

Storyline attribution of fire weather during the 2025 Mediterranean summer

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17 Abstract

18 The Mediterranean region is a climate change hotspot where increasing temperatures and changing
19 hydroclimate are intensifying wildfire risk. The extreme fire season of summer 2025 provides a timely
20 case to assess the role of anthropogenic climate change in shaping fire-conducive atmospheric
21 conditions. Here, we apply a spectrally nudged storyline approach to conditionally attribute the
22 thermodynamic contribution of climate change to the Fire Weather Index during July–August 2025, for
23 past and future climate states. We find a robust increase in fire weather across the Mediterranean under
24 climate change. The strongest and most spatially coherent signal is driven by temperature increases,
25 while reductions in relative humidity and precipitation further amplify fire-conducive conditions in specific
26 regions.

27 These results demonstrate that climate change has substantially intensified the meteorological conditions
28 conducive to wildfires during the 2025 Mediterranean summer. More broadly, this study highlights the
29 value of conditional storyline attribution for linking physically driven climate changes to impact-relevant
30 metrics such as fire weather.

31

32 1. Introduction

33 Southern Europe is increasingly recognized as a climate change hotspot, where warming trends are
34 intensifying the frequency, severity, and compound nature of extreme weather events. According to the
35 IPCC Sixth Assessment Report ¹, the region is already experiencing a warming rate exceeding global
36 mean temperature changes, with projections indicating further increases in heatwaves, droughts, and
37 wildfire risk. In recent decades, the frequency and intensity of extreme wildfires have increased globally ²,
38 driven by complex interactions between climate variability, human factors, land use, and vegetation. A
39 growing number of studies analyze the role of climate change in amplifying fire weather conditions, with
40 significant implications for ecosystems, human health, and infrastructure. In this paper, we will use the

term fire weather as defined by Jones et al. ³, which is ‘weather conditions conducive to the ignition and spread of wildfires’.

A methodological approach for global-scale fire weather assessments was initiated by Field et al. ⁴, developing a comprehensive global fire weather database that enables consistent analyses across regions. Jolly et al. ⁵ studied fire weather season lengths and demonstrated that climate-induced variations have led to a marked increase in global wildfire danger from 1979 to 2013. More recent studies have deepened our understanding of the drivers and regional characteristics of fire risk, showing that warming temperatures, prolonged droughts, and shifting atmospheric circulation patterns are intensifying fire weather conditions ^{6,7}. Richardson et al. ⁸ show the growing global wildfire potential under compound fire weather and drought conditions, and a recent study of Ghasemiazma et al. ⁹ confirms this result for the Mediterranean region. An extensive overview of global and regional trends was provided by Jones et al. ³, emphasizing the influence of warming temperatures and altered precipitation patterns. There is growing global evidence that climate change increasingly explains burned area trends ¹⁰. A study by Grillakis et al. ¹¹ explores the climate drivers behind these trends, such as relative humidity and temperature, which are found to be the most important factors for many regions worldwide like Europe.

European-focused research highlights a trend towards more frequent and severe fire weather events ^{12,13}. Southern Europe experienced some of the most pronounced changes, being one of the most climate-sensitive regions in terms of wildfire risk. Here and in the adjacent seas, compound atmospheric and marine heatwaves and droughts strongly correlate with increased wildfire activity ⁶. Recent studies highlight the growing influence of climate change on fire weather across Europe and the Mediterranean. A significant expansion of pyro-regions in the Iberian Peninsula was detected by Calheiros et al. ¹⁴, with more frequent extreme fire weather events under future climate scenarios. Rovithakis et al. ¹⁵ similarly identify increased wildfire danger in Greece, driven by rising temperatures and drought frequency. Matteo et al. ¹⁶ emphasize the methodological challenges in assessing fire weather trends, recommending the inclusion of sub-daily meteorological data in future climate model intercomparison projects to enhance fire weather indices accuracy. Even modest warming scenarios (1.5°C and 2.0°C) substantially alter fire weather climatology globally and in the Mediterranean specifically ¹⁷. Sutanto et al. ¹⁸ warn of intensifying compound drought-heatwave events, which amplify fire risk across Europe. Escalating wildfire disasters, featuring a concentration in the Mediterranean and temperate conifer biomes, can be linked to extreme climatic conditions ². A wildfire prediction system that combines satellite images, environmental data, and machine learning can be used for wildfire risk assessments ¹⁹. Cilli et al. ²⁰ illustrate how explainable AI can enhance the understanding and detection of fire risk hotspots for Italy. These results highlight the necessity for region-specific fire risk assessments and its attribution to climate change for Southern Europe. Recent summers have illustrated these risks vividly. In 2025, Southern Europe faced exceptional heatwaves, with very strong heat stress in large parts of western and southern Europe with, for instance, Spain experiencing its warmest June in 64 years ²¹. These conditions triggered widespread wildfires, evacuations, and heat-related fatalities, with over 1,025,224 ha burned across the EU by late September ²². Associated record-breaking wildfire emissions occurred in Turkey, Cyprus, the Balkans, southwestern Europe, and the UK ²³, summing up to the highest annual total in the 23 years of the CAMS Global Fire Assimilation System (GFAS) dataset ²⁴.

