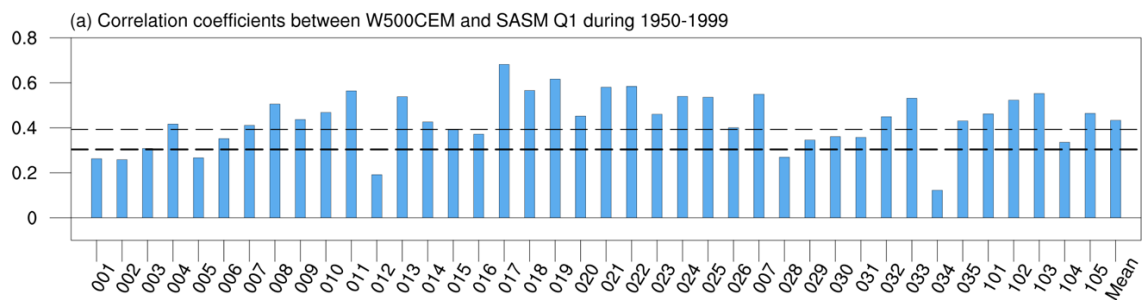


Fig. R14. Correlation coefficients between CEM ω_{500} and SASM diabatic heating index during 1950-1999 in CESM1LE. Thick (thin) dashed line denotes the $p=0.01$ ($p=0.05$) significance level.

17. Fig. 1: not fully clear how to quantitatively interpret it. I understand that the authors plot a regression of the 500-hPa vertical velocity on a normalized SASM interannual index based on Q1? Would units in something like hPa/hr per W/m² provide a better quantitative analysis? What are the typical interannual variations of SASM Q1? Besides, can the authors add a level of significance (e.g., 95%) on panel (d)?

Response:

Thanks. Yes, the shadings in Fig. 1a-c represent the regressed 500hPa vertical velocity onto the standardized SASM diabatic heating index estimated based on Q_1 . Thus, the value (in hPa/hr) indicates the change of ω_{500} in response to one-standard-deviation enhancement of SASM heating. Because the Q_1 series is standardized in advance (i.e. no unit), the unit in Fig. 1a-c is hPa/hr rather than (hPa/hr)/(W/m²).

The magnitude of bar in Fig. 1d refers to the future change of SASM-related ω_{500} average over CEM region. The significance of future change is estimated by comparing the MME from the two time periods. We have performed the students' t-test and found that SASM-related ω_{500} weakens in the future in the significance at $p < 1 \times 10^{-10}$.

We have re-written the figure caption and implemented the significance information on Fig. 1d in the revised manuscript.

18. Fig 5: how does this impact of the SASM-CEM teleconnection on precipitation compares with the total CEM precipitation interannual variability? Isn't -4 mm/month small?

Response:

Thanks. The variance of Mediterranean summer precipitation explained by SASM is ~15% in terms of CESM1LE MME and the variance drops sharply to less than 4% under global warming (see Fig. 5d in the revised manuscript).

For your second concern, “-4 mm/month” is small but it should be considered that summer is dry season for Mediterranean regions. Despite the small value of absolute precipitation, SASM still could explains ~15% of precipitation variance (over 40% for some members), suggesting its important role in shaping Mediterranean interannual climate variability in the present climate.

19. *Extended Figure 3: the plot show the period 1975-2075, while the caption indicates 1920 to 2099.*

Response:

Thanks. The x-axis (time period) ranges from 1975 to 2075. For any given time t in the plot, the shadings at t indicates the regional mean of SASM-related ω_{500} over CEM during year $t-25$ to year $t+24$. For instance, value at year=2000 indicates the regional mean ω_{500} response to SASM during 1975-2024.

We have supplemented more detailed explanations in **Line 483-485** of the revised manuscript.

20. *Extended Figure 5: unclear what is the “zonal contrast of SASM-related air temperature anomalies.*

Response:

Thanks. The strength of SASM-related zonal thermal structure is measured by zonal contrast of SASM-related T_{500} . To be specific, SASM-related T_{500} is firstly meridionally weighted averaged from 25°-45°N. Then, the zonal temperature contrast is calculated by the difference between meridionally averaged SASM- T_{500} at 40°E and 10°E. Larger zonal contrast indicates stronger zonal temperature gradient (i.e. steeper isentropic surface) over CEM, which is favorable for intensified SASM-CCF_x.

We have included a more detailed explanation in **Line 375-376** in the revised

manuscript.

21. Extended Figure 6: I was not convinced that this figure with potential temperature anomalies add much to the same figure with temperature anomalies (Fig. 3). I would keep only the potential temperature.

Response:

Thanks. This figure has been removed in the revised manuscript.

