The responses to the reviewers are below in blue.

Reviewer #1

The authors have highlighted research work on one of the most catastrophic events in Spain in recent years. Cut-off Lows (COLs) are events that require our dedication and in-depth research to understand them as thoroughly as possible and comprehend their role in a changing climate in the Mediterranean area, a climate change hotspot region.

The work is well-organised and well-written. However, the immediacy and impact of the event have meant that multiple studies have already been published by different scientific groups.

We thank the reviewer for the evaluation of our manuscript and for highlighting the relevance of recent related studies. In this revised version, we focus on highlighting the innovative aspects of our study and better positioning our results within the context of the existing literature, taking into account both reviewers' comments.

The initial part of the article, the synoptic characterisation of the event, can already be seen in the article entitled "Synoptic background conditions and moisture transport for producing the extreme heavy rainfall event in Valencia in 2024", published in Atmospheric and Oceanic Science Letters, 2025, https://doi.org/10.1016/j.aosl.2025.100666, by Huang et al. And, in the same paper, an in-depth analysis of moisture transport, using the same model (HYSPLIT), was done.

We agree with the reviewer that Huang et al. (2025) provide a detailed synoptic description of the event, with a particular emphasis on circulation patterns and moisture transport, including the use of HYSPLIT backward trajectories. In this sense, part of our synoptic characterisation is inevitably similar. However, the purpose of this analysis in our study is different. While Huang et al.(2025) focus on identifying moisture sources and obtaining the moisture budget along air parcels, our synoptic analysis is primarily intended to:
(i) assess the ability of the coupled IFS-FESOM simulations we used to reproduce the large-scale circulation during the event. For this reason, we used IFS-FESOM directly to describe the synoptic environment during the event.
(ii) identify key variables and regions of interest relevant for the subsequent attribution analysis.
In particular, the synoptic context and trajectory analysis are used to motivate the selection of variables such as CAPE, TCWV, IVT, or vertical velocity and to define the spatial domains over which time series are computed (such as the regions we defined: VAL, MED or NWA), which is a necessary step prior to the attribution framework applied in this study. The MED and NWA regions are defined to capture air parcels crossing over the Mediterranean and Northern Africa, respectively. The latter region is specifically defined to capture the organised moisture transport reaching Valencia in the form of an atmospheric-river-like structure. While Huang et al. (2025) identify moisture transport across northern Africa, the organisation of this transport into an AR-like structure is not explicitly addressed in their study. Finally, the VAL region used in our study is derived from the synoptic analysis and intended to capture precipitation over the Valencia region as represented in the IFS–FESOM simulation.

In the revised manuscript, we explicitly include Huang et al. (2025) in the Introduction, acknowledging it as a key reference for the synoptic description of the event and using it to further motivate the selection of different regions for the attribution analysis, reflecting the fact that moisture contributions to this event originated from multiple distinct sources.
In addition, we revise Section 2 to more clearly emphasise its specific objectives, explicitly focusing on (i) the validation of the large-scale circulation and the description of key variables identified as relevant for the extreme precipitation in the IFS–FESOM simulations, and (ii) the identification of regions of interest that support the subsequent attribution analysis.

On the other hand, in this recent paper by Barriopedro, D. et al., 2025: A Multimethod Attribution Analysis of Spain's 2024 Extreme Precipitation Event. published in the BAMS, 106, E2440–E2460, https://doi.org/10.1175/BAMS-D-25-0049.1, a multi-method attribution analysis is carried out, one of which is similar to the methodology and results of the paper under evaluation.

