Reply to the review of the manuscript “An energetic perspective on the impact of the Atlantic Multidecadal Variability on the West African Monsoon” by reviewer 3

Review of “An Energetic Perspective on the Impact of the Atlantic Multidecadal Variability on the West African Monsoon”

This study employs a large set of SST-restoring simulations to investigate the mechanisms by which the Atlantic Multidecadal Variability (AMV) influences the West African Monsoon and Sahel rainfall. From an energetics perspective, this paper argues that the positive AMV SST anomalies induce a northward shift of the Atlantic ITCZ and the monsoon circulation, thereby intensifying Sahel rainfall through circulation compensation of cross-equatorial atmospheric heat transport.

Overall, I find the paper well written and the results clearly presented. I have only some general questions that I hope will help further improve the paper.

We thank the reviewer for the careful reading and constructive suggestions made to improve it. In the following, we provide a reply to them and the modifications we propose to address them.

1. It would be very helpful if the authors could expand the simulation description (section 2.1). Currently, the manuscript only states that in the simulations, “North Atlantic SSTs are restored to follow a fixed, idealized anomalous pattern of the AMV”. I assume this means that the models are run in the fully-coupled configuration (as hinted in Table 1), and that some sort of SST nudging approach is applied. How exactly is the SST restoring implemented - by adjusting surface heat fluxes? Also, how are the targeted SST anomalies derived from observations? I assume they are defined in the two projects cited in this study, but for readers who may not be familiar with those projects, a more detailed description of the simulation design would be very helpful.

We thank the reviewer for this suggestion. The details of the experimental design are provided in three separate technical reports (https://www.wcrp-esmo.org/projects-and-panels/dcpp/dcpp-resources, last accessed 26 March 2026), which were summarised in the paper by Boer et al. (2016).

Regarding the SST pattern used as target, it is derived from observations following the procedure documented in Ting et al. (2009) and using ERSSTv4 observational-based data set (Huang et al. 2015). First, estimates of the externally forced signal are obtained using a signal-to-noise maximizing EOF analysis applied to global, annual-mean SSTs derived from the multi-model ensemble of the historical experiment in CMIP5. Second, once the time series of the principal component associated with the leading EOF is obtained, the observed annual-mean SSTs are regressed onto it, and the result is subtracted from the original field. The resulting residual SST field represents the estimation of the internal component of the observed SST variability. Third, the AMV index is defined as the spatial average of the annual SST residual field over the North Atlantic (0ºN-60ºN, excluding Mediterranean and Baltic Seas), which is then low-pass filtered with a cutoff period of 10 years to focus on the decadal timescale. Finally, the SST pattern for AMV is obtained by regressing the residual SST field on the AMV index over the 1900-2013 period.

Regarding the implementation of the SST restoring, the recommendation is to alter the non-solar total heat flux by adding the term $\gamma_T(SST_{MODEL}-SST_{TARGET})$, where SST_{MODEL} and SST_{TARGET} are the simulated and target SSTs, respectively, and γ_T is a feedback coefficient (Haney 1971). To avoid spurious alterations, the recommendation is to use a weak restoring value of γ_T=-40 $Wm^{-2}K^{-1}$, which is equivalent to a restoring time scale of about 60 days for a 50-meter mixed layer depth. Most models follow this recommendation (Ruprich-Robert et al. 2021; Hodson et al. 2022). Another method to constrain SSTs is to directly add the following Newtonian damping term in the temperature equation at the first level of the ocean model: $\lambda(SST_{MODEL}-SST_{TARGET})$, where λ is the inverse of the relaxation time scale. IPSL-CM6A-LR uses this latter approach with a restoring term that depends on the mixed layer depth as described in Ortega et al. 2017.

