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Regional and weather-type modulation of global warming-driven intensification of Italian precipitation extremes from multi-year storyline simulations

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Abstract

Extreme precipitation has recently caused substantial damage in Mediterranean countries, including Italy, but robustly attributing such regional extremes to climate change remains difficult due to the interplay between thermodynamic and atmospheric circulation changes. Event-storyline approaches, where the same meteorological events are simulated under different climate conditions, are increasingly used to isolate the thermodynamic impact. However, the potential of multi-year, spectrally-nudged storyline simulations to investigate statistical changes—rather than individual events—remains largely unexplored. Here, we exploit this potential using 2017–2024 data from the Destination Earth Digital Twin for Adaptation, demonstrating robust changes in the statistics of both mean and extreme precipitation over Italy and their implications for interpreting signals in individual extreme events. Results show that, despite fixed large-scale circulation, the number of wet days and annual mean precipitation decrease in southern Italy in summer, while annual mean precipitation increases slightly over northern Italy. In contrast, mean annual precipitation maxima increase nearly uniformly from north to south at rates close to 7% per degree of global-mean warming. Higher precipitation quantiles are more strongly amplified, with local maximum responses reaching up to 15–25% °C^{−1}. Using weather-type composites of precipitation extremes, we find that these amplified responses are regional, seasonal, and circulation-dependent, and primarily associated with weather types (WTs) occurring in autumn and winter. These amplified responses are illustrated via four individual extreme precipitation events representative of the identified WTs: Storm Vaia of 2018, the Emilia-Romagna floods of 2023, the Marche flood of 2022, and a Pre-Alpine convective event of 2020. In these events, daily precipitation increases exceed local total-column water vapour scaling, implying super-Clausius–Clapeyron behaviour. Overall, our results demonstrate that, under identical synoptic forcing, anthropogenic global warming is already manifesting its impacts on Italian precipitation extremes, but the response is varied and cannot be reduced to a single scaling relationship.

1. Introduction

Italy is particularly vulnerable to extreme precipitation due to its complex geography (Brunetti *et al* 2006, Caporali *et al* 2021) and densely populated lowland areas. Recent events such as the Vaia storm of October 2018 (Cavaleri *et al* 2019, Davolio *et al* 2020) and the Emilia-Romagna floods of May 2023⁹ (Cremonini *et al* 2024, Dorrington *et al* 2024) have caused severe socio-economic impacts and fuelled debate on the role of anthropogenic global warming (AGW) in amplifying heavy rainfall. Observations show an overall increase in the frequency of daily extremes over Italy (Iacomino *et al* 2025), but regional magnitude changes remain unclear, with the exception of a modest intensity increase in the North-East during autumn (Pavan *et al* 2019, Caporali *et al* 2021). At sub-daily scales, convection-permitting reanalyses (Cavalleri *et al* 2026) and observations (Bartolini *et al* 2014, Piccarreta *et al* 2026) suggest increased extreme hourly precipitation in many locations, though a spatially consistent intensification signal remains elusive.

Italy lies within the Mediterranean basin, a climate-change hotspot (Giorgi 2006, Tuel and Eltahir 2020, Cos *et al* 2022, Jézéquel *et al* 2025), where future precipitation changes remain uncertain despite projected substantial warming (Lelieveld *et al* 2012, Jacob *et al* 2014, Seneviratne *et al* 2021). At the global scale, AGW is increasing both the likelihood and intensity of heavy precipitation events, consistent with the Clausius–Clapeyron (CC) relationship, which predicts an increase in saturation water vapour of about 6–7% °C^{−1} (Pall *et al* 2007, Min *et al* 2011, Asadieh and Krakauer 2015, Hartmann 2016, Pfahl *et al* 2017). In the Mediterranean region, precipitation changes are particularly heterogeneous because extreme rainfall reflects not only thermodynamic amplification but also dynamical processes governing vertical motion and moisture convergence, with large uncertainty in projected circulation changes (Zappa and Shepherd 2017). These include variations in storm tracks, blocking frequency, mesoscale convective organisation, and orographic uplift (O’Gorman and Schneider 2009, O’Gorman 2015), such that individual events may exhibit sub- or super-CC scaling, especially at sub-daily timescales (Lenderink and van Meijgaard 2008, Berg *et al* 2013, Fischer and Knutti 2016).

Disentangling thermodynamic and dynamical contributions to extreme precipitation is challenging in observed extreme precipitation events (EPEs), where both components evolve simultaneously. Changes in the frequency, persistence, or structure of circulation regimes are intertwined with thermodynamic amplification occurring within individual events, making it difficult to attribute projected

changes in extremes to either mechanism. In addition, confidence in the ability of global climate models to simulate regional dynamical responses remains limited, particularly regarding circulation changes that strongly influence precipitation (Zappa *et al* 2015, IPCC AR6 2023).

One approach to addressing this challenge is provided by the event-storyline framework, which constrains the large-scale circulation while allowing thermodynamic responses to unfold (Trenberth *et al* 2015, Shepherd 2016, Shepherd *et al* 2018, Zappa 2019, van Garderen *et al* 2021, García-Portela and Maraun 2023, Hawkins *et al* 2023, Feser and Shepherd 2025). By conditioning on the realised large-scale circulation and perturbing only the thermodynamic background state, storyline simulations provide a conditional estimate of how the magnitude or impacts of a given event may change under different climate conditions. In this context, the spectrally nudged coupled climate simulations from the Destination Earth Climate Twin for Adaptation (hereafter DestinE simulations; John *et al* 2026) offer the opportunity to extend this framework to a statistical, multi-year analysis of precipitation extremes. While spectrally nudged multi-year simulations have recently been applied to study droughts (Kettaren *et al* 2026), their application to precipitation has remained limited, partly because precipitation is particularly sensitive to model resolution. With a global atmospheric horizontal resolution of approximately 9 km—substantially finer than other available nudged datasets (van Garderen *et al* 2021, Sánchez-Benítez *et al* 2022, Pfleiderer *et al* 2026)—these simulations preserve realistic large-scale circulation while embedding it within different background climate states, allowing for a physically-consistent analysis of observed extreme events (Doblas-Reyes *et al* 2026, Grayson *et al* 2026).