A growing number of studies tackle the attribution of fire weather to anthropogenic climate change. Liu et al. ²⁵ highlight increasing trends in fire weather extremes on a global scale, though attribution remains complex due to uncertainties associated with the selection of indices and metrics to represent extreme fire weather. Lanet et al. ²⁶ demonstrate that conditions that were favourable for wildfire development in Southwest France were made two times more likely by climate change, with elevated fire weather indices driven by prolonged heat and drought. In two reports ^{27,28}, the World Weather Attribution group analyzed

the 2025 fire weather over Europe. For Türkiye, Cyprus, and Greece, observations and climate models show that events once expected every 100 years now occur every 10 to 20 years, with further warming projected to intensify fire weather conditions²⁷. In a recent study, Keeping et al.²⁹ analyzed extreme wildfire events in 2025 for several regions in Europe and found an increase in the likelihood and intensity of weather drivers of wildfires. For Spain and Portugal, extreme wildfire-driving conditions and record-breaking heat in the Iberian Peninsula, which were once expected less than once every 500 to 2500 years, now occur roughly every 13 to 15 years, with significantly increased intensity due to human-induced climate change²⁸.

The use of storyline approaches, as discussed by Shepherd et al.³⁰, offers a framework for attribution by focusing on physically plausible pathways rather than probabilistic metrics alone. While such approaches have been applied to wildfire impacts³¹, attribution studies of fire weather have so far relied predominantly on probabilistic methods or trend analyses, limiting the ability to isolate the physical processes underlying specific events. In particular, a conditional attribution of fire weather, in which the dynamical evolution of an event is constrained while thermodynamic conditions are varied, has not yet been explored.

Here, we address this gap by applying a spectrally nudged storyline approach to attribute the fire weather conditions of the Mediterranean summer of 2025. Using the Canadian Forest Fire Weather Index³², we quantify how the same event would have unfolded under different climate states, thereby isolating the thermodynamic contribution of climate change. This approach provides a physically consistent perspective on the drivers of extreme fire weather, complementing existing probabilistic attribution methods and enabling a more process-based understanding of wildfire-conducive conditions.

2. Results

The Canadian Fire Weather Index (FWI) is widely used across Europe to indicate meteorological conditions conducive to wildfire activity, with daily values provided through the European Forest Fire Information System (EFFIS). As a consistency check, in Figure 1, we compare the FWI calculated from the ECHAM6 factual storyline simulations with the Copernicus Emergency Management Service (CEMS) product used within EFFIS³³ for 1 July 2025. The CEMS FWI is derived from the Global ECMWF Fire Forecast model (GEFF), driven by meteorological input from ERA5 reanalysis.

Figure 1a shows the ECHAM6-derived FWI categories for 1 July 2025, while Figure 1c presents the corresponding CEMS product regridded to the ECHAM6 grid. Despite the difference in native resolution, there is good qualitative agreement in the dominant spatial patterns. Both datasets show (i) a transition from low to higher FWI from northern to southern Spain, (ii) very high to extreme FWI over Sardinia, and (iii) elevated to extreme FWI extending across south-eastern Europe. While the exact spatial structure of these features differs, the large-scale patterns are consistent between the two datasets.

Figure 1b shows the difference between CEMS and ECHAM6 (CEMS – ECHAM6), and Figure 1d presents the corresponding land-only zonal mean. Over the Iberian Peninsula and southern France, CEMS indicates higher FWI values than ECHAM6, whereas along the Adriatic region the values are broadly comparable. Further east, towards Greece and the Black Sea region, ECHAM6 tends to show higher FWI values than CEMS.