We propose to modify the manuscript by including a more detailed explanation of the target SST pattern, a new figure showing the pattern in the supplementary material (Fig. R1, which will be Fig. S1), and further explanation of how the SST restoring is performed. The first paragraph in section 2.1 (lines 74-78) would read as follows:

"We use two sets of sensitivity experiments, consisting of 10-year runs with global coupled models in which North Atlantic SSTs are constrained to follow a fixed, idealised anomalous pattern of the AMV in its positive (AMV+) and negative (AMV−) phases, respectively. The anomalous pattern (see supplementary Fig. S1) is derived from an estimation of the internal component of the observed SST variability, following the procedure proposed by Ting et al. (2009) and using the ERSSTv4 dataset (Huang et al. 2015). The SST AMV signal is imposed in the North Atlantic, from 10ºN to 65ºN, with an additional 8º buffer zone in which the amplitude of the AMV anomaly is reduced. Within this region, SSTs are constrained either through alteration of the surface fluxes or through a Newtonian SST nudging. Hereinafter, we will refer to this jointly as SST restoring. Further details on how the AMV pattern is obtained and on how the models' SST is constrained can be found in Boer et al., (2016) and the technical notes for AMV simulations (https://www.wcrp-esmo.org/projects-and-panels/dcpp/dcpp-resources, last accessed 26/03/2026). Four models follow the protocol of the Decadal Climate Prediction Project - Component C (DCPP-C Boer et al., 2016), while nine others follow the protocol proposed in the EU Horizon 2020 PRIMAVERA project (Hodson et al., 2022). The protocols differ in the applied radiative forcing (pre-industrial conditions in the DCPP-C protocol and 1950s conditions in the PRIMAVERA protocol) and in the magnitude of the

anomalous AMV pattern, which is twice as large in the PRIMAVERA runs. Changes associated with a positive AMV phase are estimated by subtracting the negative experiment from the positive one ($AMV^+ - AMV^-$). Since this estimation assumes linearity, the changes associated with a negative AMV phase can be obtained by reversing the sign of the anomalies. To facilitate comparison between protocols, changes in the model driven by the PRIMAVERA protocol are halved. For each experiment, we first calculate the 10-year mean of the simulation, and then we average all ensemble members for each model. The climatology for a given model and field is computed as half the sum of the positive and negative experiments, after averaging across ensemble members and the ten simulated years. Although there could be non-linear effects in the AMV impacts (e.g. Monerie et al., 2019b, 2025), the current protocol does not allow their estimation."