Extreme precipitation over Italy is strongly modulated by the large-scale atmospheric circulation. Recent studies (Grazzini *et al* 2020, Iannuccilli *et al* 2021, Mastrantonas *et al* 2022, Capozzi *et al* 2023, Iacomino *et al* 2025) have shown that heavy rainfall tends to occur preferentially within specific synoptic configurations, often referred to as weather types (WTs). By summarising atmospheric variability into a limited set of representative circulation patterns, these classifications provide an effective framework to link precipitation extremes to their governing dynamical structures. While previous work has examined either the thermodynamic scaling of heavy precipitation (e.g. Pumo *et al* 2019, Luppichini *et al* 2023) or the influence of circulation regimes (e.g. Zappa *et al* 2015), no studies have explored how thermodynamic amplification manifests for different circulation regimes using a storyline approach.

In this study, we address this gap by analysing the thermodynamic response to AGW of mean and extreme precipitation over Italy and their dependence

⁹ www.cimafoundation.org/en/news/the-italian-floods-of-may-2023-a-scientific-analysis/.

on atmospheric circulation regimes in the DestinE simulations. While previous storyline applications—using either nudged or pseudo-global-warming simulations—have typically focused on counterfactual analyses of individual high-impact events (e.g. Risser and Wehner 2017, Patricola and Wehner 2018, Brogli et al 2023, Hawkins et al 2023, Lenderink et al 2025, Doblas-Reyes et al 2026, Grayson et al 2026), DestinE simulations spanning 2017–2024 provide a sufficiently long and dynamically consistent dataset to examine the *statistical* response of precipitation under circulation-constrained conditions. Specifically, we ask whether the EPEs observed over Italy during this period would have been less intense in a cooler climate representative of the mid-twentieth century, when global mean surface temperatures were about 1.2°C lower. By further conditioning the analysis on the six WTs of Iacomino et al (2025), we assess whether thermodynamic amplification is uniform across circulation regimes or whether certain dynamical environments have favoured stronger intensification. This provides the first multi-year, circulation-constrained statistical evaluation of AGW impacts on Italian precipitation extremes.

2. Data and methods

2.1. Observations and reanalyses

EPEs and model validation over Italy are based on three datasets: ArCIS, ERA5, and CERRA.

ArCIS (Archivio Climatologico per l'Italia centro-Settentrionale) is a high-resolution (~5 km), daily gridded precipitation dataset covering North-Central Italy for the period 1961–2023 (Pavan et al 2019). It is derived from quality-controlled rain-gauge observations and provides a benchmark for precipitation extremes in complex terrain. ERA5 (Hersbach et al 2020) is a global, hourly reanalysis at ~31 km resolution, used as a large-scale reference for atmospheric variables such as sea level pressure, geopotential height, and total column water vapour (TCWV). The Copernicus Regional Reanalysis for Europe (CERRA; Ridal et al 2024), with ~5.5 km resolution over Europe, is used for precipitation validation.

2.2. Destination earth digital twin for climate change adaptation

We use the newly produced, high-resolution storyline dataset generated with the global coupled Integrated Forecasting System (IFS) - Finite-Element/VolumE Sea ice-Ocean Model (FESOM), developed by the Alfred Wegener Institute within the Destination Earth Digital Twin for Climate Change Adaptation initiative (Wedi et al 2022, Hoffmann et al 2023, Doblas-Reyes et al 2026), to reconstruct recent extreme events under different background climate states (John et al 2026). IFS–FESOM couples the ECMWF IFS for atmosphere, land, and waves with

the ocean–sea-ice model FESOM2, at approximately 9 km atmospheric horizontal resolution. Convection remains parameterised.

To ensure that the simulated events follow the realised large-scale circulation, the atmospheric component is constrained using spectral nudging toward the ERA5 reanalysis. Nudging is applied only to the large-scale, i.e. the spherical harmonic components up to T60 truncation for vorticity and divergence, in the mid- and upper troposphere (between 700 and 100 hPa). This configuration allows mesoscale processes, the planetary boundary layer, local orographic convection, and surface coupling to freely evolve while effectively constraining the large-scale dynamics, enabling physically consistent, high-resolution reconstructions of historical extreme events under different levels of AGW. Additional technical details of the nudging implementation are provided in John et al (2026) and in section S1, S2, S3 of the Supplementary Information.

We analyse two simulations covering January 2017 to October 2024: a *Historical* experiment representing present-day climate (hereafter *Present* simulation) and a *Control* experiment representing a cooler climate broadly consistent with mid-20th-century conditions (hereafter *Past* simulation). Changes between the Present and Past simulations are normalised by the simulated difference in global mean surface temperature between the two experiments (~1.2°C), so that all percentage changes are expressed in % °C⁻¹ and are directly comparable with analogous metrics from other studies. In both, the large-scale circulation is constrained through spectral nudging toward ERA5, so that differences primarily reflect changes in the thermodynamic background state. Daily precipitation fields are spatially averaged over the operational Warning Areas (WAs) of the Italian Department of Civil Protection, allowing extremes to be examined at a scale consistent with the operational framework for weather risk management.

The realism of the DestinE simulations at the global scale has been evaluated in John et al (2026) and Grayson et al (2026). We conduct an additional validation of precipitation over Italy using the seven complete years available (2017–2023), comparing the annual number of wet days, annual mean precipitation, and mean annual maxima with ArCIS and CERRA (See section S6 and figure S1, S2 of SI).

