

Reply to Referee #3

Structural warming biases distort extreme rainfall intensification estimates in event attribution

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The referee's comments are reproduced in full and in their original order, followed by our replies.

The paper investigates the bias of pseudo-global warming signals in widely used CMIP6 climate models and evaluates how this bias influences the counterfactual simulation and therefore the outcome of attribution studies, here exemplarily shown for the extreme precipitation event over Valencia in October 2024. The authors show systematic differences in vertical and horizontal temperature trend patterns between CMIP6 and ERA5 reanalysis as well as differences in thermodynamical and dynamical changes, that are justified by higher vertical stability from weaker vertical lapse rates and low-level moistening as well as by weaker low-level horizontal winds due to a weak land-sea temperature contrast in the CMIP6 simulations. The paper is very well structured and understandably written, outlines methodology and possible caveats in detail and offer important results that should be taken into account by attribution studies. Although the differences in dynamical changes need further explanation, I suggest minor revisions.

Reply: We thank the referee for a careful and constructive report, and for the positive assessment of the manuscript's structure and methodological transparency. We address the major comment and each of the seven minor ones in turn below, and indicate in each case what has changed in the manuscript.

Major comment

Major comment

The explanation of the differences in dynamical mechanisms with the thermal wind balance is quite vague. Although the land-sea temperature contrast is higher in ERA5, I'm not convinced that this temperature gradient propagate upwards and influences the upper winds in that way, especially because the low levels winds do not show significant changes in CMIP6 or ERA5. In order to stick with this explanation, I suggest to do a more detailed analysis on the actual thermal wind and/or synoptic circulation features that might explain 500 hPa wind differences.

Reply: We thank the referee for this comment. The passage carried little weight in the submitted paper. It occupied two sentences of Sect. 3.4, was framed as a consistency statement rather than a claim of attribution, and could have been deleted without altering a figure, a number or a conclusion. Its closing clause was nonetheless more assertive than that framing warranted, and all three referees raise the same objection. That is more friction than we had anticipated, and it shows that a statement of this kind is better quantified,

which is what we have done.

From the imposed δT we integrate the thermal-wind relation to obtain the geostrophic increment between 1000 and 500 hPa,

$$\delta \mathbf{v}_g(p) = \frac{R}{f} \mathbf{k} \times \int_p^{p_0} \nabla_h \delta T \, d \ln p',$$

evaluated on the ERA5 grid with f varying with latitude and the integration truncated at the local surface pressure. The temperature perturbation is smoothed to 150 km before differentiation, identically for both families, since the ERA5 trend is computed on the native grid and retains orographic fine structure that the gradient operator amplifies.

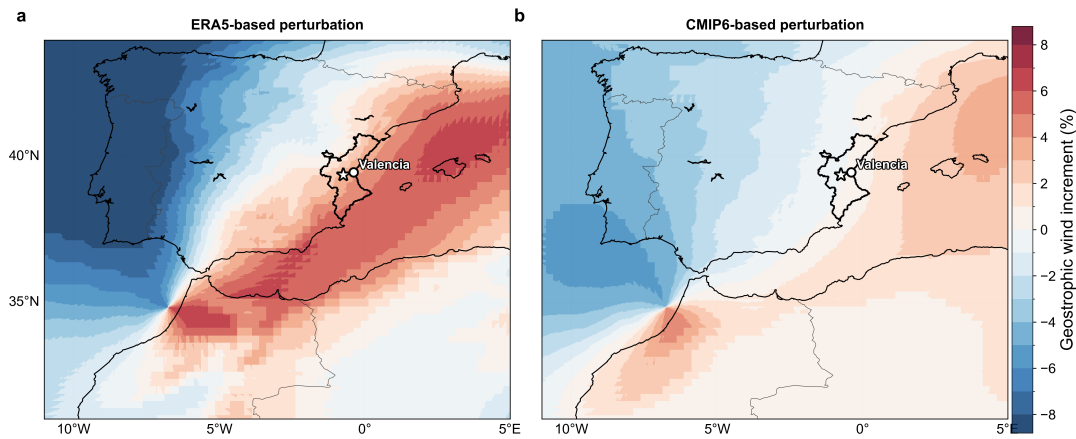


Figure R1. Geostrophic wind increment between 1000 and 500 hPa implied by the imposed temperature perturbation, for (a) the ERA5-based and (b) the CMIP6-based perturbation. The increment is a vector field determined solely by $\nabla_h \delta T$, and is shown projected onto the factual 500 hPa flow, as a percentage of the factual wind speed, so that positive values strengthen that flow. The projection is applied identically to both panels. The outline marks the Valencian Community, the star Turís and the circle the city of Valencia. This figure has been added to the revised Supplement.

Under the ERA5 perturbation the increment forms a coherent south-west to north-east band from northern Morocco across the western Mediterranean and over the Valencian Community, reaching +6.9% of the factual 500 hPa wind speed where it is strongest and averaging +3.3% over the Valencian Community. The CMIP6 ensemble mean gives +0.1% there, with no comparable organised structure. The simulated response is $\sim 13\%$, so the implied increment is of the right sign and order but accounts for only part of it. The revised Sect. 3.4 presents it as one of three candidate contributions, alongside the instability–latent-heating pathway raised by Referee 2 and a possible displacement of the cut-off low.