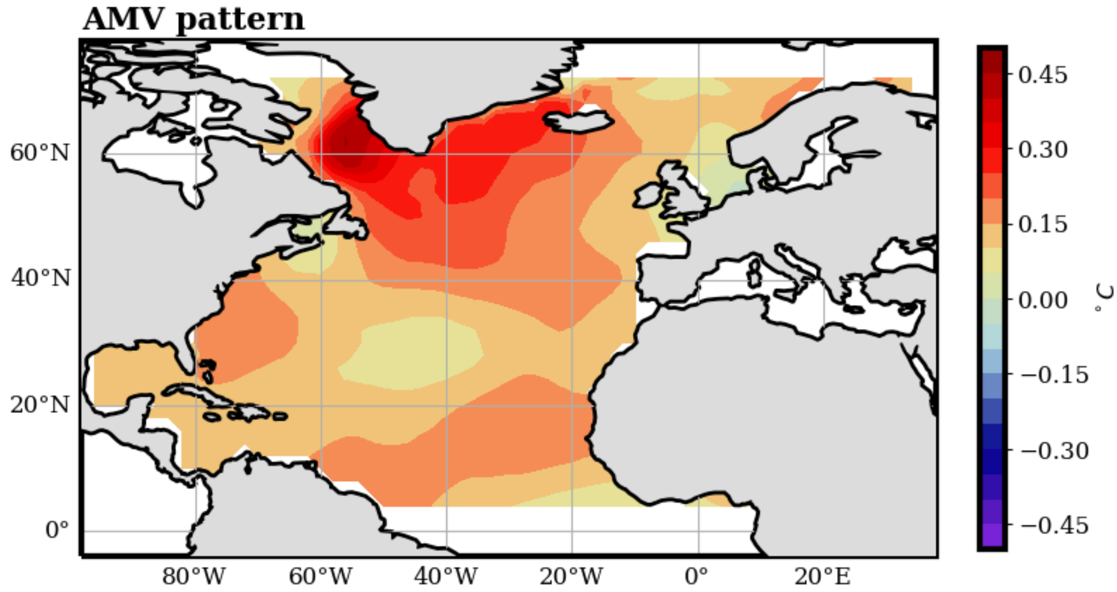

Fig. R1: Full AMV^+ pattern (ºC). SSTs are restored to follow the pattern between 10ºN and 65ºN. The AMV anomalies to which SSTs are restored are gradually reduced in an additional buffer zone 8º to the north and south of this box.

2. Perhaps related to the point above, my second question is regarding the energetics diagnosis. The authors argue that the warm SST anomalies drive positive atmospheric energy input in the North Atlantic, which subsequently induces circulation anomalies to compensate for the energy imbalance. This seems somewhat expected, as the AMV simulations are essentially forced by surface heat flux to restore specific SST anomalies (if I'm correct about the restoring approach). However, I wonder if this mechanism (atmospheric energy anomalies in response to SST forcing) also holds in other fully coupled scenarios, where the atmospheric heat budget and SSTs evolve interactively rather than through a one-way coupling in which SSTs drive the atmospheric response. This may be addressed by analyzing AMV composites from fully-coupled piControl simulations. The authors could test if the fully-coupled models without SST

restoring would also produce similar patterns of atmospheric energy and precipitation changes associated with positive and negative AMV anomalies.

We agree with the reviewer that the SST restoring performed in the North Atlantic can alter energy exchanges, and this represents one of the limitations of our approach: the extent to which the experimental setup can represent the effect of the AMV in observations. We also agree that the comparison between SST-restored and fully coupled simulations could shed light on this issue. And in fact, this is the approach taken by O’Reilly et al. (2023), who investigate this potential problem in depth by focusing on the relation of surface heat fluxes (which are the relevant ones according to our Fig. 4) and SST anomalies in the subtropical and midlatitudes of the North Atlantic for decadal timescales (see their Figs. 2 and supplementary Fig. 3). Their results suggest that the SST-surface heat flux relationship in the AMV experiments is consistent with that of fully coupled models and observations for the midlatitudes. However, discrepancies appear in the subtropical North Atlantic between the SST-restoring experiment, where the relation is positive, meaning heat fluxes tend to respond to SSTs and damp them, and the observations and fully coupled models, where the relation is weakly negative, suggesting heat fluxes might drive SST changes. Nevertheless, for the subtropical region, there is a seasonal dependence in the SST-surface heat flux relationship for the observations and fully coupled models: the negative relationship in observations and fully coupled models is restricted to the winter months, while for the boreal summer months, the relationship is positive (their supplementary figure 12). Thus, the AMV experiments are more consistent with the fully coupled runs and with observations during the boreal summer months, which is the season under study in our analysis. The analysis by Kim et al. (2020) of the AMV in a fully-coupled simulation also suggests that the surface heat fluxes in the tropical Atlantic could be responding to ocean processes only during the summer months (their Figs. 5 and supplementary figure S5, allowing for a change of sign of the heat fluxes taken as positive into the ocean in this study).

As the analysis suggested by the reviewer was already undertaken by O’Reilly et al. (2023), we refrain from adding the proposed test in our manuscript and resort to discussing our results in light of those of O’Reilly et al. (2023) and Kim et al. (2020). In fact, this limitation of our study was already discussed in section 4 (lines 368-379). We propose to extend the discussion further by modifying the sentence in lines 375-377 to: *“Nevertheless, the potential issues associated with SST restoring for surface heat fluxes are likely smaller during boreal summer, our season of interest. A comparison of fully-coupled and SST-restoring simulations suggests the latter are more realistic during boreal summer, when surface heat fluxes tend to dampen SST anomalies also in the tropical and subtropical regions (Kim et al. 2020; O’Reilly et al. 2023)”*

3. While the study focuses on regional precipitation and circulation (within a narrow longitude range in the Atlantic), the key mechanisms invoke the zonal-mean energetics constraint on ITCZ shift and the associated cross-equatorial heat transport. Since the positive AMV surface temperature anomalies extend across much of the northern hemisphere, it raises the question of whether there is also evidence for a zonal-mean ITCZ shift and corresponding changes in MSE and rainfall. In other words, is the mechanism proposed for the Sahel region part of the broader zonal-mean energetics constraint?