2.3. EPEs and WT classification

To analyse the response of EPEs to AGW over Italy, we adopt the WT classification of Iacomino et al (2025), derived from the CERRA-based EPE catalogue. EPEs are defined from daily precipitation spatially averaged over the 156 operational WAs of the Italian Department of Civil Protection as days exceeding the 99th percentile of wet-day (≥ 1 mm) precipitation over 1985–2019 in at least one WA. To exclude highly localised convective events, only cases affecting

Table 1. Summary of the six weather types (WTs) used in this study, including their synoptic characteristics, associated moisture flux, primary areas of impact, and typical seasonality. Adapted from Iacomino *et al* (2025).

	Synoptic Configuration	Moisture Flux	Affected Areas	Seasonality
WT1	Atlantic cyclone over France / northern Tyrrhenian Sea, associated with a deep upper-level trough over the British Isles	Southerly to southwesterly flow	Tyrrhenian side, Liguria, central and eastern Alps	Late autumn, winter, early spring
WT2	Mediterranean cyclone over central Italy, associated with an upper-level trough over north-central Europe	Weak cyclonic circulation: northwesterly over northern Italy, westerly over southern Italy, easterly over the eastern Po Valley	Eastern Po Valley, southern Tyrrhenian side	Autumn, winter, and spring
WT3	Western Mediterranean cyclone associated with an upper-level trough over the Iberian Peninsula	Southerly flow	Northwestern Italy, north-central Tyrrhenian side, eastern Alps, Sardinia, Sicily	Spring and autumn, especially Oct–Nov
WT4	Zonal westerly flow associated with a broad North Atlantic upper-level trough and a shallow cyclone over the Ligurian Sea	Westerly to southwesterly flow with high TCWV	Northern Italy, central Alps, Tyrrhenian side	Year-round, especially summer and autumn
WT5	Upper-level cut-off low	Cyclonic circulation: southerly over central and southern regions, recurving southeasterly over the Po Valley	Adriatic side of north-central Italy, Calabria, Basilicata, Sicily, and Sardinia	Year-round, especially autumn and spring
WT6	Mediterranean cyclone centred over the Tyrrhenian Sea	Cyclonic circulation: southwesterly over southern Italy, easterly over the Po Valley	Adriatic and Ionian sides, eastern Po Valley, Sicily, eastern Sardinia	September–July

a total area of at least 1000 km² are retained (Grazzini *et al* 2020). Using Self-Organizing Maps, the events are categorised into six WTs based on the large-scale atmospheric circulation, following Iacomino *et al* (2025). A summary of the main characteristics of the WTs is provided in table 1. Here, using the same EPE definition, we consider a DestinE-based EPE catalogue and assign each identified event, i.e. day, to one of the six WTs according to its large-scale atmospheric fields. More details in section S4, SI.

2.4. Statistical significance analysis

Statistical significance is assessed using paired comparisons between the *Past* and *Present* simulations, which share identical large-scale circulation and can thus be interpreted as ‘two realisations of the same experiment’.

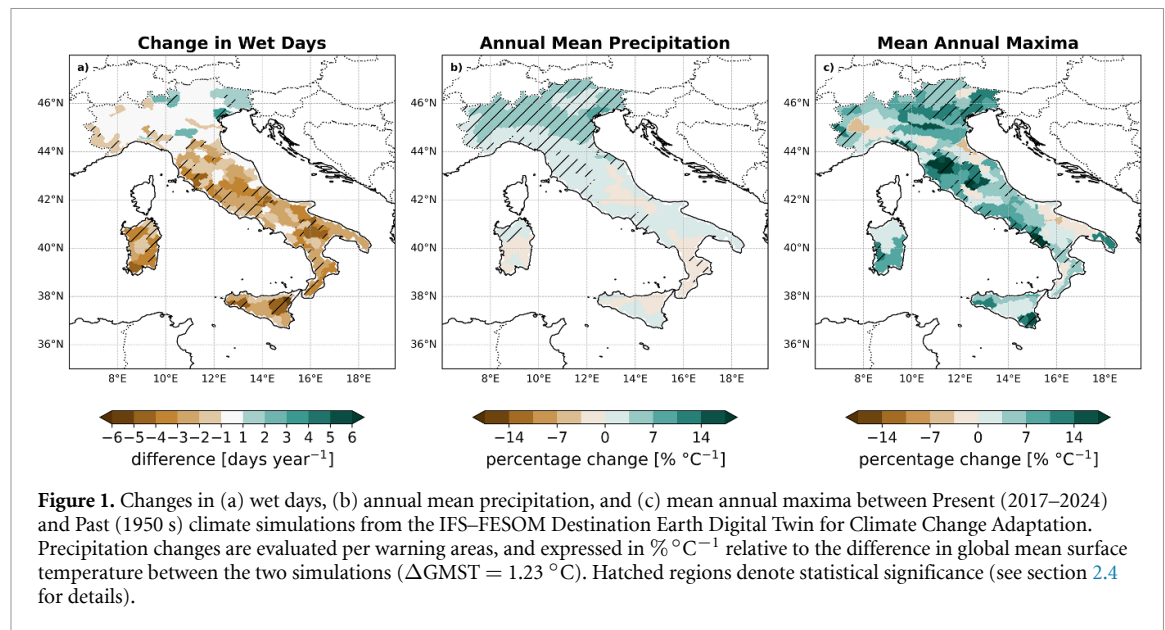
For daily fields, statistical significance is evaluated using a paired *t*-test applied to daily differences at each grid point with the conventional $p < 0.05$ threshold. For diagnostics based on annual aggregates (e.g. quantiles and mean annual maxima), a non-parametric binomial (sign) test is applied to yearly paired values over 2017–2023. We highlight the regions where at least 6 out of 7 years exhibit the same sign, corresponding to a one-sided significance level of approximately 0.06. More details in section S5, SI.