References

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**Title: Impact of Asian monsoon on Mediterranean summer
climate will fade away in a warming world**

Authors: H. Yu, T. Zhou and Z. Guo

Overview and major comments

I reviewed the first version of the manuscript. The authors provide thorough and convincing responses to all the points I had, as well as to those of the other reviewer. In particular, I appreciate the addition of CMIP6 models' simulations, further theoretical arguments and numerical experiments based on a linear baroclinic models. They all do provide the appropriate robustness of the authors' results and enhance their physical interpretation. Besides, I find that the manuscript has been significantly clarified. Thus, following this first round of reviews, I think the manuscript is almost ready for publication, pending to the very few minor comments that follow below.

Minor comments

1. p5, l121: "consistently explains" would sound more appropriate than "can largely explain".
2. p5, l123-124: "are well reproduced" would be better than "can be well reproduced".
3. Figure 3: a few remaining "Qp" in some panel titles.
4. p9, l183-194: to fully agree with the theoretical argument based on the Rossby radius increase due to increased heating height, have you quantify the possible change in the vertical stability? Similarly, in your experiments with a LBM, have you separated the role of the heating profile change from that of the temperature basic state change?
5. p18, l398: should be "deep convection in the SASM region warms"
6. Extended Data Figure 4: why do you use the 1900-1949 period for CMIP6 models while you used 1950-1999 for the CESM1 large ensemble simulations? Is the signal less consistent?

Reply to Reviewers #1:

Thank you for the valuable comments and comprehensive instructions on enhancing the manuscript. We sincerely appreciate the time and effort you dedicated to reviewing our work and providing us with insightful feedback. Your comments have been instrumental in significantly improving the manuscript's quality. To ensure clarity, we have highlighted your original comments in *italic font*, and our responses are presented in normal font below each comment.

1) “Local contribution from dynamical feedback”:

L208–232: This section introduces new analysis and results; however, the presentation is somewhat unclear. I found the description difficult to follow even after multiple readings, and I believe that a general reader may struggle to grasp the main message, particularly in the second paragraph.

a) L213–215 and Fig. 4b:

The SASM–V500 signal shows a southerly flow over the core CEM region, particularly near the area of maximum climatological subsidence over Greece. I find this result difficult to interpret. Does this imply that, in the future period (2050–2099), a stronger SASM is associated with weaker northerlies at the margins of the CEM box but southerlies in its centre? The authors are encouraged to elaborate on the physical interpretation of this pattern.

Response:

Thanks for your question. Your interpretation is correct. South Asian Summer Monsoon related V500 (SASM-V500) over the Central-to-Eastern Mediterranean (CEM) in present-day climate is negative (i.e. northerly wind) and plays an important role in SASM-related subsidence. Previous studies suggest that the SASM-related

northerly wind over mid-to-lower level is caused by negative vertical gradient of SASM-related subsidence via Sverdrup balance¹⁻⁴:

$$f \frac{\partial \omega'}{\partial p} \approx \beta v'$$

Here, f and β indicates Coriolis parameter and its meridional gradient, respectively. ω' and v' refers to SASM-W500 and SASM-V500, respectively.

By the end of this century, SASM-related 500hPa northerly wind weakens substantially (32 out of 40 members agrees on sign of change), even turns into southerly flows over Central Mediterranean, as you have noticed. The decline of SASM-related northerly flow tends to reduce SASM-CCFy (Fig. 4c in the revised manuscript), thereby reducing SASM-W500.

The decrease of SASM-V500 can also be interpreted through Sverdrup balance. Under global warming, the weakening of SASM-related subsidence is most evident over mid-to-high troposphere (~ 400 hPa) (Extended Data Fig. 3b), suggesting that the magnitude of $\frac{\partial \omega'}{\partial p}$ also decreases in the future (Fig. 4d, e in the revised manuscript). Therefore, the SASM-related northerly wind declines accordingly based on the Sverdrup balance. This process further reduces the SASM-W500, act as local dynamical feedback.

We have re-organized this part and hope the main message is now clarified and friendly to general readers. Please see Line 204-225 in the revised manuscript for clarification of the physical interpretation.

b) L224–225: The reference to 88% is unclear. Please clarify what this percentage represents and rephrase accordingly. In addition, the meaning of the symbols v' and ω' should be explicitly defined.

Response:

Thanks for your comment.

The reference to 88% is obtained by calculating the ratio between Multi-member ensemble mean of future change of $f \frac{\partial \omega'}{\partial p}$ and $\beta v'$, the two terms of Sverdrup balance as discussed in the response above. This is also illustrated in Fig. 4d in the revised manuscript (compare the rightmost purple bar with the rightmost yellow bar). This percentage represents that 88% of the future weakening of SASM-V500 can be explained by the change of vertical gradient of SASM-related subsidence via Sverdrup balance.