We agree with the reviewer that the coexistence of multiple attribution studies on the same event requires a clear articulation of their respective scope and added value. In the revised manuscript, we explicitly clarify the methodological and conceptual differences between their study and ours. Although both studies employ a storyline framework, the experimental designs and underlying questions differ substantially.
Barriopedro et al. (2025) implement a pseudo-global warming (PGW) approach within AI-based weather prediction models, in which thermodynamic perturbations derived from CMIP6 multi-model means are subtracted from the atmospheric initial conditions for short-range forecasts (10 days). This setup isolates the thermodynamic contribution of anthropogenic climate change in a forecast framework, while keeping circulation constrained by the initial state. As acknowledged in their Discussion section, these simulations do not explicitly incorporate interactive ocean-atmosphere coupling, evolving radiative forcing, or slow boundary-condition adjustments, and therefore may provide conservative estimates of climate change effects (Jiménez-Esteve et al., 2024, 2025).
In contrast, our study uses a coupled atmosphere-ocean global km-scale model (IFS–FESOM; Rackow et al., 2025) within the DestinE ClimateDT framework (Doblas-Reyes et al., 2025), employing spectral nudging (on divergence and vorticity from 700 hPa upwards) to constrain only the large-scale circulation while allowing the model to evolve freely at smaller scales. The Factual and Counterfactual simulations differ not only in atmospheric thermodynamic conditions, but also in ocean initial states and external radiative forcing (1950 conditions held fixed versus transient SSP3-7.0 forcing in the Factual scenario). Both scenarios are run continuously over 2017-2024, ensuring dynamically and thermodynamically consistent background climate states prior to the event (John et al., 2024). This design allows us to assess how an identical large-scale synoptic configuration unfolds within two physically coherent climate systems, rather than under perturbed initial atmospheric conditions alone (as shown by Barriopedro et al. 2025). We acknowledge that our approach has its own limitations, which are discussed in depth in the revised version of our manuscript.

Thus, while Barriopedro et al. (2025) primarily illustrate the effect of conditioning across a spectrum of attribution methods (from unconditional to highly conditional approaches), our objective is different: we aim to quantify the thermodynamic amplification of the synoptic environment using a process-based, coupled Earth system framework that explicitly represents ocean–atmosphere interactions and externally forced climate states.

More broadly, event attribution is widely recognised as a field that benefits from the convergence of independent and conceptually distinct methodologies addressing complementary questions (Faranda et al., 2024; Otto et al., 2024; Stott et al., 2016). Recent publications explicitly argue that advancing attribution science requires combining results from multiple methods, spanning from probabilistic approaches to strongly conditioned storyline frameworks, in order to draw more robust conclusions from different lines of evidence (Otto 2023). In particular, Thompson et al. (2025) emphasise that different attribution methods answer different research questions and operate under distinct assumptions; therefore, comparing and combining them strengthens overall scientific understanding rather than creating redundancy.

In fact, Barriopedro et al. (2025) themselves frame their analysis within a multi-method perspective, highlighting the importance of examining events across different levels of conditioning. Similarly, within our own study, we also adopt complementary methodological lenses: beyond the inter-scenario comparison (Factual vs Counterfactual), we contextualise the event against long-term climatological simulations and reanalysis-based percentiles. These distinct but consistent lines of analysis provide both a statistical framing of extremeness and a process-based attribution of thermodynamic amplification. In this context, our study does not duplicate their findings, but instead provides an independent and physically coupled line of evidence based on a distinct storyline configuration.

In the revised manuscript, we (i) explicitly situate our work within this broader multi-method attribution framework in the Introduction, clarifying the specific research question addressed by our experimental design; and (ii) expand the Discussion to outline the strengths and limitations of our approach as applied to this event.

That is why, much to my regret, the authors must reformulate the article, given that the information provided is no longer new at this point.

We respectfully consider that, while other studies have examined this event, the novelty of our work lies in the methodological framework (storylines with spectral nudging as opposed to PGW) and approach (e.g., the selection of synoptic-scale variables, different regions, the climatological context, among others), which contributes to the multiple lines of evidence needed for a proper climate attribution analysis. In the revised manuscript, we explicitly highlight the novel aspects of our study, based on the DestinE ClimateDT spectrally-nudged coupled km-scale storyline framework, and represent one of the first applications of DestinE ClimateDT simulations for attribution studies. This approach provides an independent and complementary line of evidence for this and future extreme event analyses, and the convergence of results across methodologies increases confidence in the attribution conclusions.

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Reviewer #2

This study presents an event-based attribution analysis of the extreme precipitation event that affected Valencia in October 2024, utilizing the "storyline" approach with spectrally nudged simulations. The authors employ the coupled IFS-FESOM model within the Destination Earth (ClimateDT) framework at a relatively high global resolution (~9 km). By comparing Factual (present-day) and Counterfactual (1950s) scenarios, the manuscript quantifies the thermodynamic amplification of the event, reporting significant increases in precipitation (~20-36%), CAPE (~25%), and moisture transport due to anthropogenic warming.

The manuscript is well-structured and addresses a topic of high scientific and societal relevance. While recent literature has begun to address this specific event (e.g., Huang et al., 2025; Barriopedro et al., 2025; Calvo-Sancho et al., 2026), the present study offers a distinct and necessary contribution through its methodological framework. Unlike other studies that may rely on uncoupled simulations or purely statistical attribution, this work leverages a coupled atmosphere-ocean system (IFS-FESOM) with high-resolution global coverage. This setup allows for a more physically consistent representation of the thermodynamic and dynamic drivers.