3. Results

3.1. Thermodynamic impacts on precipitation statistics

Event-storyline simulations have been extensively used to examine the impact of AGW on specific weather events (Trenberth *et al* 2015, Sánchez-Benítez *et al* 2022, Zhuo *et al* 2025, Grayson *et al* 2026). However, the 7 year span covered by the DestinE simulations also enables assessing the thermodynamic impact of AGW on different precipitation metrics normally assessed in coupled climate models (figure 1). Changes in the number of wet days (≥ 1 mm) show decreases over central and southern Italy, with moderate-to-negligible increases over the Alpine region (figure 1(a)). The seasonal decomposition (figure 2) indicates that this signal is primarily associated with spring (MAM, figure 2(d)), which exhibits a clear north–south dipole, and with summer (JJA, figure 2(g)), during which wet days decrease almost uniformly across the domain.

The reduction in the number of wet-days is particularly striking given the spectrally nudged configuration of the simulations. In the warmer Present climate, the atmosphere holds more moisture, yet the number of precipitation events decreases under essentially identical synoptic forcing. This implies that sub-nudging-scale thermodynamic and



mesoscale processes are impacted by AGW sufficiently to modify precipitation occurrence.

The signal, concentrated in JJA, is consistent with changes in atmospheric static stability driven by the land–ocean warming contrast (e.g. Brogli *et al* 2019). Indeed, in summer, precipitation over Italy is strongly associated with convective activity. Under AGW, the lower troposphere over continents warms more rapidly than the mid-to-upper troposphere, where the land–ocean contrast is weaker, leading to a vertically heterogeneous warming structure. As land warms more than the surrounding seas, AGW reduces near-surface relative humidity over land, increasing the lifting condensation level and strengthening lower-tropospheric convective inhibition. This suppresses convective initiation, consistent with reduced precipitation frequency. At the same time, stronger near-surface warming relative to the free troposphere increases conditional instability, and it is consistent with higher Convective Available Potential Energy (CAPE; Seeley and Romps 2015, Chen *et al* 2020). CAPE quantifies the positive buoyant energy available to an air parcel after it reaches the level of free convection, with larger values indicating a greater potential for strong updrafts and intense convective precipitation. The combined effect of a strengthened lower-tropospheric convective inhibition and increased CAPE, is a regime characterised by reduced convective frequency—despite the increase of atmospheric moisture—but increased precipitation intensity once convection is initiated, consistent with the canonical response found in Mediterranean climates (Brogli *et al* 2019, Tuel and Eltahir 2021). Further details are provided in section S7 and figures S3, S4 of the SI.

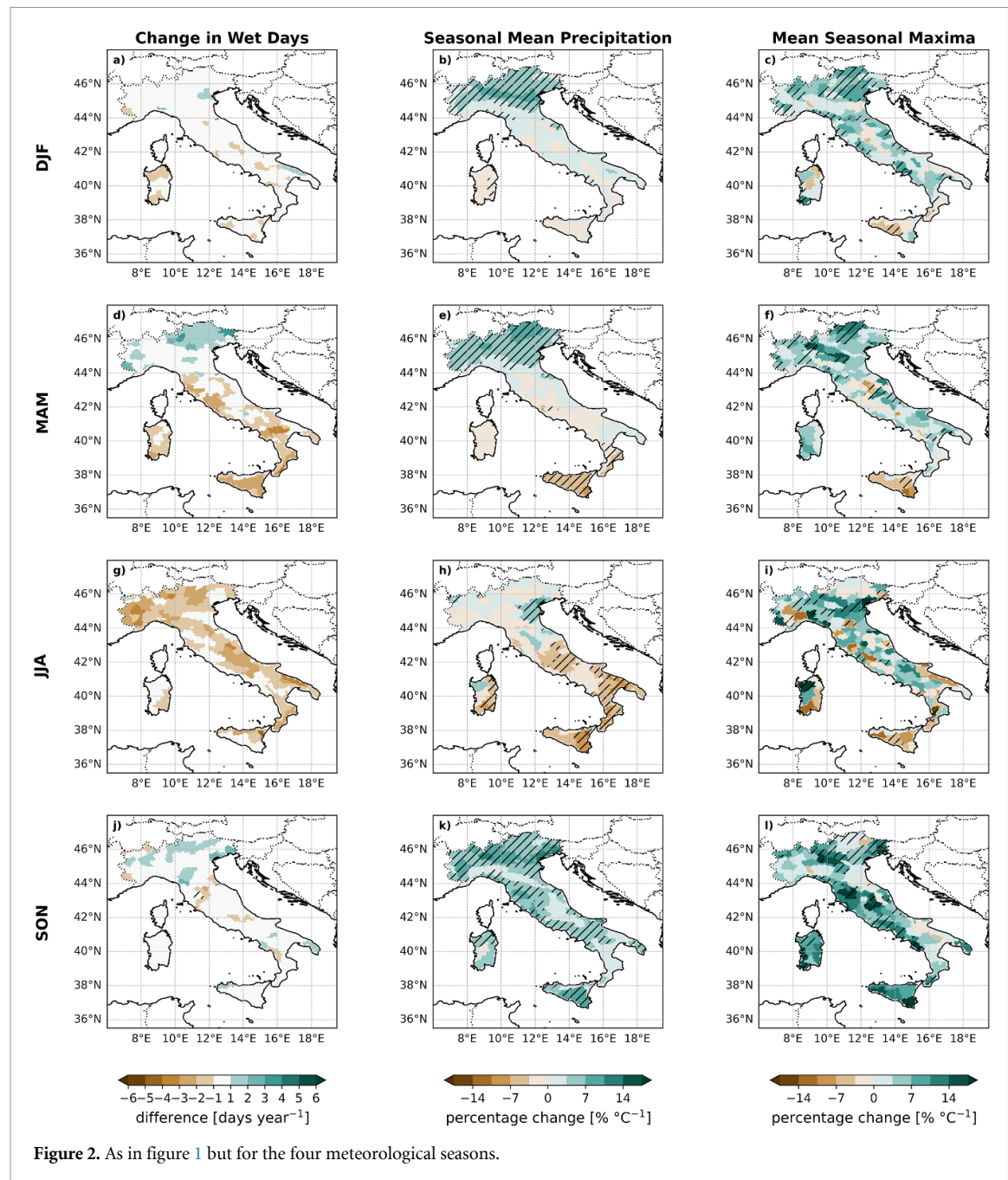
Variations in annual mean precipitation (figure 1(b)) show increases over northern Italy, with weaker or negligible changes over central

and southern regions. This pattern closely mirrors the wet-day response, especially in MAM and JJA (figures 2(d) and (g)), indicating that changes in event frequency contribute substantially to the annual and seasonal mean precipitation signal. Seasonally, SON is characterised by widespread wetting, particularly over mountainous areas, whereas MAM shows contrasting patterns between northern and southern Italy that are consistent with the seasonal changes in wet days. DJF largely follows the spatial pattern of the annual mean, while JJA exhibits pronounced drying over central and southern Italy, in agreement with projections of Mediterranean summer drying (Tuel and Eltahir 2021).