The symbols v' and ω' represents SASM-related meridional wind and vertical motion, respectively.

Please see Line 216-220, Line 237-238 and Line 439-440 in the revised manuscript.

c) Fig. 4d: It is not clear whether the two terms in the Sverdrup balance shown in the bar plot correspond specifically to the SASM-related signal. This ambiguity complicates the interpretation of the results. If the Sverdrup balance holds, one would expect the magnitudes of the two terms to be comparable. Why, then, does the discrepancy between the two bars increase in the future period?

Response:

Thanks for your question. In Fig. 4d-f, v' and ω' are calculated by regressing interannual component of meridional wind and vertical motion to the standardized SASM heating index, thus representing SASM-related signal.

To understand the discrepancy between $f \frac{\partial \omega'}{\partial p}$ and $\beta v'$, we have examined the

neglected terms in Sverdrup balance:

$$f \frac{\partial \omega'}{\partial p} - ADV' = \beta v'$$

Here, ADV' is SASM-related relative vorticity advection with the form of:

$$ADV = \vec{V} \nabla \cdot \zeta$$

Where $\vec{V}$ is horizontal wind and ζ denotes relative vorticity. Based on the linearized assumption, vorticity advection is neglected to obtain Sverdrup balance. We further calculated the SASM-related vorticity advection term and its change under global warming (Fig. R1). The advection term is negligible in present-day climate, and acts to balance the discrepancy between the two terms of Sverdrup balance.

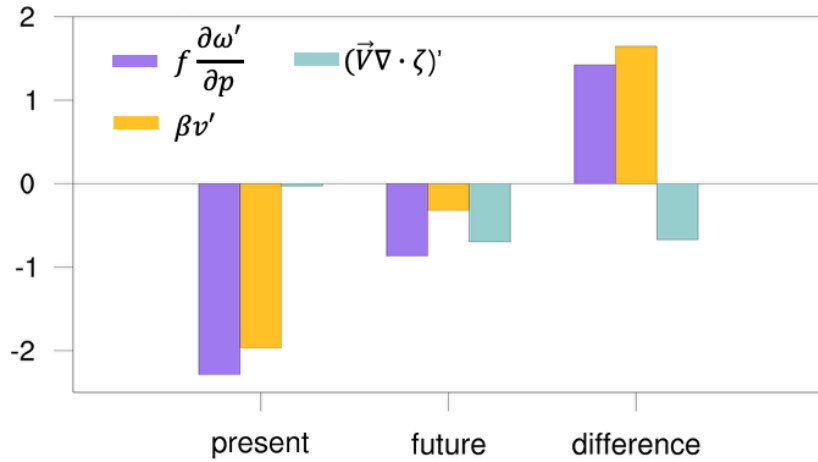


Fig. R1. Bar plot of each term in Sverdrup relation and their Multi-member ensemble mean future change. Note that each term is the regional averaged over the CEM (25°-46°N, 10°-40°E) at 500hPa (unit: 10^{-12}s^{-2}).

Although the importance of advection term grows under global warming, the contribution to weakened SASM-related northerly flow is still dominated by change of vertical gradient of SASM-W500 (compare rightmost bars in Fig. R1), suggesting that Sverdrup balance is effective in determining the driver of weakened SASM-V500. Thus, to maintain the brevity and readability of the main text, we omitted the advection term as a minor role in the equation.

2) *Argument involving the Rossby radius of deformation:*

L179–183: I find the discussion difficult to follow, particularly the motivation for invoking the Rossby radius of deformation. In mid-latitudes, weather systems tend to have scales comparable to the Rossby radius because baroclinic instability grows most efficiently at that scale. However, it is not clear how this concept applies to the case of monsoon-related deep moist convection discussed here. The authors should clarify the relevance and physical interpretation of the Rossby radius in this context.

Response:

Thanks for your comment. We have re-written the paragraphs concerning the effect of elevated monsoon convective heating on the westward expansion of SASM-related thermal structure. We believe the physical mechanism is well explained. The reference of Rossby Radius of Deformation in the original manuscript is unnecessary and lack of continuity with section 3 of the manuscript. To avoid any ambiguity, we have removed the statements about Rossby Radius of Deformation.

Please see Line 182-202 in the revised manuscript.

3) *L101: The statement appears inaccurate. The SASM-related vertical motion remains positive over the western and northern parts of the CEM box. Please revise accordingly.*

Response:

Thanks for your careful examination. We have revised the expressions. Please see Line 100-103 in the revised manuscript.

Minor comments

1) L57, 81 and elsewhere: it should read “timescales”

Response:

Done.