The results regarding the "Super-CC" scaling of precipitation intensity on the peak day are particularly interesting, suggesting non-linear amplification mechanisms that warrant further discussion. The methodology is robust, particularly the use of spectral nudging to isolate the thermodynamic signal while preserving the large-scale circulation.

However, to fully distinguish this work from the rapidly growing body of literature on the Valencia 2024 event and to clarify some physical mechanisms, I suggest several improvements. Detailed comments are provided below, which require Minor Revisions before it can be considered for publication WCD.

General comments:

1. While the authors cite recent works like Barriopedro et al. (2025) and Calvo-Sancho et al. (2025), the manuscript would benefit significantly from a more explicit discussion on how the IFS-FESOM coupled results complement these studies. Most existing studies use different attribution protocols or regional models. Does the coupled nature of IFS-FESOM (resolving SST feedbacks dynamically) offer a different perspective on the moisture supply compared to studies using prescribed SSTs? Highlighting this methodological distinction is crucial to justify the publication of this paper in a landscape where other attribution studies already exist. The "storyline" approach with a coupled Digital Twin is a strong point that should be emphasized further in the Introduction and Discussion.

We thank the reviewer for this comment. We agree that the global coupled nature of the IFS-FESOM used in this study provides an important methodological distinction relative to previous attribution studies (e.g., using prescribed SSTs, statistical approaches or regional models). On the one hand, by running the model globally and continuously from years prior

to the event, we avoid dependence on initial and boundary conditions. Additionally, the applied spectral nudging provides consistency across scenarios in the large-scale atmospheric conditions. This allows us to study how a given synoptic pattern evolves under physically consistent background climates (John et al., 2024).
Moreover, Barriopedro et al. (2025) implement a pseudo-global warming (PGW) approach within AI-based weather prediction models, in which thermodynamic perturbations derived from CMIP6 multi-model means are subtracted from the atmospheric initial conditions for short-range forecasts (10 days). As acknowledged in their Discussion section, these simulations do not explicitly incorporate interactive ocean-atmosphere coupling, evolving radiative forcing, or slow boundary-condition adjustments, and therefore may provide conservative estimates of climate change effects (Jiménez-Esteve et al., 2024, 2025).
In contrast, our study uses a coupled atmosphere-ocean global km-scale model (IFS–FESOM; Rackow et al., 2025) within the DestinE ClimateDT framework (Doblas-Reyes et al., 2025), employing spectral nudging to constrain only the large-scale circulation while allowing the model to evolve freely at smaller scales. Both scenarios are run continuously over 2017-2024, ensuring dynamically and thermodynamically consistent background climate states prior to the event (John et al., 2024).

On the other hand, the fully coupled ocean-atmosphere framework allows SSTs and upper-level ocean properties to respond dynamically to atmospheric forcings, providing a consistent representation of air-sea interactions. This is particularly important for moisture supply, as evaporation, surface heat fluxes, and feedbacks (e.g., evaporative cooling under strong wind conditions) can modulate SST anomalies and influence atmospheric moisture availability (see Fig. R5). In this sense, the coupled configuration provides a more process-consistent depiction of ocean–atmosphere exchanges than simulations that rely on prescribed SSTs.
While a formal quantification of the individual feedback contributions would require dedicated sensitivity experiments (similar to Kelemen et al., 2019; Akhtar et al., 2018), we believe the present setup ensures that these interactions are internally consistent and dynamically evolving throughout the simulation period.
In parallel, within our research group, we are conducting a study of this same event using the same IFS model version with prescribed SSTs, modifying the magnitude of SST anomalies to explore their impact. Nevertheless, these aspects are beyond the scope of the current manuscript.

Finally, the global, coupled configuration provided by the Destination Earth's ClimateDT simulations allows the same model setup to be applied across multiple events and regions, facilitating generalisable insights and comparisons (e.g., Grayson et al., 2026).

In the revised manuscript, we will explicitly highlight these novel aspects both in the Introduction and the Discussion, clarifying how they strengthen the overall evidence of the attribution assessment on the event, and emphasising the novelty and added value of the DestinE ClimateDT (Doblas-Reyes et al., 2025) simulations for the attribution community.