In contrast to mean metrics, intense precipitation, quantified by the mean annual maxima, increases nearly uniformly across Italy, with statistically significant changes over the northeast, the Apennines, and along the Tyrrhenian coast (figure 1(c)). The seasonal decomposition reveals a much weaker spatial modulation than for the changes in wet days or mean precipitation, although the strongest amplification of extremes occurs in SON (figure 2(l)). The similarity between the mean annual maxima and the SON seasonal maxima reflects that, in many Italian regions, the most intense precipitation events occur predominantly in autumn. This spatially coherent intensification highlights a fundamental distinction between the response of average precipitation and that of intense events, even under identical large-scale circulation.

3.2. Dependence of precipitation response on intensity and latitude

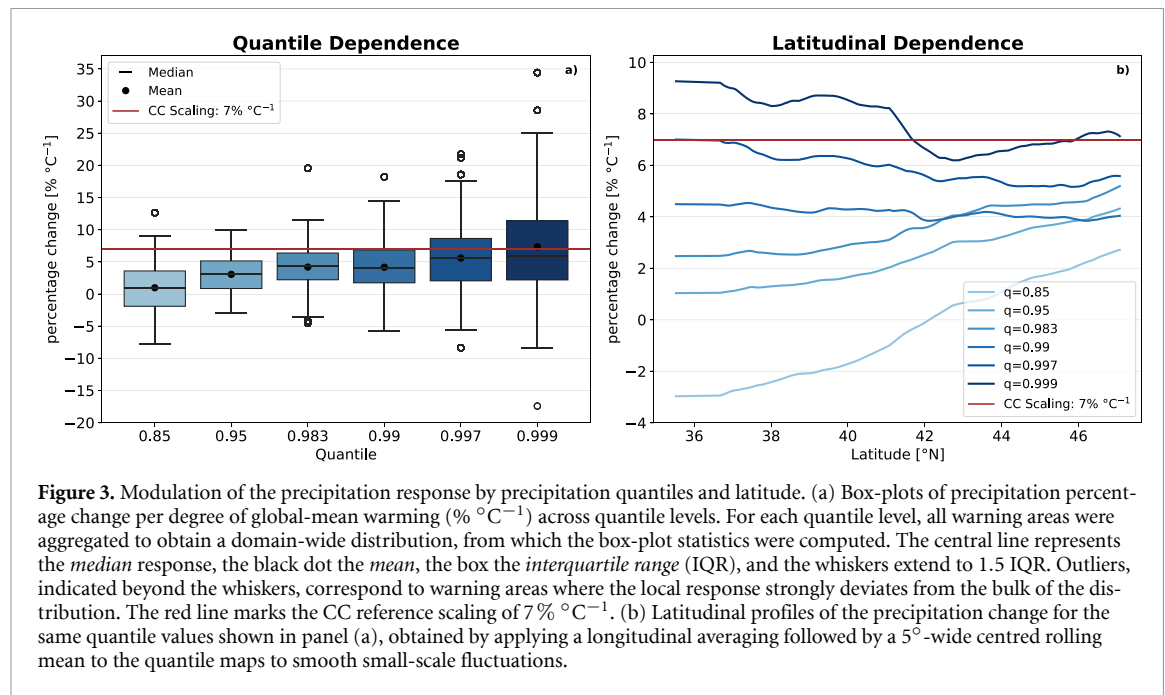
To quantify how the precipitation response to AGW varies across the intensity spectrum, we analyse precipitation quantiles. Figure 3(a) shows that the median precipitation response increases



monotonically with the quantile level, from moderate events to the most extreme ones. While low (0.85, 0.95) and intermediate (0.983, 0.99) quantiles exhibit responses below or close to the CC scaling with global-mean temperature, high quantiles (0.997, 0.999) display a broader distribution with more frequent exceedances of CC scaling. The spread of responses also increases with quantile, consistent with larger sampling uncertainty in the estimation of high quantiles. Moreover, the distribution becomes increasingly skewed toward larger positive responses, with the upper tail reaching values of about $17\% \text{ } ^\circ\text{C}^{-1}$ for quantile 0.997 and $25\% \text{ } ^\circ\text{C}^{-1}$ for quantile 0.999. This asymmetry results in mean

changes exceeding the median response and indicates that a subset of WAs experiences substantially stronger intensification. The spatial distribution of these responses is shown in figure S5, SI.

Figure 3(b) shows the latitudinal structure of the precipitation response across quantiles. Low quantiles exhibit a strong north–south gradient, with weak or negative responses over southern Italy and stronger positive responses in the north. This gradient progressively diminishes with increasing quantile level. At high quantiles, the response becomes larger in magnitude and more homogeneous across latitudes, indicating that extreme precipitation intensification is only weakly constrained by latitude. The transition



from a north–south gradient for moderate events to a nearly uniform response for extremes highlights the distinction between mean and extreme precipitation behaviour under AGW over Italy.