2) L108: Have the authors checked the only ensemble member that differs? It may reveal a different but yet interesting view on the SASM-Mediterranean circulation.

Response:

Thanks for your advice. We have checked the only member that shows enhanced CEM climate response to SASM in the future, namely member 034 (Fig. 1d in the revised manuscript). We first examined SASM-related W500 and its future change (Fig. R2). In contrast to other members, 034 represents rather weak SASM-related vertical motions in present-day climate, which strengthens significantly under global warming.

To investigate the potential underlying mechanism, we further analyzed future change of monsoon-induced thermal structure. Compared with MME SASM-related temperature, the magnitude of thermal structure in 034 in present-day climate is substantially weaker (Compare Fig. R3a and Fig. 3a in the revised manuscript), resulting in a negative zonal temperature gradient thereby weaker SASM-related W500.

These results indicate strong control of monsoon-induced thermal structure on the summer climate over the CEM. Weak thermal structure of member 034 in present-day climate implies that the interannual relation between SASM and CEM climate is also modulated by strong natural variability (because warming level during 1950-1999 is

relatively small). The behavior of this particular member offers the opportunity in exploring how the SASM-CEM climate relation is shaped by internal variability

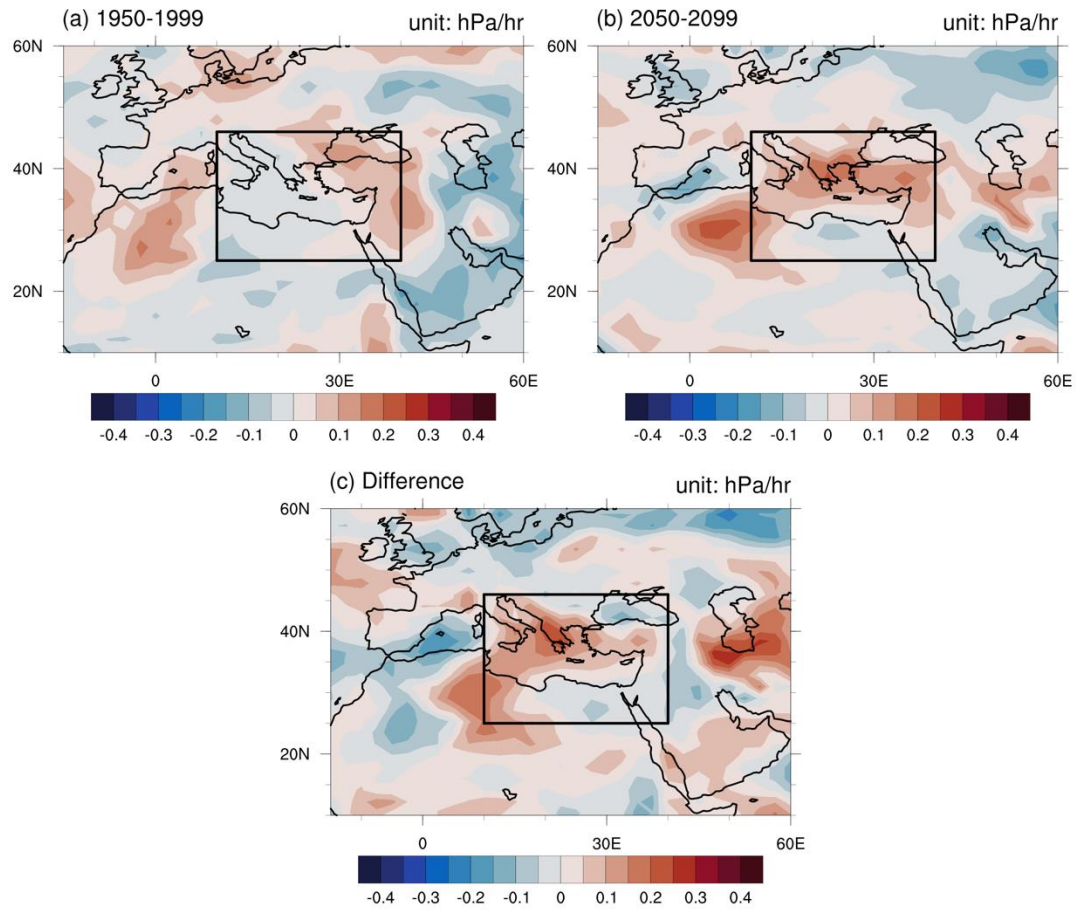


Fig. R2. SASM-related 500hPa vertical motion of member 034 during (a) 1950-1999, (b) 2050-2099 and (c) their difference.