2. The finding that precipitation rates increased by ~36% (far exceeding Clausius-Clapeyron scaling) is a key result. The authors mention this could be due to convective microphysics or dynamics. Could the authors provide a more in-depth

physical argument here? For example, is there a change in the convective efficiency or dynamic feedback where the stronger latent heat release in the Factual scenario intensifies the local updrafts (beyond just the large-scale nudging)? Calvo-Sancho et al. (2026) suggest the non-linearity in the storm dynamics changes promotes the Super-CC behavior. A brief comparison with the vertical velocity profiles (or heating rates) between Factual and Counterfactual during the peak intensity hours would strengthen this argument.

We thank the reviewer for this constructive comment and the suggestion to further investigate the physical origin of the super-Clausius–Clapeyron scaling. In response, we analysed the temporal evolution of precipitation alongside near-surface dew-point temperature, and the vertical profiles of vertical velocity and equivalent potential temperature in both the Factual and Counterfactual scenarios.
Although precipitation occurred on several days during the event (e.g., 25, 27, and 29 October), statistically significant differences in precipitation intensity between the two scenarios are found only on 29 October (Fig. 4 and 6). This day is characterised by a pronounced increase in near-surface moisture, with substantially higher dew point temperatures (Fig. R1), as well as by the strongest integrated vapour transport and the largest total column water vapour values during the event. In contrast, on 27 October, near-surface moisture remained relatively low in both simulations, and moisture transport was weaker, despite the occurrence of precipitation.

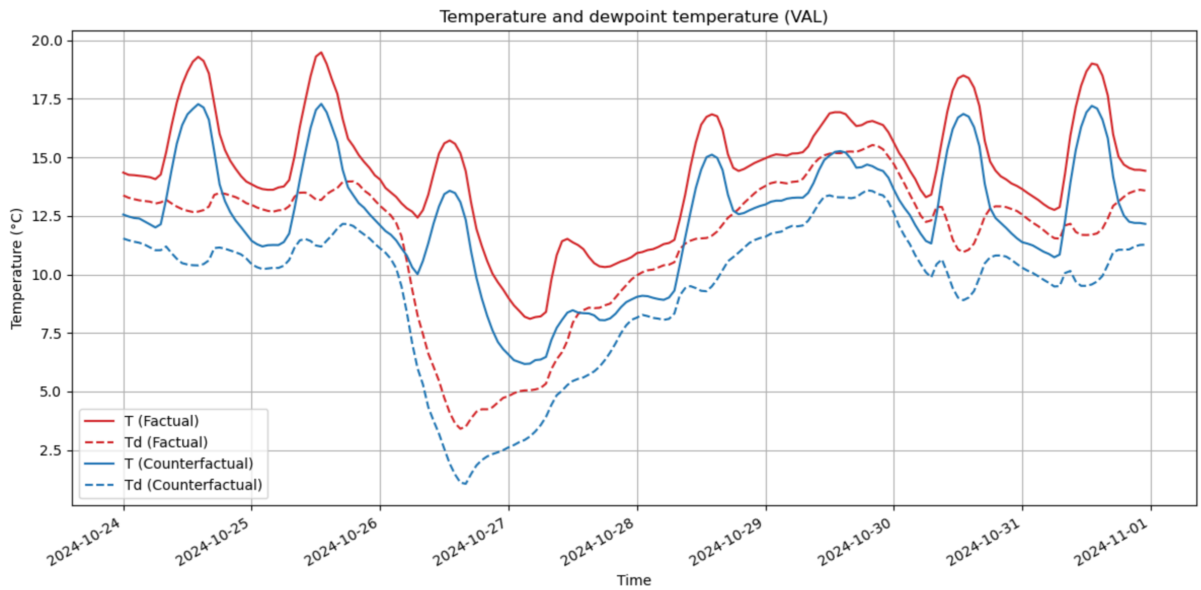

Figure R1: Temporal evolution of temperature (solid) and dewpoint temperature (dashed) for the Factual (red) and Counterfactual (blue) scenarios over the Valencia region. Values are averaged over the VAL box. This figure is included in the Supplementary Material in the revised version of the manuscript.

On 29 October, the Factual simulation exhibits markedly stronger vertical motion compared to the Counterfactual, with enhanced ascent in the lower troposphere (Figure R2a) and the largest inter-scenario differences concentrated in the mid-troposphere (approximately 600–300 hPa) (Figure R3a).