A seasonal decomposition (figure S6, SI) reveals marked contrasts across seasons. DJF exhibits a comparatively uniform response across quantiles, whereas MAM and JJA maintain a pronounced north–south contrast for low to intermediate quantiles, consistent with changes in wet-day frequency. The JJA signal is consistent with the stability-driven mechanism discussed above and in section S7 of the SI. SON, in contrast, shows the strongest and most spatially coherent amplification across quantiles, largely accounting for the positive skewness observed in the full-sample distribution. This may reflect two concurring factors. First, SON seasonal warming, second only to JJA (figure S6), enhances TCWV, favouring intensification across the full precipitation spectrum. Second, mid-tropospheric buoyancy increases broadly across the domain—indicating greater CAPE—while lower-tropospheric buoyancy remains broadly unchanged or slightly increases over northern Italy, implying that convective initiation is not suppressed (Seeley and Romps 2015, Chen *et al* 2020). The larger available CAPE is therefore realised more frequently, producing a stronger and more uniform intensification of extremes (section S7, figure S3, SI). This is consistent with the hypothesis that autumn warming may shift precipitation toward more convective regimes, increasing precipitation efficiency (Berg *et al* 2013, Da Silva and Haerter 2025); however this interpretation remains physically motivated rather than directly verified, as stratiform and convective precipitation are not saved in the model output.

3.3. Modulation by atmospheric WTs

We next examine the role of large-scale circulation by compositing EPEs (see section 2.3) according to the six WTs presented in table 1. To focus on extremes, figure 4 shows composites of the three most intense precipitation events per WA for each WT, together with their climate-change response. Marked differences emerge across circulation regimes. In particular, WT1, WT3, WT4, and WT5 exhibit substantially stronger amplification of extreme precipitation, with local responses frequently exceeding the CC scaling with global-mean temperature. The response patterns are spatially coherent, and the largest signals occur in regions where WT-associated precipitation is already intense. To emphasise the regions where the different WTs typically generate intense precipitation events, changes are shown only where the composite precipitation exceeds the 0.997 quantile threshold (i.e. the level approximately exceeded on average once per year).

The strongest responses occur over Tuscany (WT1, WT3, WT4), the pre-Alpine region (WT3), Campania (WT4), Emilia-Romagna and Sicily (WT5). These regions include Alpine and Tyrrhenian areas that are particularly exposed to very humid southwesterly flows conducive to intense precipitation, and Adriatic regions, like Emilia-Romagna, more exposed to orographic lifting due to convergence of easterly and southeasterly flows. The pre-Alpine signal in WT3 is consistent with the statistically significant observed positive trend in precipitation intensity reported by Pavan *et al* (2019).

Although formal significance testing cannot be applied to the composites because of the limited sample size (three strongest events per WA per WT), similar spatial patterns emerge for the mean of all