We thank the reviewer for this suggestion. The zonal-mean changes in rainfall and MSE meridional transport are indeed suggestive of a broader ITCZ shift (Fig. R2a) and a consistent zonal-mean southward anomalous energy transport (Fig. R2b).

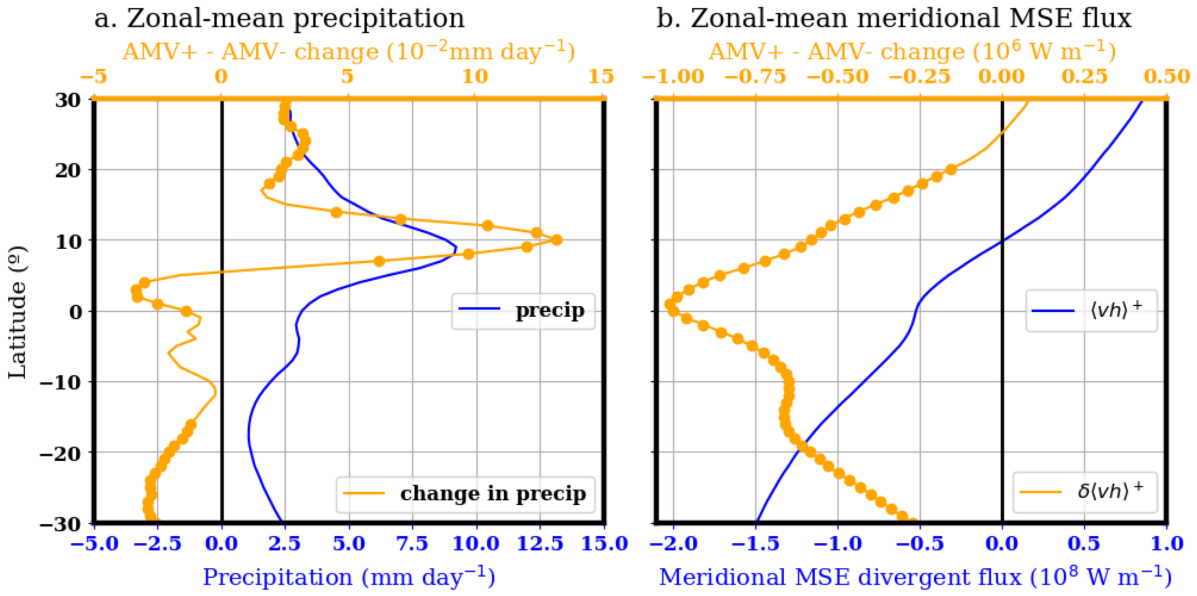

Fig. R2: AMV$^+$ minus AMV$^-$ changes (orange, top axis) and climatological values (blue, bottom axis) of zonal-mean (a) precipitation (mm day^{-1}), and (b) meridional column-integrated moist static energy (MSE) flux ($<vh>^+$, W m^{-1}). Dots in the orange lines mark changes for which at least 80% of the models agree on the sign.

Away from the Atlantic and African longitudes, the northward ITCZ shift is contributed to by enhanced precipitation over the Indian subcontinent and the Bay of Bengal, the northern shift of the rainband over the eastern Pacific and the rainfall decrease in the southtropical central Pacific (Fig. R3).