This level of agreement suggests that the ECHAM6-derived FWI captures the dominant large-scale spatial patterns of fire-conducive conditions on daily timescales. Although small-scale features cannot be

resolved at the model resolution, the consistency at larger scales supports the use of ECHAM6-derived FWI for the purposes of this study.

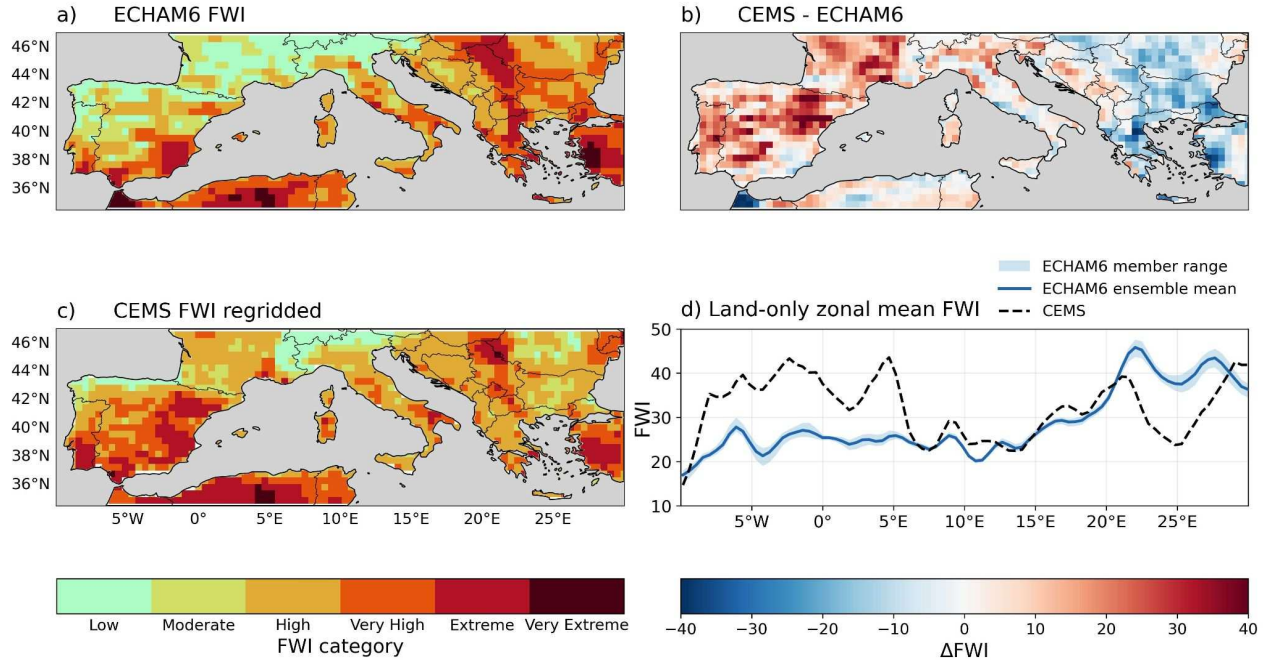
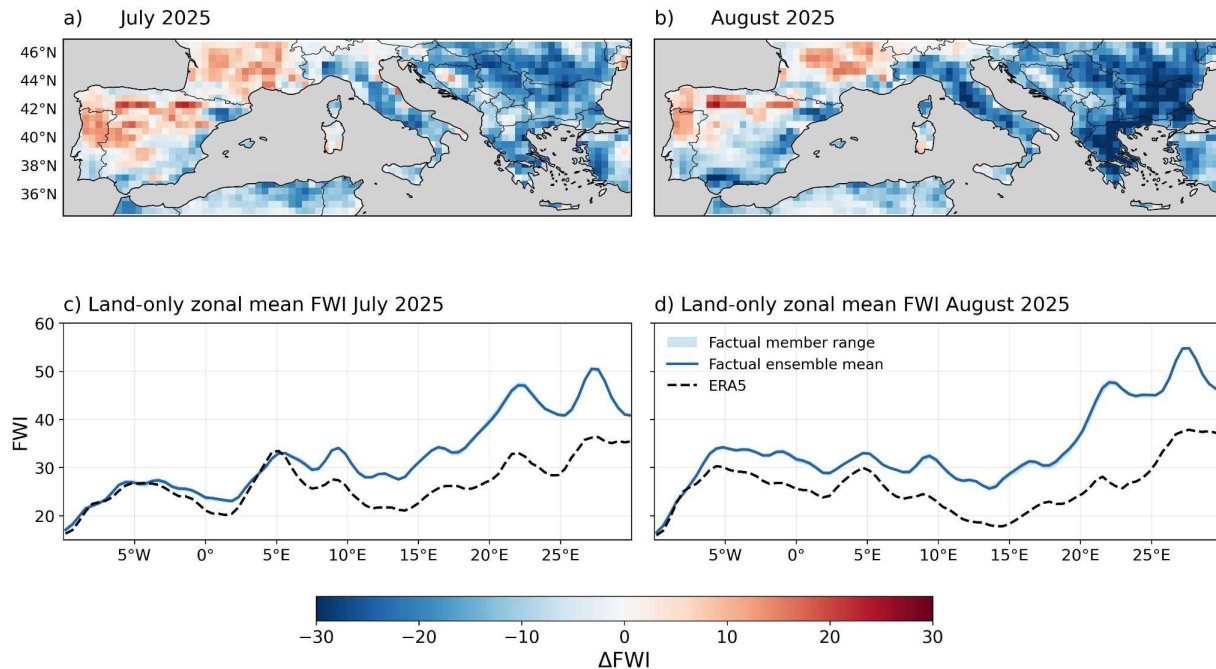