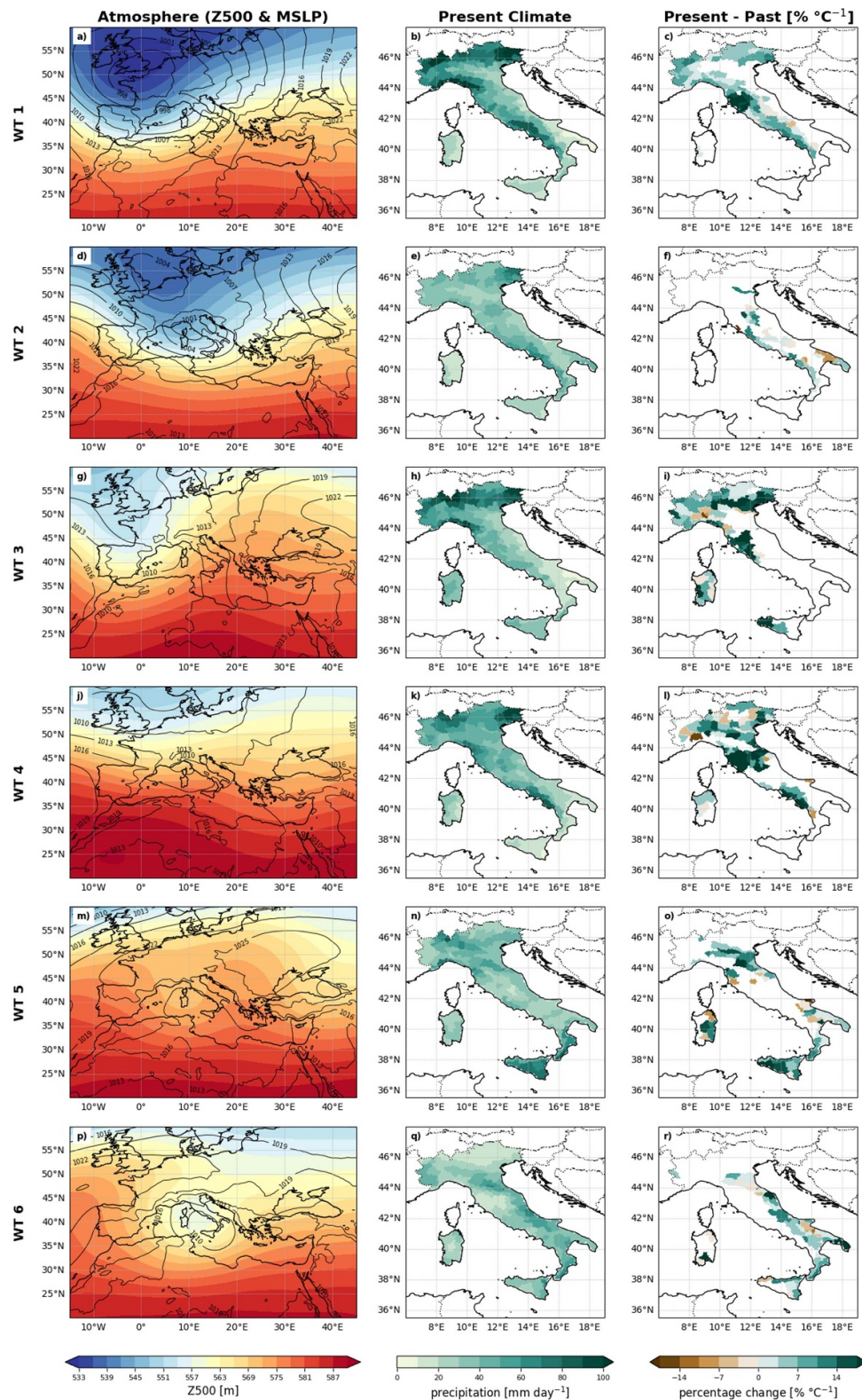
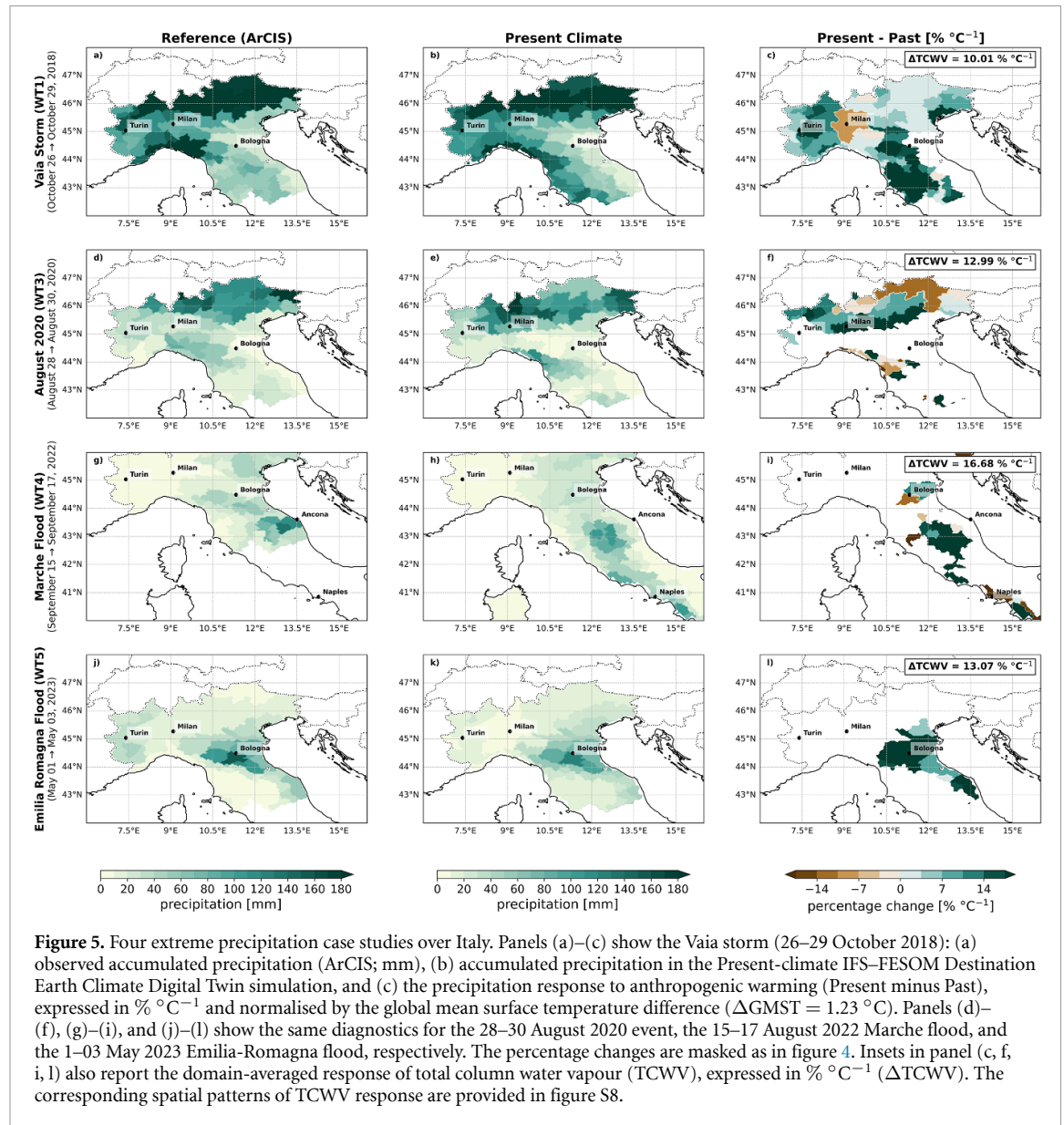


Figure 4. Response of precipitation across Weather Types associated with Italian precipitation extremes. Panels (a)–(c) show WT1: (a) Present-climate mean sea-level pressure (MSLP; contours) and 500 hPa geopotential height (Z500; shading), (b) Present-climate composite precipitation of the top three extreme events per warning area, and (c) the climate-change response ($\% \text{ } ^\circ\text{C}^{-1}$), computed as the Present–Past (1950 s) difference normalised by Past precipitation and by the global-mean surface temperature difference ($\Delta\text{GMST} = 1.23 \text{ } ^\circ\text{C}$). Panels (d)–(f), (g)–(i), (j)–(l), (m)–(o), and (p)–(r) show WT2–WT6 with the same layout. Response maps are masked using the precipitation corresponding to the 0.997 quantile (mean of Present and Past quantile maps), highlighting regions where the precipitation composite exceeds the average once per year event.



EPEs associated with each WT (34–81 EPEs per WT; figure S7, SI), supporting the robustness of the WT-level conclusions (see SI section S8 for a detailed discussion).

The dynamical environments associated with WT1, WT3, WT4, and WT5 are preferentially linked to autumn and winter circulation patterns (Iacomino *et al* 2025), consistent with the dominant role of SON (and, to a lesser extent, DJF) in the intensification of precipitation extremes identified above. The thermodynamic component of these responses is further supported by the corresponding increase in TCWV for the same event composites (figure S8, SI). However, the presence of differences between the relative increases in TCWV and in precipitation likely reflects additional contributions from sub-nudged-scale moisture transport, convergence, and event-specific dynamical feedbacks that remain beyond the reach of the present diagnostics.