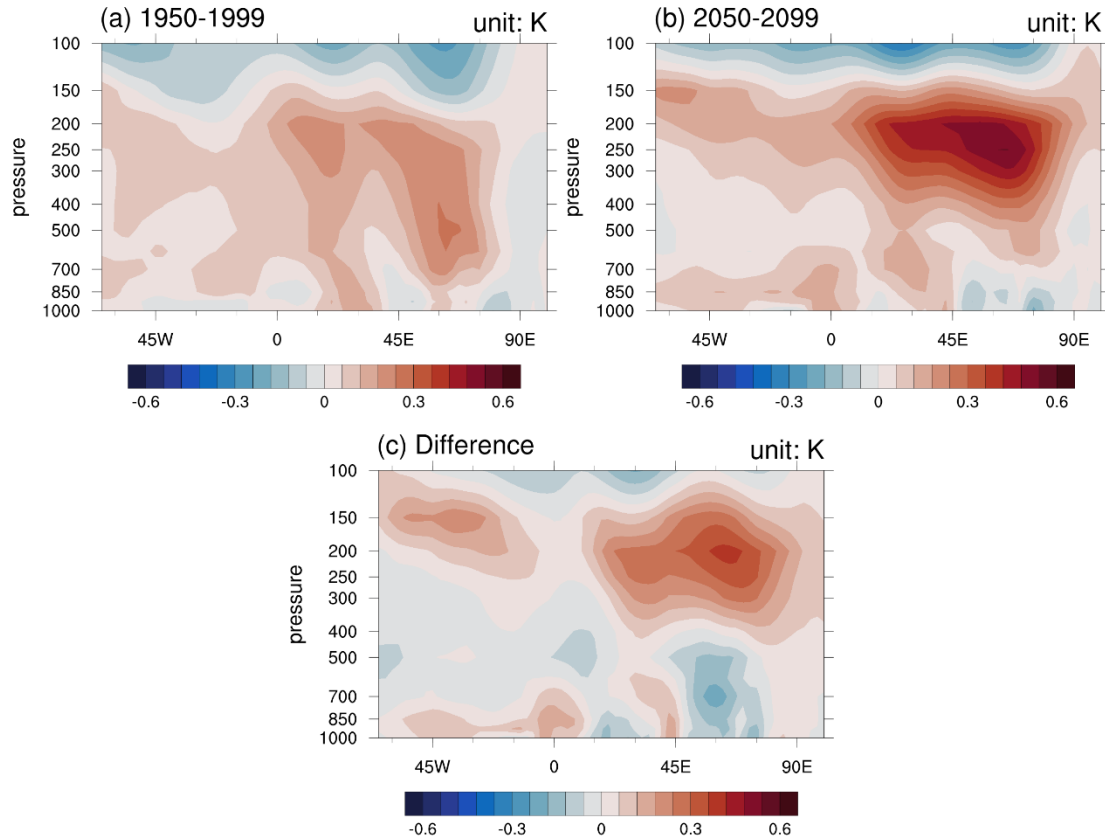


Fig. R3. 25°-46°N Meridionally averaged SASM-related temperature of member 034 during (a) 1950-1999, (b) 2050-2099 and (c) their difference (unit: K).

3) L160-162: *I cannot see the relevant information on Fig. 6.*

Response:

The citation should be “Extended Data Fig. 6a-d”. We have corrected this. Please see Line 163 in the revised manuscript.

4) L179: *“Why does SASM-related” -> “Why does the SASM-related”*

Response:

Done.

5) L218: *“Fig. 6e” - > “Fig. 7e”. Please check all references to the extended figures because there are some mistakes.*

Response:

Done. We have examined through the manuscript and corrected all the typos on Figure reference.

References

1. Rodwell, M. J. & Hoskins, B. J. Subtropical anticyclones and summer monsoons. *J Clim* **14**, 3192–3211 (2001).
2. Tyrlis, E., Lelieveld, J. & Steil, B. The summer circulation over the eastern Mediterranean and the Middle East: influence of the South Asian monsoon. *Clim Dyn* **40**, 1103–1123 (2013).
3. Levine, X. J. & Boos, W. R. Sensitivity of subtropical stationary circulations to global warming in climate models: a baroclinic Rossby gyre theory. *Clim Dyn* **52**, 4873–4890 (2019).
4. Barcikowska, M. J. *et al.* Changes in the future summer Mediterranean climate: contribution of teleconnections and local factors. *Earth Syst Dyn* **11**, 161–181 (2020).

Reply to Reviewers #2:

Thank you for the valuable comments and comprehensive instructions on enhancing the manuscript. We sincerely appreciate the time and effort you dedicated to reviewing our work and providing us with insightful feedback. Your comments have been instrumental in significantly improving the manuscript's quality. To ensure clarity, we have highlighted your original comments in *italic font*, and our responses are presented in normal font below each comment.