On the referee’s specific concern about upward propagation, the thermal wind integrates the gradient over the whole layer, so what matters is the depth over which the horizontal gradient extends rather than whether it survives to 500 hPa, and the contrast we impose is not confined to a shallow surface layer. The weak low-level response is not evidence against this: a thermal-wind argument concerns the shear between two levels, not the wind at the lower one. We have also added 500 hPa wind difference maps to the revised Supplement at the referee’s request.

Minor comments

Minor comment 1

Line 65: Why did you use SSP2-4.5 instead of SSP3-7.0 for more pronounced signals and still realistic future scenario? Is it the currently most realistic scenario?

Reply: The scenario plays a limited role in our design. The CMIP6 warming signal comes from the historical experiment, and SSP2-4.5 is used only to extend the record over 2015–2024, because the historical experiment ends in 2014 while our reference period follows ERA5 to 2024. Over that ten-year window the scenarios have barely diverged, so the choice has little influence on the derived trend. Comparing the two datasets over their common historical-only period (1940–2014) yields closely aligned spatial patterns and biases (Fig. S5). We have rephrased the sentence to make this explicit.

Minor comment 2

Lines 171-173: 700 hPa (3km) are rather low- than mid-tropospheric. I suggest to use 500 hPa (5.5km) for mid troposphere.

Reply: We take the point, and Referee 1 raises it as well. We would note that 700 hPa is conventionally the boundary between the lower and middle troposphere, so it sits at the edge of both labels and neither is strictly wrong. We agree, nonetheless, that calling it mid-tropospheric invites the reading that the level is free of surface influence, which at 700 hPa it is not.

We have therefore avoided the ambiguity rather than swapping one imprecise label for another. Where a genuinely mid-tropospheric reference is needed we now use 500 hPa, which is also the level at which the wind response is diagnosed, and elsewhere we refer to 700 hPa by its pressure rather than by a layer name.

Minor comment 3

Lines 192-194: It seems that the trend is quite similar between Fig. 2c and f for Iberian Peninsula and no distinct signatures, especially compared e.g. to the US west coast?

Reply: The referee is right that the annual-mean bias over Iberia itself is modest, especially next to regions such as the western North American coast. It is nonetheless present, and clearer in Fig. 3a, b, where the ERA5-based perturbation warms the land more than CMIP6 does, in particular over the eastern half of the peninsula. We would add that the bias relevant to this event is not confined to Spain: Fig. 2c, f show CMIP6 underestimating the European and North African warming hotspots, and that can reach Valencia through the circulation. What shapes the rainfall response is the warming over a broad region around the event and throughout the column, not the surface warming near Valencia alone.

Minor comment 4

Line 285: Good idea not to nudge. It would be interesting to see, if a comparison to a simulation with nudging would lead to substantial dynamical differences during the event, given that such a simulation would not be too time consuming.

Reply: This is an interesting test and we thank the referee for raising it. We have not run it here because the sensitivity of attribution results to nudging deserves a dedicated study rather than a single additional simulation, and we are aware of groups working specifically on that question. We note it in Sect. 3.4 as a direction for future work.

Minor comment 5

Lines 363-365: Why should the imposed warming lead to a higher persistence of the event? Especially when an even higher warming (ERA5 future counterfactual) could lead to opposite changes with shorter accumulation duration?

Reply: We do not know why the imposed warming might lengthen the event. What we observe is that for the past counterfactuals the response grows with the accumulation window, and greater persistence would account for that. We offered it as one possibility rather than a result. The revised sentence says that this would account for the behaviour we find but that we do not know the mechanism behind it, nor whether the past/future contrast in window dependence is a general feature or specific to this event and setup.

Minor comment 6

Fig. 4d-f & Fig. 6a,b: Rainbow colours are not optimal for people with visual disabilities. I suggest a color scale that, of course, can include different colours but with consistently decreasing brightness. Additionally, I would more standardise the labels of the scale instead of jumping from 3 - 5 - 10 - 20 - 30 by almost every second label.

Reply: We would prefer to keep this palette. Its class boundaries follow the discrete intervals widely used in radar and precipitation products, and the non-monotonic steps are what make threshold-crossing legible. In the zoom panels of Fig. 4d-f, for instance, the contraction of the area exceeding 70 mm between the factual and the ERA5 counterfactual is immediately apparent, whereas a continuous brightness ramp would render the same change as a gradual fade. The uneven label spacing follows those same class boundaries.

The new difference maps added to the revised Supplement do use a perceptually uniform diverging scale, since there the quantity of interest is the sign and magnitude of the change rather than where thresholds are crossed, so both conventions now appear in the paper and complement each other. If the referee or the editor would still prefer a perceptually uniform scale in Figs. 4 and 6, we are happy to make the change.

Minor comment 7

Fig. 8: I would like to see the dot for Valencia for better comparison as well.

Reply: Added. Valencia now appears in Fig. 8, highlighted in black so that the case examined in detail can be compared directly against the wider sample. In ERA5 it sits essentially on the one-to-one line (1.47°C in the lower troposphere against 1.46°C aloft), whereas the CMIP6 multi-model mean gives 1.38°C below and 1.91°C aloft, which is the vertical structure the manuscript discusses.