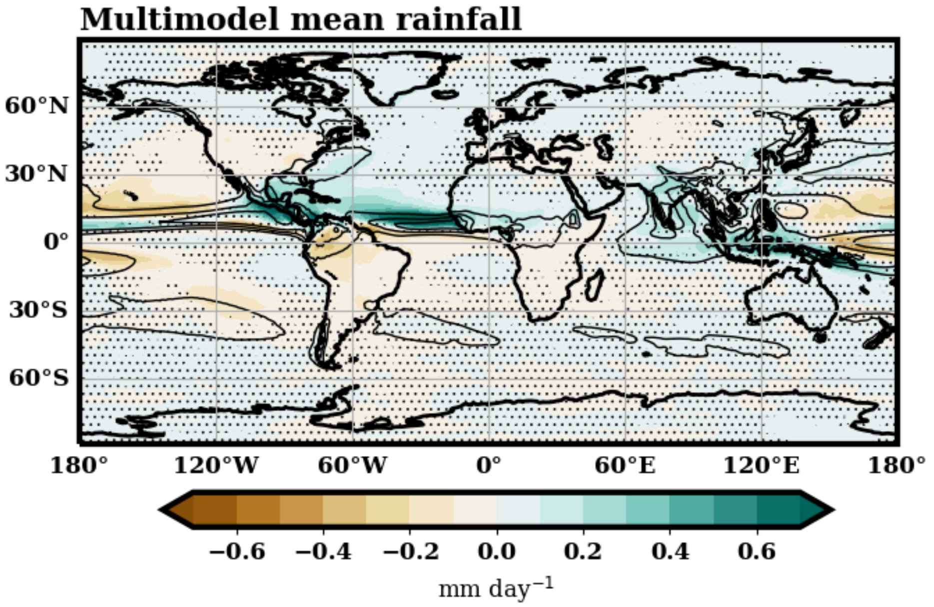

Fig. R3: Multimodel mean AMV^{+} minus AMV^{-} change in JAS for rainfall over West Africa (mm day^{-1}). Dots mark regions where less than 80% of the models (less than 9 out of 11) agree on the sign of changes. Contours show multimodel mean JAS rainfall (grey contours are drawn every 4 mm day^{-1} with the starting black contour at 4 mm day^{-1}).

We propose to include Fig. R2 in the supplementary material as Fig. S4 and modify the sentence in lines 221-222 of the current manuscript to include the zonal-mean analysis:

"*In response to a positive AMV, a robust anomalous southward cross-equatorial column-integrated MSE flux develops in the Atlantic and along African longitudes (*$\langle vh\rangle^{+}$ *, with v the meridional wind, Fig. 4b), and is also observed in zonal-mean estimates (Fig. S4 in the supplementary material).*"

Minor comment:

The anomalous results from the MPI models seem confusing, especially that the discrepancies are mainly in tropical surface temperature responses (Fig. 1d). Although I understand that fully elucidating the behavior of these models is beyond the scope of this study, it would be interesting to show the global surface temperature and precipitation response maps from individual models in the Supplement Information.

We thank the reviewer for this suggestion. Figs. R4 and R5 show the global plots of the surface temperature and precipitation response to the positive phase of AMV for individual models, including the MPI-ESM1-2-HR and MPI-ESM1-2-XR. We propose to add them to the supplementary material as Figs. S2 and S3, respectively, and refer to them in section 3.1 in the manuscript.