Figure 1 a) Comparison of Fire Weather Index (FWI) between ECHAM6 factual simulations and the Copernicus Emergency Management Service (CEMS) Global Fire Weather Index system for 1 July 2025. (a) ECHAM6 factual ensemble mean FWI shown in standard FWI categories. (b) Difference between CEMS and ECHAM6 (CEMS - ECHAM6). (c) CEMS FWI regridded to the ECHAM6 grid. (d) Land-only zonal mean FWI, showing the ECHAM6 ensemble range (min-max envelope) and mean alongside CEMS.

For a second test, we compare the ECHAM6 factual FWI to FWI calculated consistently from ERA5 data. The ERA5-based FWI is computed with the same input variables and algorithm as the ECHAM6 FWI. Figure 2a and b show the differences between the ERA5-derived FWI (regridded to the ECHAM6 grid) and the ECHAM6 factual ensemble mean for July and August. A clear west-east gradient in the differences is apparent, ranging from approximately +20 FWI units over northern Spain to -30 FWI units over eastern Greece. Panels c and d show the zonal mean over land FWI of the difference maps, showing that ECHAM6 tends to have higher FWI values in the Adriatic coast and south-east Europe than ERA5. Such discrepancies are not unexpected. The Fire Weather Index is highly sensitive to precipitation, and both models and reanalyses are known to exhibit uncertainties in the timing, location, and magnitude of rainfall³⁴. In addition, ERA5-based FWI estimates have documented biases, likely linked to these precipitation uncertainties³⁵. As a result, differences between ERA5 and ECHAM6 do not have a straightforward interpretation in terms of model performance. Rather, they provide an indication of the spread that can arise from using different, yet plausible, representations of the atmospheric state.



151

152 Figure 2 Differences in Fire Weather Index between ERA5-derived FWI (regridded to the ECHAM6 grid)
 153 and the ECHAM6 factual ensemble mean and ensemble range (min-max envelope), for (a) July 2025
 154 and (b) August 2025 averages. Panels (c) and (d) show the corresponding land-only zonal mean FWI for
 155 July and August 2025, respectively.