This intensification of ascent coincides with higher low-level equivalent potential temperature and a distinct maximum between 1000 and 700 hPa (Figure R2b), as well as the largest differences in θe below 700 hPa between scenarios (Figure R3b). Similar θe differences are present on earlier days (around 24 and 25 October), but without strong ascent or extreme precipitation rates.

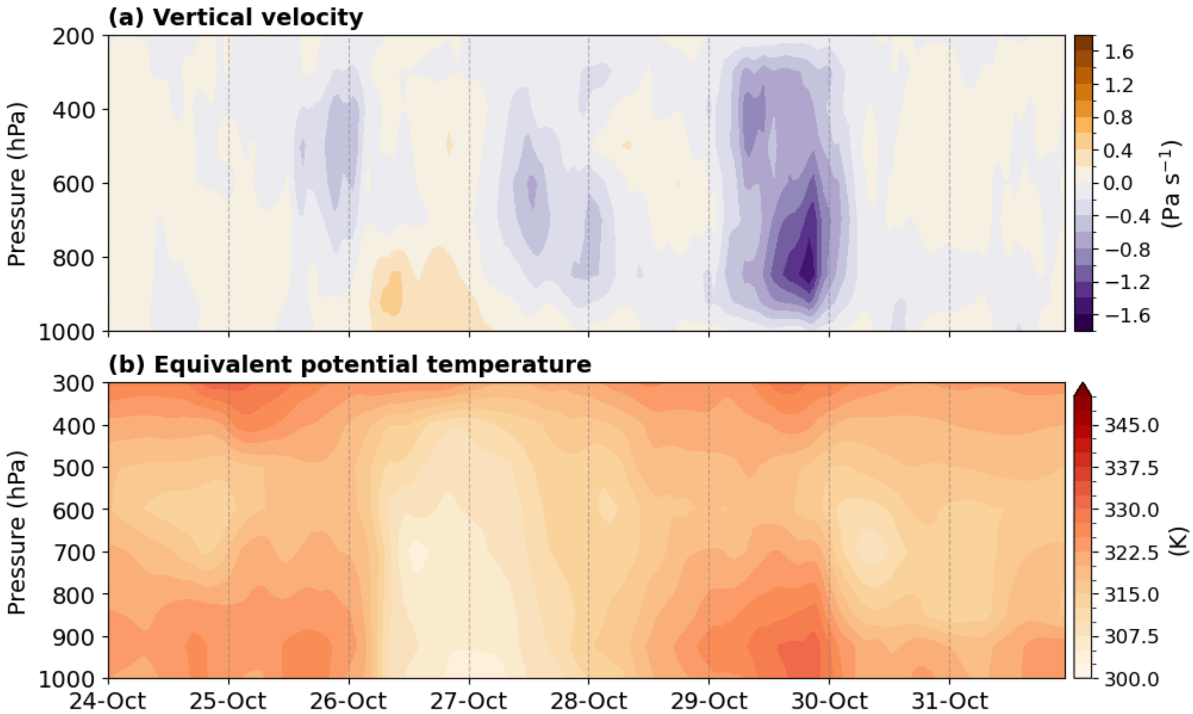

Figure R2: Time-pressure evolution of (a) vertical velocity (Omega, Pa/s) and (b) Equivalent potential temperature (in K) over the VAL region for the Factual scenario. This figure is included as Supplementary Material in the revised version of the Manuscript.