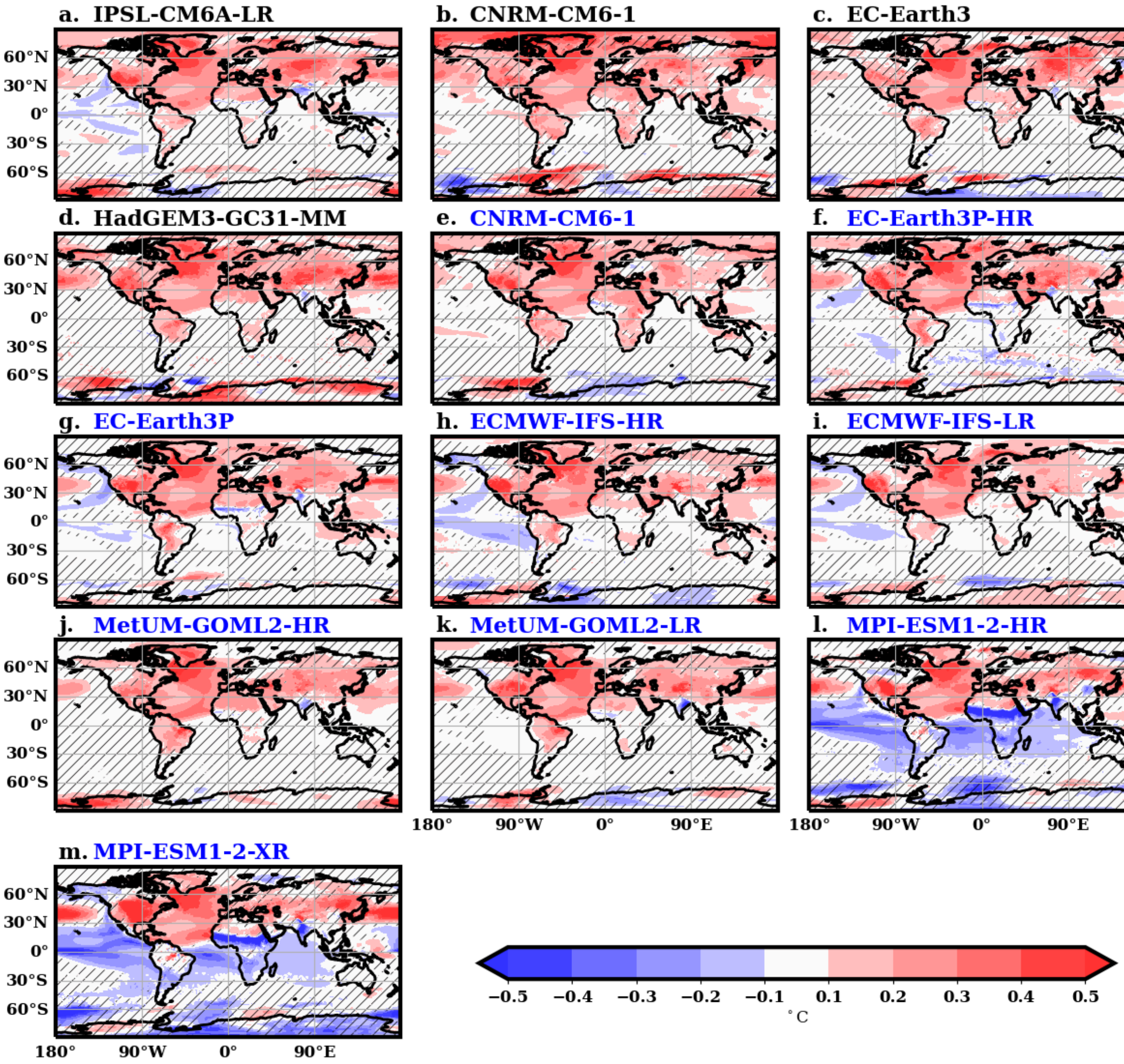

Fig. R4: Difference in mean JAS seasonal surface temperature between AMV$^+$ and AMV$^-$ experiments (shaded; ºC). For simulations under the PRIMAVERA protocol (marked blue in the model name labels), only half the anomalous values are shown. Regions where differences are not statistically significant ($p < 0.05$) according to the parametric t-test for differences in the means under independence, assuming a Gaussian distribution for the samples, are hatched.