3.4. Case studies of extreme events

Figure 4 shows responses exceeding CC scaling with global-mean temperature in several WAs within the WT1, WT3, WT4, and WT5 composites. To exemplify these signals, figure 5 presents four EPEs representative of the identified WTs, which exhibit strong responses during 2017–2024. Specifically, we examine the October 2018 Vaia/Adrian storm associated with WT1 (Cavaleri *et al* 2019, Davolio *et al* 2020, Sioni *et al* 2023), an August 2020 pre-Alpine convective events associated with WT3, the September 2022 Marche flood associated with WT4 (Rrokaj *et al* 2025, Bendia *et al* 2026), and the first Emilia-Romagna flood of 1–03 May 2023 associated with WT5⁹ (Cremonini *et al* 2024, Dorrington *et al* 2024). All four events caused widespread and severe flood damage in the affected areas.

From figure 5 it is evident that, across all case studies, *Present* simulations show substantially

stronger precipitation intensities than their *Past* counterparts. Local precipitation responses averaged over the WAs frequently exceeded 14% per degree of global-mean warming, providing event-level confirmation of the large signals inferred from the quantile-based and composite analyses. These results provide strong support for the conjecture that these recent EPEs have been intensified by AGW. Further analysis shows that the precipitation amplification is closely linked to enhanced atmospheric moisture availability. For the same events, the TCWV response (figure S9, SI) generally exceeds the CC scaling, consistent with strong thermodynamic moistening in the Present climate. In some cases (e.g. Emilia-Romagna flood of 1–03 May 2023, figure 5(l), however, the intensification of precipitation substantially outpaces the corresponding TCWV increase, indicating that thermodynamic scaling alone cannot fully account for the observed precipitation response. This mismatch points to an important contribution from processes operating below the spatial scales constrained by spectral nudging.

Taken together, the case studies demonstrate that, under favourable large-scale circulation patterns, daily extreme precipitation over Italy can intensify well beyond thermodynamic expectations. They provide concrete, physically consistent examples showing that the largest statistical deviations identified earlier correspond to coherent, high-impact events. More broadly, these results suggest that applying a uniform thermodynamic scaling to individual events can underestimate the true impact of AGW. At the same time, the magnitude of the amplification should be interpreted with caution, as part of the signal may also reflect internal variability at sub-nudged scales or event-specific dynamical feedbacks that cannot be fully disentangled without an ensemble of spectrally-nudged simulations.

4. Discussion and conclusion

By combining spectrally-nudged storyline simulations of 2017–2024 under mid-20th century and present-day climate conditions with a WT classification, we assess how the thermodynamic response of precipitation to AGW varies across circulation patterns associated with extremes over Italy. Our results show that, under the same large-scale dynamical conditions, precipitation responses are strongly intensity-dependent, seasonally modulated, and closely linked to the prevailing WTs. While mean precipitation increases mainly over northern Italy and wet-day frequency decreases, particularly in summer, over Central and Southern Italy, the most intense events intensify nearly everywhere across the country. Event-level analyses of four EPEs—representative of the four WTs and exhibiting the strongest responses

to warming—indicate that under specific synoptic configurations, precipitation amplification can substantially exceed that expected from increases in column water vapour alone.

These findings have direct implications for extreme event attribution and risk assessment. Consistent with previous studies (Trenberth *et al* 2003, O’Gorman and Schneider 2009, O’Gorman 2015, Pfahl *et al* 2017, Thackeray *et al* 2022), extreme precipitation responds more strongly to warming than mean precipitation. Our results are also consistent with observational evidence showing that heavy precipitation has intensified in many regions at rates consistent with, or—especially at sub-daily timescales—exceeding thermodynamic expectations (Fischer and Knutti 2016). Mesoscale ascent, changes in small-scale dynamics, and increased precipitation efficiency in a warmer and moister atmosphere may further amplify rainfall during extreme events (O’Gorman and Schneider 2009, Berg *et al* 2013, O’Gorman 2015). These processes appear to be preferentially activated under specific synoptic configurations, as suggested by the concentration of the strongest responses within a limited subset of WTs. Spectrally-nudged storyline simulations therefore provide a transparent framework to isolate thermodynamic and mesoscale contributions while holding large-scale circulation fixed, highlighting that assessments based solely on column moisture may underestimate future hydrological risks, particularly for high-impact events (Fowler *et al* 2021).

Several limitations should be acknowledged. Some of the strongest event-level amplifications may reflect mesoscale internal variability, which cannot be robustly assessed given the short record (2017–2024), the single realisation per experiment, and the parameterisation of convection. Multi-member simulations would improve sampling of rare extremes and better separate forced from stochastic variability. Furthermore, while the current framework enables a circulation-conditioned assessment of thermodynamic responses, freely coupled climate model simulations could additionally evaluate projected shifts in WT frequency, thereby quantifying the dynamical contribution to future changes in precipitation extremes within each regime as in León-FonFay *et al* (2026). Lastly, it should be noted that the changes per degree of warming reported in this manuscript were obtained as differences between the Present and Past climate states; therefore, their applicability beyond this warming range should be interpreted with caution. More broadly, the approach presented here is transferable to other regions and storyline simulations of future climates, providing a physically interpretable link between present-day attribution studies and future projections of extreme precipitation changes.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://www.arcis.it/wp/> (Pavan et al 2019), <https://cds.climate.copernicus.eu/datasets> (Hersbach et al 2023 and Schimanke et al 2021) and <https://doi.org/10.21957/d3f982672e> (DestinE 2025).

Destination Earth data have been reduced with the AQUA code (Nurisso et al 2026). Scripts used for the data reduction are available upon request.

Supplementary Information available at: <https://doi.org/10.1088/1748-9326/ae8fea/data1>.

Conflict of interest

The authors declare no competing interests nor conflicts of interest. No human or animal data have been used in this study.

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