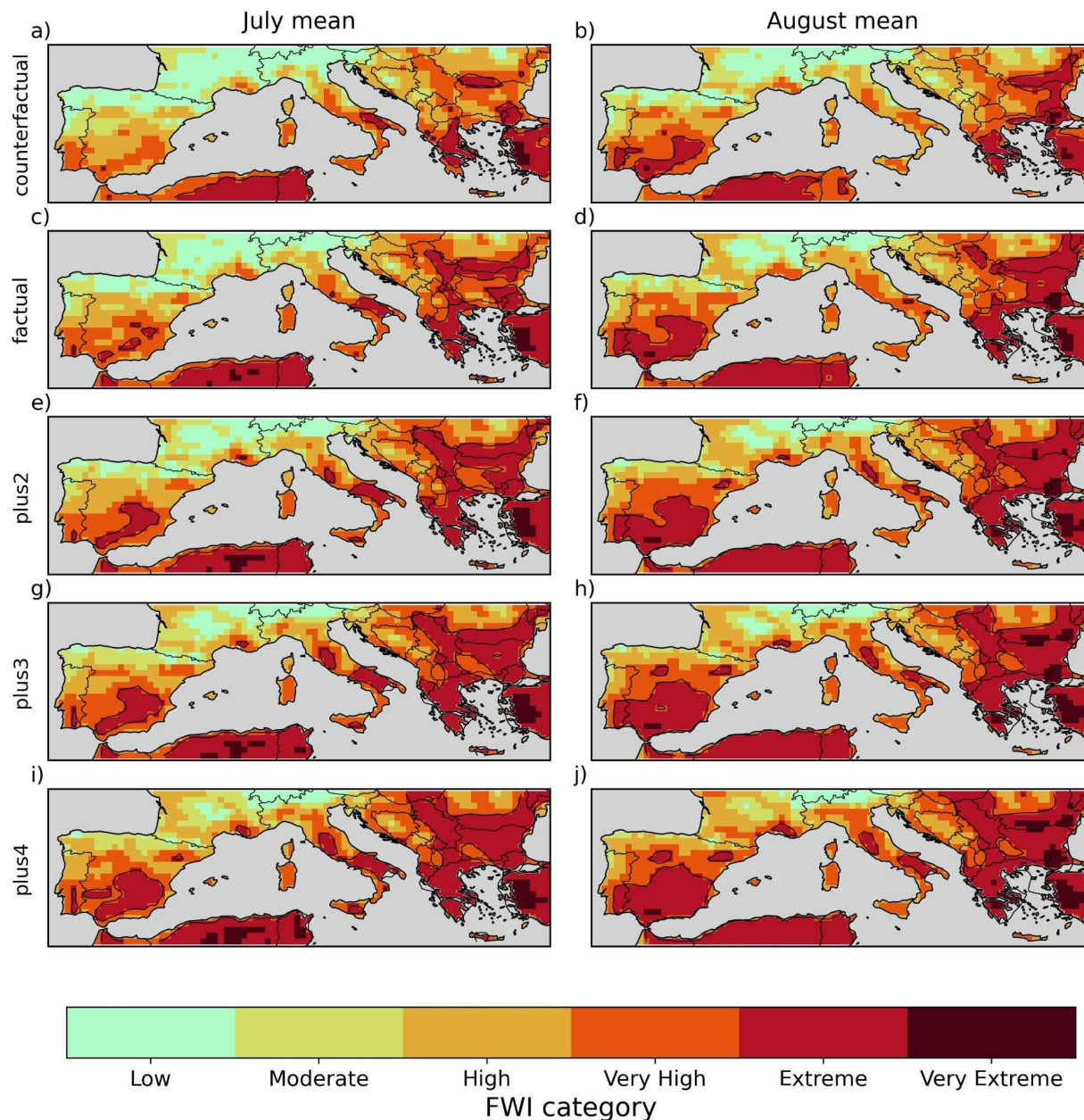
156 The magnitude of the differences (order ~20 FWI units) is generally insufficient to shift conditions across
 157 more than one FWI danger class when averaged over a month, although larger deviations may occur on
 158 daily timescales. ERA5 is therefore included as a reference dataset to provide context for the ECHAM6
 159 spectrally nudged simulations, rather than as a benchmark for evaluation.

160

161 3.1 Fire Weather Index (FWI)

162

163 The differences in FWI categories for the different storylines can be seen in Figure 3. Here the spatial
 164 distribution of the FWI index monthly average for July 2025 and August 2025 are shown for each storyline
 165 ensemble mean. When looking from panel a and b (counterfactual) to bottom panels i and j (plus 4K)
 166 there is a clear increase in FWI index due to climate change. The low FWI index is nearly lost completely
 167 to higher index values by the time we reach the plus 4K world, with exception of mountainous areas
 168 (Alpes and Pyrenees). Though the exact pattern of the extreme and above FWI differs between the two
 169 months, the trend seems comparable with a northbound FWI increase.