Minor comments

1. P5, L121: “consistently explains” would sound more appropriate than “can largely explain”.

Response:

Thanks. We have replaced the expression accordingly. Please see Line 122-124 in the revised manuscript.

2. P5, L123-124: “are well reproduced” would be better than “can be well reproduced”.

Response:

Replaced. Please see Line 124-125 in the revised manuscript.

3. *Figure 3: a few remaining “Qp” in some panel titles.*

Response:

Thanks for your careful examination. We have changed the panel titles accordingly.

4. *P9, L183-194: to fully agree with the theoretical argument based on the Rossby radius increase due to increased heating height, have you quantified the possible change in the vertical stability? Similarly, in your experiments with a LBM, have you separated the role of the heating profile change from that of the temperature basic state change?*

Response:

Thanks for your question. According to the definition of Rossby Radius of Deformation ($L_R \sim \frac{NH}{f}$), the horizontal scale of Rossby wave response is proportional to both Brunt-Väisälä frequency (BVF) (vertical stability) and scale height (here, the convection height of South Asian Summer Monsoon). Since the location of convective heating elevate from 452hPa to 417hPa under global warming, we calculate the difference between future BVF at 417hPa and present-day BVF at 452hPa to quantify the change in vertical stability. Similarly, the difference of geopotential height is calculated to quantify the change of height.

Both BVF and height increase in response to global warming (Fig. R1) but with distinct magnitude. Note that the changes of BVF and height are in percentage shown in Fig. R1. Over SASM region where convective heating releases, BVF increases by ~2.5% (Fig. R1e) under global warming while height elevates over 12% (Fig. R1f), suggesting the dominant role of uplifted convection height on Rossby Radius of Deformation.

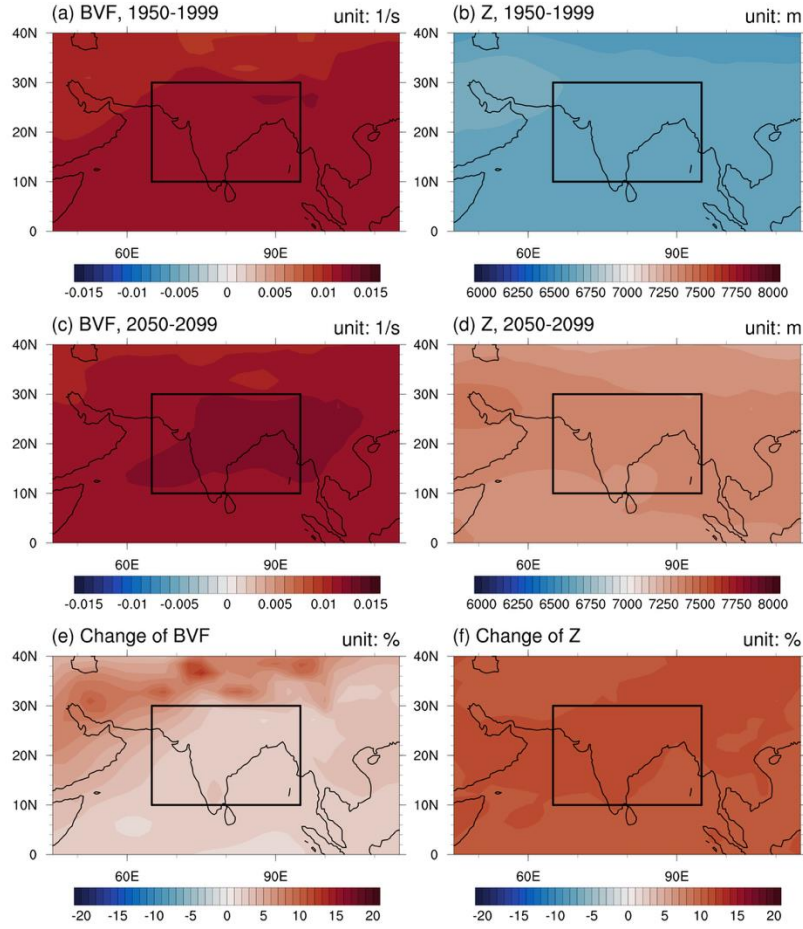


Fig. R1. Climatological Brunt-Väisälä frequency (a) during 1950-1999 at 452hPa (unit: 1/s), (b) during 2050-2099 at 417hPa and (c) their difference (unit: %). (b), (d), (f): as in (a), (c), (e), but for geopotential height. Black rectangles indicate SASM region.