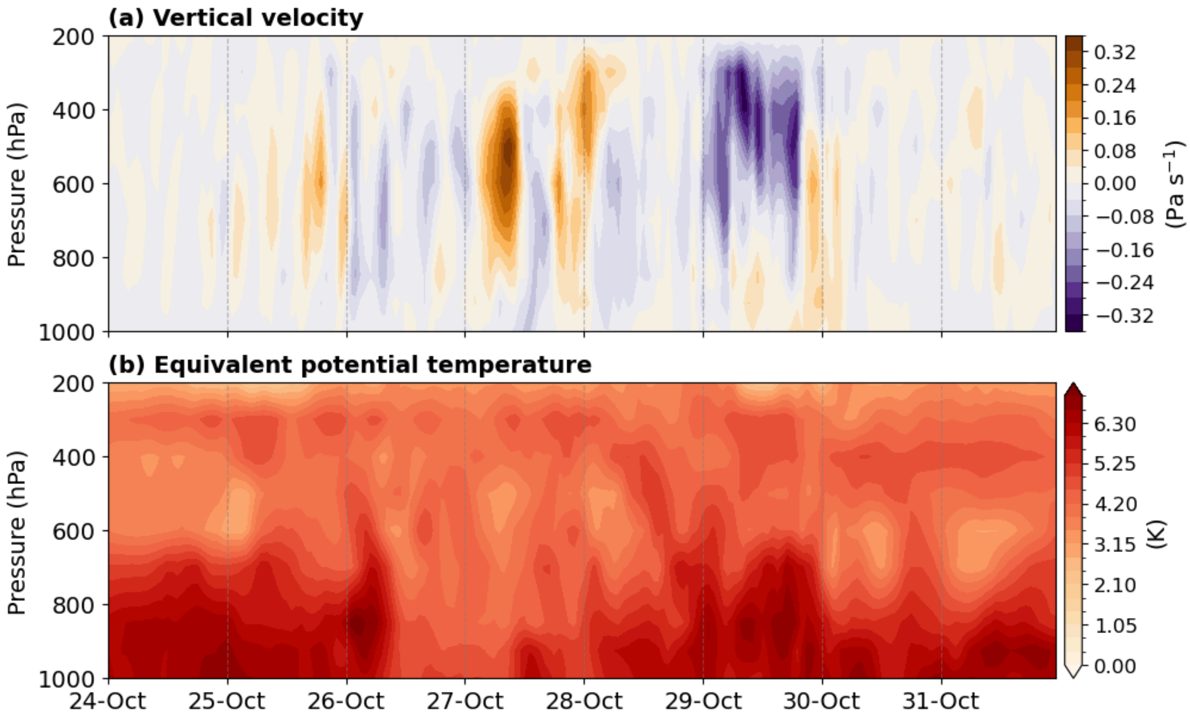

Figure R3: Time-pressure evolution of Factual – Counterfactual differences in (a) vertical velocity (Omega, Pa/s) and (b) equivalent potential temperature (in K) over the VAL region. This figure is included in the revised version of the Manuscript in Section 3.3. To maintain consistency throughout the manuscript, the manuscript's version of this figure covers the period from 26 October to 31 October.

Taken together, these results suggest that, on 29 October, the combination of enhanced moist instability and stronger ascent in the Factual simulation is associated with a non-linear dynamical response that increases the efficiency of moisture conversion into precipitation. While diabatic heating is not explicitly diagnosed, the co-occurrence of stronger mid-tropospheric ascent, enhanced low-level θe, and the confinement of precipitation differences to the peak-intensity day is consistent with a non-linear dynamical feedback associated with latent heat release, which can locally intensify updrafts beyond the large-scale forcing. These signals, enhanced ascent and elevated θe in the low and mid-troposphere, are consistent with similar types of dynamical contributions to accelerated scaling beyond Clausius-Clapeyron reported in previous observational and modelling studies (Lenderink et al., 2017; Molnar et al., 2015; Singleton & Toumi, 2013; Fowler et al., 2021; Da Silva & Haerter, 2025) and were also suggested by Calvo-Sancho et al. (2026).

Accordingly, we have included this description and Figure R3 in the Manuscript Section 3.3 and we have updated the discussion to highlight the largest differences between the Factual and Counterfactual scenarios on 29 October, including mid-tropospheric vertical velocity, low-level equivalent potential temperature, and the increase in near-surface dew point, which together suggest a non-linear dynamical contribution to the extreme precipitation. In addition, these analyses motivated us to replace the 700-hPa vertical velocity with vertically averaged vertical velocity in the diagnostics shown in Figures 1, 2, and 4, providing a more representative measure of convective ascent. We thank the Reviewer again for motivating these analyses, which, in our opinion, will strengthen our paper.

To illustrate the relationship of precipitation with temperature and dewpoint temperature during this event over VAL, Fig. R4 shows hourly precipitation for all the gridboxes in the VAL box together with 2-meter temperature, dewpoint temperature and vertical velocity (Omega).