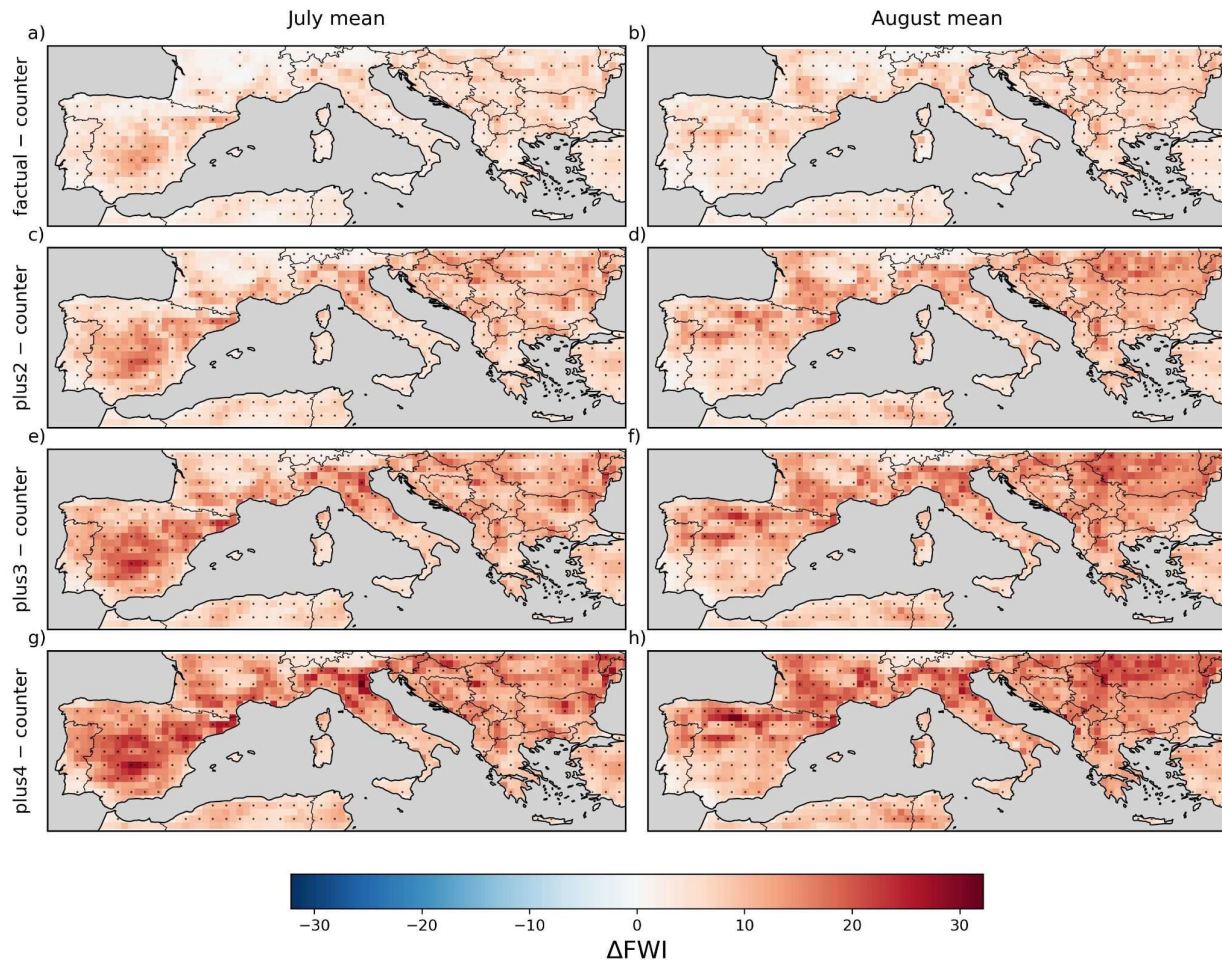


170

171 Figure 3 Fire Weather Index by category for July 2025 (left) and August 2025 (right) monthly averages,
 172 for each storyline starting at counterfactual at the top and ending with plus 4 degrees warmer at the
 173 bottom. Extreme FWI is contoured for a clearer visual.