Furthermore, we conducted another LBM experiment to separate the influence of background field and the increased height of heat source (Table R1). Results show that the steady response of Mediterranean subsidence to increasing height of heat source corresponds well with that of both increasing heating height and basic state, exhibiting evident weakening over Eastern and Southern Mediterranean (Fig. R2a, c, e). Similarly, tropospheric thermal structure in both HIST_high and FUT_high enhances and expands westward in comparison with HIST_low (Fig. R2b, d, f).

To summarize, both quantitative estimations and numerical experiments indicate that the expansion of SASM-induced thermal structure is primarily caused by elevated convection height, further testifying our conclusion.

Table R1. Details of LBM experiments

Name	Location of heat source	Height of heat source	Basic state
HIST_low	78°E, 24°N	~500hPa	1950-1999
HIST_high	78°E, 24°N	~400hPa	1950-1999
FUT_high	78°E, 24°N	~400hPa	2050-2099

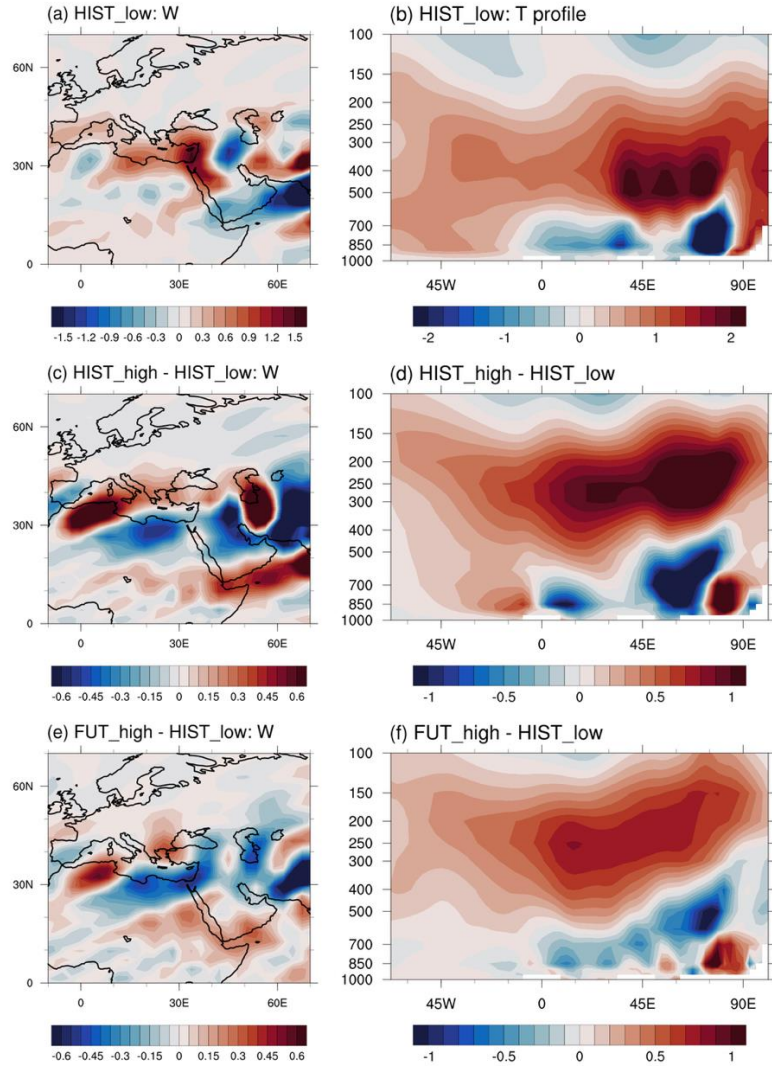


Fig. R2. Steady response of (a) 500hPa vertical motion and (b) 25°-46°N meridionally averaged temperature in LBM HIST_low run. (c) Difference of 500hPa vertical motion response between HIST_high and HIST_low run. (d) as in (c), but for 25°-46°N meridionally averaged temperature. (e), (f): as in (c), (d), but for difference between FUT_high run and HIST_low run.

5. P18, L398: should be “deep convection in the SASM region warms”

Response:

Thanks. We have revised this, please see Line 391-392 in the revised manuscript.

6. Extended Data Figure 4: why do you use the 1900-1949 period for CMIP6 models while you used 1950-1999 for the CESM1 large ensemble simulations? Is the signal less consistent?

Response:

Thanks for your question. This is due to the data availability of CESM1 large ensemble. We have compared the results of 1900-1949 and 1950-1999 with that of 2050-2099, respectively. SASM-related 500hPa vertical motion sees an evident positive anomaly over the Central-to-Eastern Mediterranean (CEM) for both 1900-1949 and 1950-1999 (Fig. R3a, b), but both significantly weakens under global warming with similar spatial patterns (Fig. R3d, e).