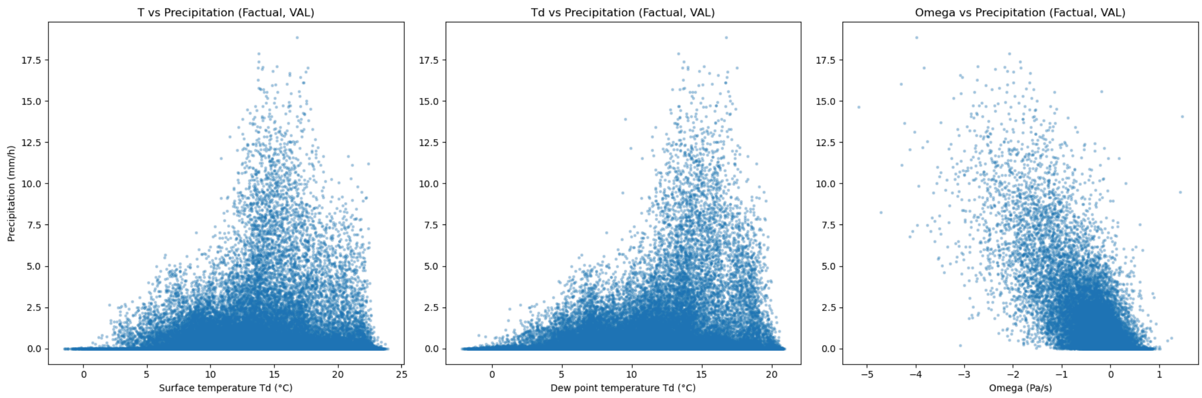

Figure R4: Hourly dewpoint temperature and precipitation for all the gridboxes over the VAL box from 24 October to 31 October.

3. The simulation runs at ~9 km. While impressive for a global run, this is still within the "gray zone" for deep convection and arguably coarse for the complex orography of the Valencia region. The paper acknowledges the underestimation of peak rainfall compared to observations. The authors should add a discussion regarding the limitation of parameterized convection at 9 km versus convection-permitting models used in other studies (e.g., Calvo-Sancho et al., 2025).

We thank the reviewer for this comment. We agree that a horizontal resolution of ~9 km lies within the convective "grey zone" and is coarse for explicitly resolving deep convective processes and the fine-scale orography of the Valencia region. This limitation likely contributes to underestimating local peak rainfall intensities relative to station observations, as noted in the manuscript.
In the IFS Cycle 48r1 used here, deep convection remains partially active, following the scale-aware formulation described in Rackow et al. (2025). The activity of the convective scheme is progressively reduced with increasing resolution by adjusting the cloud-base mass flux, allowing a gradual transition toward resolved convection rather than a binary on/off behaviour. At 9 km resolution, as in the storyline simulations, precipitation results from both the partially active convective scheme and the dynamics resolved by the model. As discussed in Rackow et al. (2025), 9 km simulations capture large-scale circulation reasonably well but fail to reproduce mesoscale convective systems, produce weaker and more spatially diffuse precipitation, and systematically underestimate local precipitation peaks.
In contrast, convection-permitting regional simulations such as those of Calvo-Sancho et al. (2025), conducted at 1-3 km resolution with explicitly resolved deep convection, are better suited to representing mesoscale organisation, orographic triggering, and local rainfall maxima. These models can therefore reproduce extreme precipitation more realistically at

the local scale.
The modelling strategy used in our study was designed with a complementary objective. The globally consistent, spectrally nudged IFS-FESOM framework constrains the large-scale circulation to a reanalysis (ERA5) while allowing thermodynamic and small-scale dynamical responses to develop freely. This approach is particularly well suited to isolating the thermodynamic contribution of climate change to event-scale precipitation under identical synoptic conditions, albeit at the expense of fully capturing local convective extremes.
That being said, we acknowledge that our simulations remain subject to limitations. In particular, the ~9 km horizontal resolution constrains the representation of local convective organisation, extreme rainfall peaks, and certain small-scale dynamical feedbacks, which could affect the quantitative estimates of the contribution of climate change to this event.

We have strengthened the discussion in the manuscript by explicitly addressing the limitations of the 9-km horizontal resolution for representing deep convection and local precipitation extremes. We now clarify how the partially active convective parameterisation interacts with the model-resolved dynamics, and we contrast this with convection-permitting regional simulations (e.g., Calvo-Sancho et al., 2025).

4. Figure 5 shows the evaporation evolution. Since this is a coupled model experiment, it would be interesting to know if the enhanced evaporation in the Factual scenario is purely thermodynamic (warmer SST) or if there are differences in the surface wind stress between scenarios (even with nudging). The evaporation difference seems to peak before the event (Oct 27-28). Please clarify the lag/lead relationship between the local Mediterranean evaporation peak and the precipitation peak on the 29th. Is the moisture locally sourced "pre-loaded" days in advance?