174 To get a better look at the exact differences, the differences per storylines relative to the counterfactual
 175 storylines have been plotted in Figure 4. Stippling indicates grid cells where the difference between the
 176 storyline and counterfactual simulations is robust across ensemble members. Specifically, stippling is
 177 applied where the range of values across all members of the storyline ensemble does not overlap with
 178 the range of values across all members of the counterfactual ensemble. We see that the differences for
 179 July show a somewhat different pattern of increased FWI than August, where in July the South of Spain
 180 seems to be more affected by climate change, and in August it shows up more in the North of Spain. For
 181 Italy, the patterns for both months are comparable, with a larger increase in FWI values in the north

182 (though south of the Alps). For Greece, the FWI value increase seems to be moderate over the different
 183 storylines; however, one should consider that the FWI values for Greece were already extreme (see
 184 Figure 3). The climate signal is most prominent in areas that did not have an extreme FWI yet, but move
 185 towards it throughout the different levels of global warming.
 186



187
 188 Figure 4 Differences maps for July 2025 (left) and August 2025 (right) between the different storylines
 189 and the counterfactual. Stippeling is a robustness test to show that all the members of the storylines
 190 included are away from all the counterfactual members (a true split).

191
 192 To provide an overview of how daily changes in FWI respond to climate change at the country level, time
 193 series are shown in Figure 5. Panels (a–h) present results for Portugal, Spain, southern France, Italy,
 194 Bosnia and Herzegovina, Montenegro, Albania, and Greece, respectively. It should be noted that smaller
 195 countries, such as Albania and Montenegro, are represented by only a limited number of grid cells at the
 196 ECHAM6 resolution (see Supplementary Table S1), which requires careful interpretation.

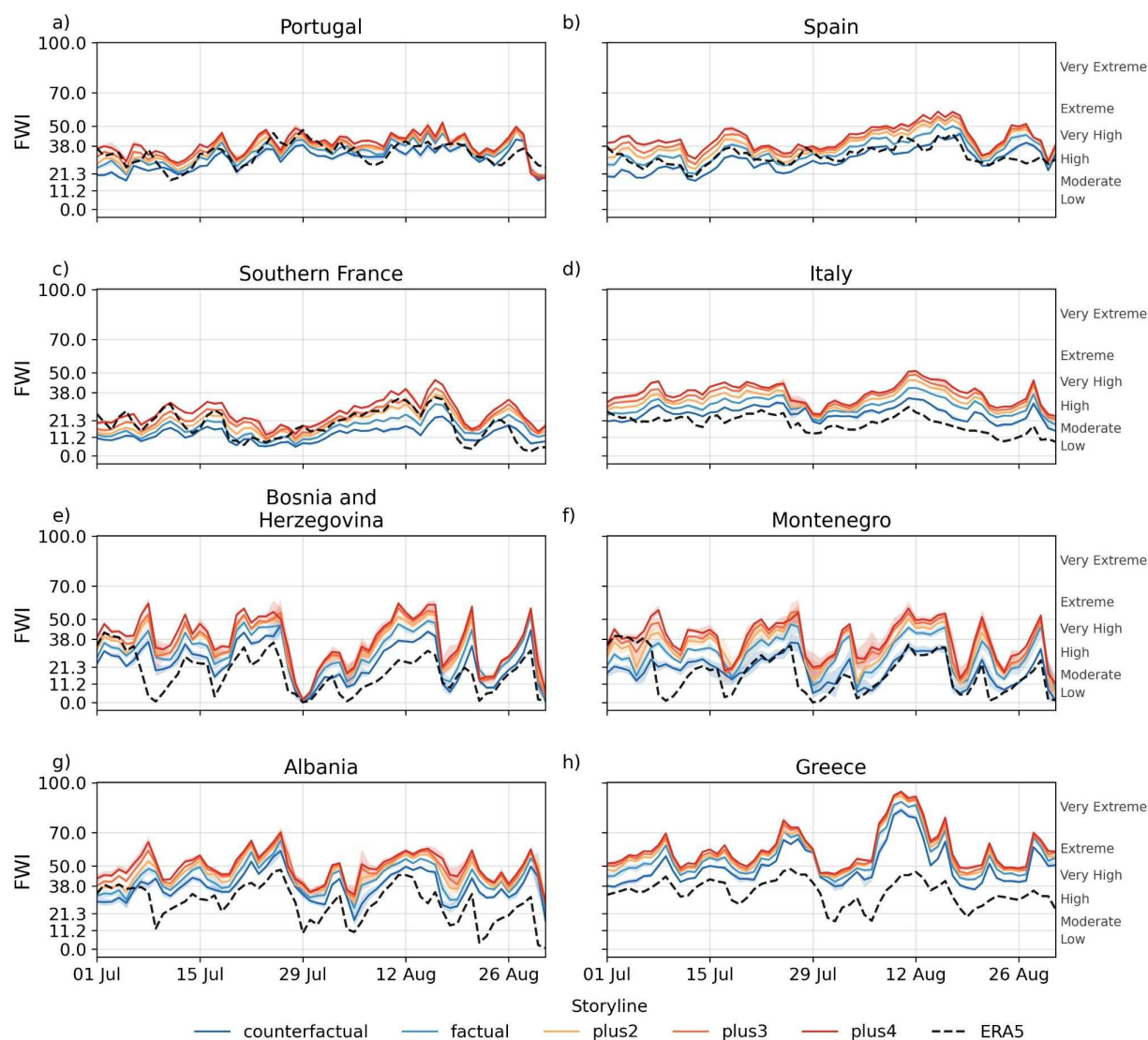
197 For all countries, FWI values are consistently higher in the factual storyline compared to the
 198 counterfactual, indicating a robust climate-change signal. However, the response to additional warming in
 199 the plus2, plus3, and plus4 storylines is not uniform across regions. Spain, Italy, and southern France
 200 exhibit a clear and robust increase in FWI, with minimal overlap between ensemble members across