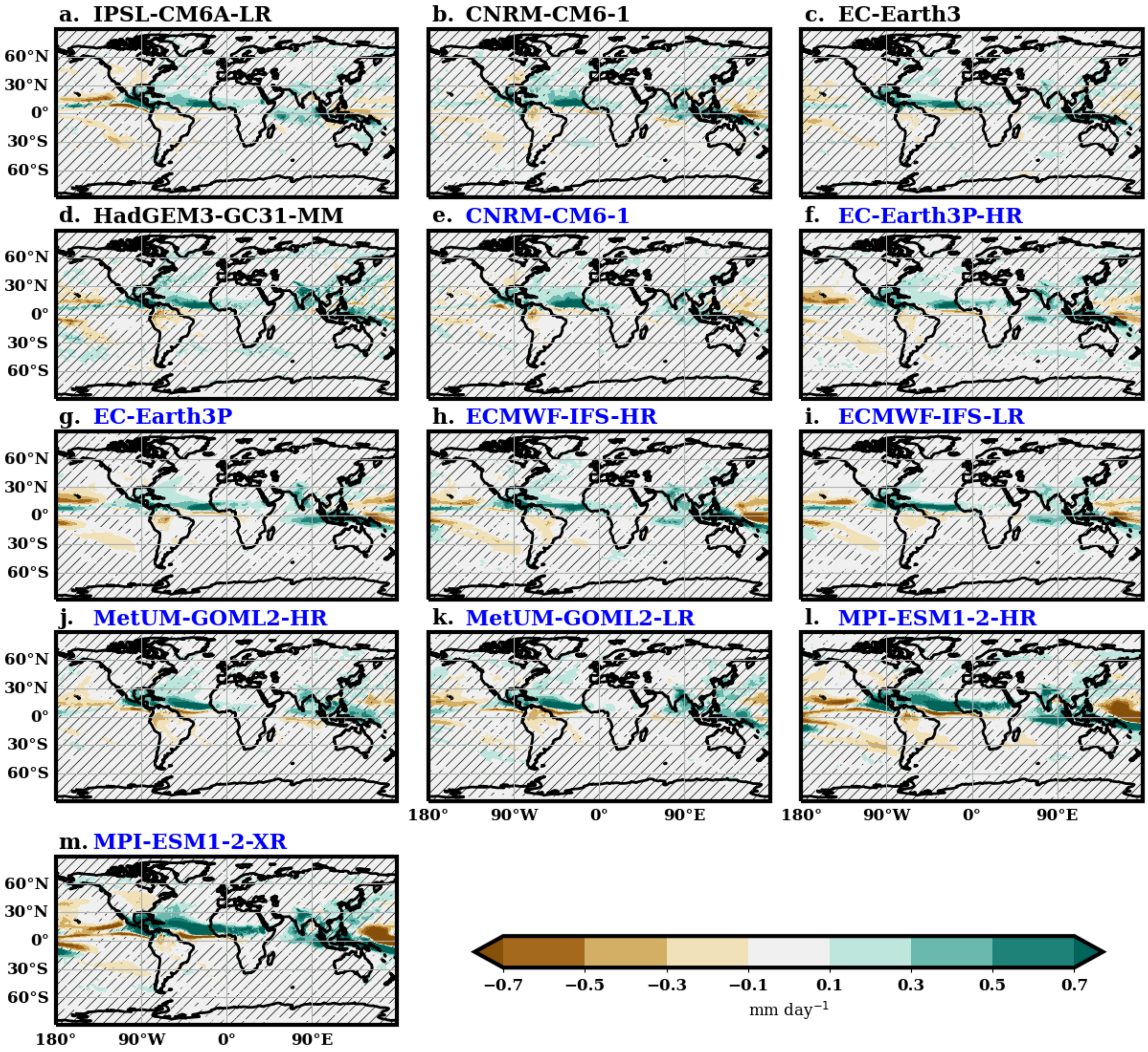

Fig. R5 Difference in mean JAS seasonal rainfall between AMV$^+$ and AMV$^-$ experiments (shaded; mm day^{-1}). For simulations under the PRIMAVERA protocol (marked blue in the model name labels), only half the anomalous values are shown. Regions where differences are not statistically significant ($p < 0.05$) according to the parametric t-test for differences in the means under independence, assuming a Gaussian distribution for the samples, are hatched.

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