In terms of inter-model consistency, there are total 27 out of 33 models (82%) exhibits weakened SASM-related 500hPa vertical motions comparing 1900-1949 and 2050-2099. For 1950-1999, there are total 25 out of 33 CMIP6 models (76%) simulate diminished SASM-W500 in comparison to 2050-2099.

These results suggest that the signal from period 1900-1949 shows slightly higher model consistency compared with 1950-1999 but the future changes under global warming are both statistically significant.

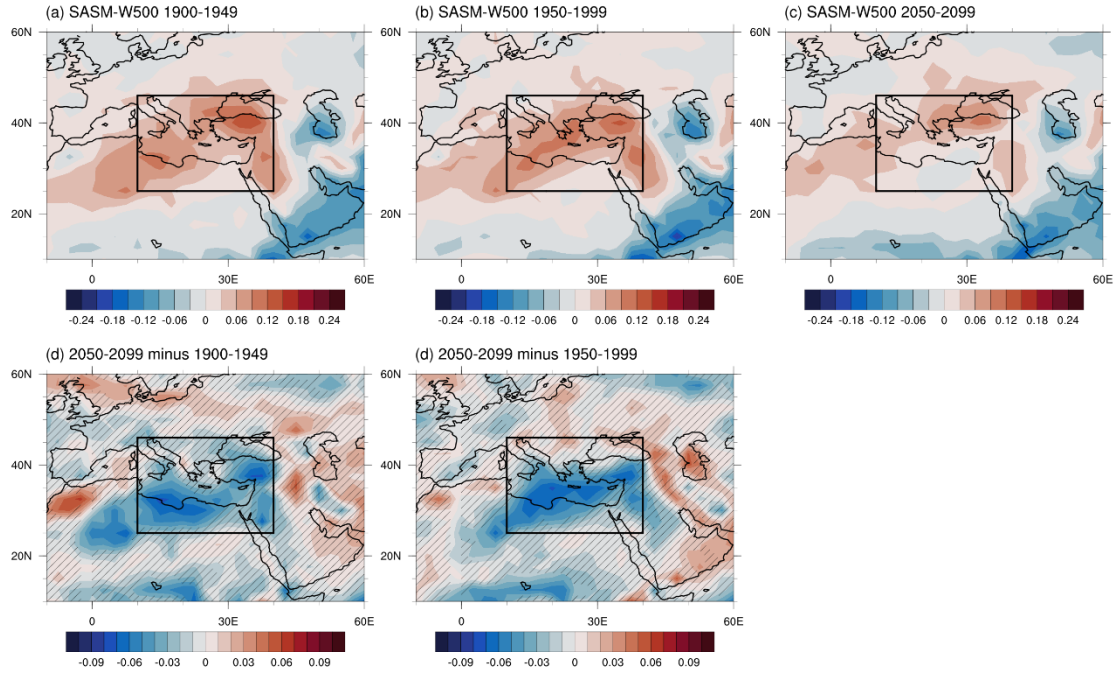


Fig. 3R. SASM-related 500hPa vertical motion during (a) 1950-1999, (b) 1900-1949 and (c) 2050-2099 (unit: hPa/hr). (d) Difference of SASM-W500 between 2050-2099 and 1900-1949. (e) same as (d), but for difference between 2050-2099 and 1950-1999. Slashes in (d) and (e) indicate changes not significant at 90% confidence level. Black rectangles denote the CEM region.

Reply to Reviewers #1:

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I thank the authors for their careful and thorough responses to my comments in the previous rounds of review. The authors have adequately addressed all of my concerns and have made the necessary revisions. I have no further comments or suggestions. In my opinion, the manuscript is now suitable for publication in its present form.

Response:

Thank you for your time and effort that you dedicated to reviewing our work. Your insightful comments have significantly enhanced the quality of this paper.

Reply to Reviewers #2:

Thank you for the valuable comments and comprehensive instructions on enhancing the manuscript. Your comments have been instrumental in significantly improving the manuscript's quality. To ensure clarity, we have highlighted your original comments in *italic font*, and our responses are presented in normal font below each comment.

1. Extended Data Fig. 5: Qp in panel (f) should be replaced by Q1 for consistency with the rest of the manuscript

Response:

Done.

2. p25, l487: I would use the plural form of area in its two occurrence.

Response:

The figure caption has been properly revised. Please see inventory of supporting information for detailed information.

3. The authors wrote that the code is "available on request from the corresponding author." I haven't been able to access the code and thus did not review it.

Response:

Source data and code to reproduce main figures in this article has now been publicly available via <https://doi.org/10.5281/zenodo.21500988>.