Regarding the first question, we analysed both the dynamical and thermodynamic contributions to evaporation by computing the surface wind stress and the saturation deficit over the same EXTMED domain, using the ensemble members for each scenario. The temporal evolution of these two quantities is shown in the following figure, together with additional animations of specific humidity and precipitation.
The temporal evolution of evaporation can be mainly explained by the evolution of the saturation deficit, defined as the difference between the saturation specific humidity at the sea surface temperature and the near-surface air specific humidity. During 26–27 October, cold air associated with the cut-off low penetrated the Mediterranean Sea from the Atlantic Ocean after crossing the Iberian Peninsula, creating favourable thermodynamic conditions for enhanced evaporation. In particular, the saturation deficit reaches its maximum during these days, coinciding closely with the peak in evaporation (Figure R5).
On 29 October, surface wind stress was higher than on previous days, which likely contributed to the slight relative increase in evaporation observed that day. However, the wind stress shows no significant differences between the Factual and Counterfactual scenarios (Figure R5), even though spectral nudging was applied from 700 hPa upwards. In contrast, the saturation deficit exhibits significant differences between scenarios, with higher values in the Factual scenario, especially during the days preceding the storm.
Overall, these results indicate that the enhanced evaporation observed in the Factual scenario is mainly driven by thermodynamic factors, associated with a larger air–sea humidity contrast, rather than by dynamical differences in surface wind stress.

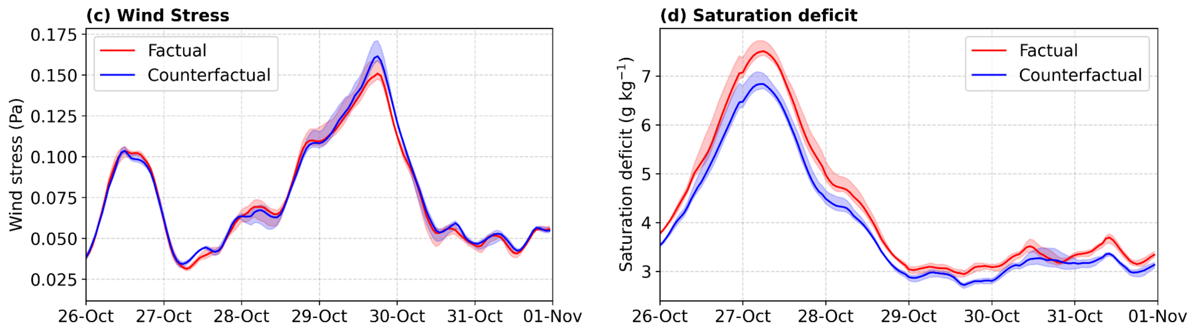

Figure R5: Temporal evolution of wind stress (left panel) and saturation deficit (right panel) for the Factual (red) and Counterfactual (blue) scenarios over the Valencia region. Values are averaged over the EXTMED box. This figure is included in the revised version of the manuscript in Section 3.3.

Regarding the second part of the question, the peak in the evaporation difference between scenarios occurs prior to the main precipitation event (27–28 October), reflecting the timing of the most favourable thermodynamic conditions for evaporation over the Mediterranean (EXTMED domain). During these days, relatively cold air associated with the cut-off low was present over the basin, enhancing the saturation deficit and promoting stronger surface evaporation (see the drop in T and Td in Figure R1 and the evolution of the COL in the attached animations).

From 28 October onwards, the synoptic situation evolved towards warm, moist advection from the south (NWA), altering local surface conditions and reducing the role of evaporation in controlling near-surface moisture. As a result, the peak in precipitation on 29 October does not coincide with the maximum in local evaporation.

Moreover, based on our interpretation of the results presented here and the animations of the evolution of atmospheric water vapour content and precipitation, the system does not appear to behave as a static reservoir of moisture over the EXTMED in the days preceding the event. While enhanced evaporation contributed to an increase in regional atmospheric moisture (see Fig. 2g), a fraction of this moisture was advected northward and contributed to precipitation over southern France on 26–27 October.

By 28 October, the moisture content over the basin was increasingly influenced by large-scale advection from NWA (Fig. 2e, g), which ultimately fed moisture transport towards the Valencia region. Therefore, we interpret the event as the result of a continuous moisture recycling process involving local evaporation, horizontal moisture transport, and precipitation that occurred prior to the main event, rather than a preconditioning by local evaporation alone.

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