201 storylines. In contrast, Albania, Bosnia and Herzegovina, and Montenegro show substantial overlap
 202 between storylines, indicating a less robust signal.

203 For Greece, the differences between the counterfactual, factual, and plus2 storylines are robust, while the
 204 plus3 and plus4 storylines show only limited additional change relative to plus2.

205 The ERA5 and ECHAM6 FWI time series show broadly consistent temporal behaviour, suggesting that
 206 the large-scale dynamical conditions are well represented in ECHAM6. However, differences between
 207 ERA5 and ECHAM6 increase towards the eastern Mediterranean, consistent with the spatial patterns
 208 discussed earlier.

209



210

211 Figure 5 Daily Fire Weather Index (FWI) time series for July and August 2025 for each country and
 212 storyline (counterfactual, factual, plus2, plus3, and plus4). Lines indicate the ensemble mean and shading
 213 shows the member range (min-max envelope). ERA5 is included for comparison (black dashed line). The
 214 left y-axis shows FWI values, while the right y-axis indicates the corresponding FWI danger categories
 215 (low, moderate, high, very high, extreme, very extreme).

216

217 3.2 Component analysis

218 To investigate the origin of the climate-change signal in the Fire Weather Index (FWI), daily country-mean
219 time series of its individual components are shown in Figure 6. The FWI is based on near-surface
220 temperature at noon, relative humidity at noon, wind speed at noon, and total precipitation accumulated
221 over the preceding 24 hours. As the large-scale dynamics in the model are nudged, wind speed and
222 direction are identical across all storylines and are therefore not considered in this analysis. Moreover,
223 wind speed has shown to make little contribution to the general FWI value ³⁶.

224

225 Greece stands out as the only country where near-surface wind shows a substantial divergence between
226 the storyline simulations and ERA5 (Supplementary Figure S1). While wind is identical across the
227 different storyline simulations due to the applied nudging, it can still differ from ERA5. For most countries,
228 wind variability is broadly comparable between the storyline simulations and ERA5, supporting the
229 assumption that wind plays a minor role in explaining differences in FWI.

230 However, over Greece the storyline simulations exhibit a pronounced wind event in August that is much
231 weaker in ERA5 (Supplementary Figure S3d). This event coincides with the peak in FWI, indicating that
232 wind contributes to the enhanced fire weather conditions in the storyline simulations for this region. In
233 addition, Greece shows consistent differences in other components, including higher temperatures, lower
234 relative humidity, higher VPD, and lower cumulative precipitation in the storyline simulations compared to
235 ERA5 (Supplementary Figure S3). Overall, the divergence between storyline simulations and ERA5 is
236 larger for Greece than for the other countries, reflecting a combination of thermodynamic and dynamical
237 differences, with wind acting as an additional driver in this specific case.

238 The climate-change signal in temperature is robust across all countries and storylines. Relative humidity
239 shows a consistent decrease under climate change, with robust signals for Spain, southern France, Italy,
240 and intermittently for Greece.

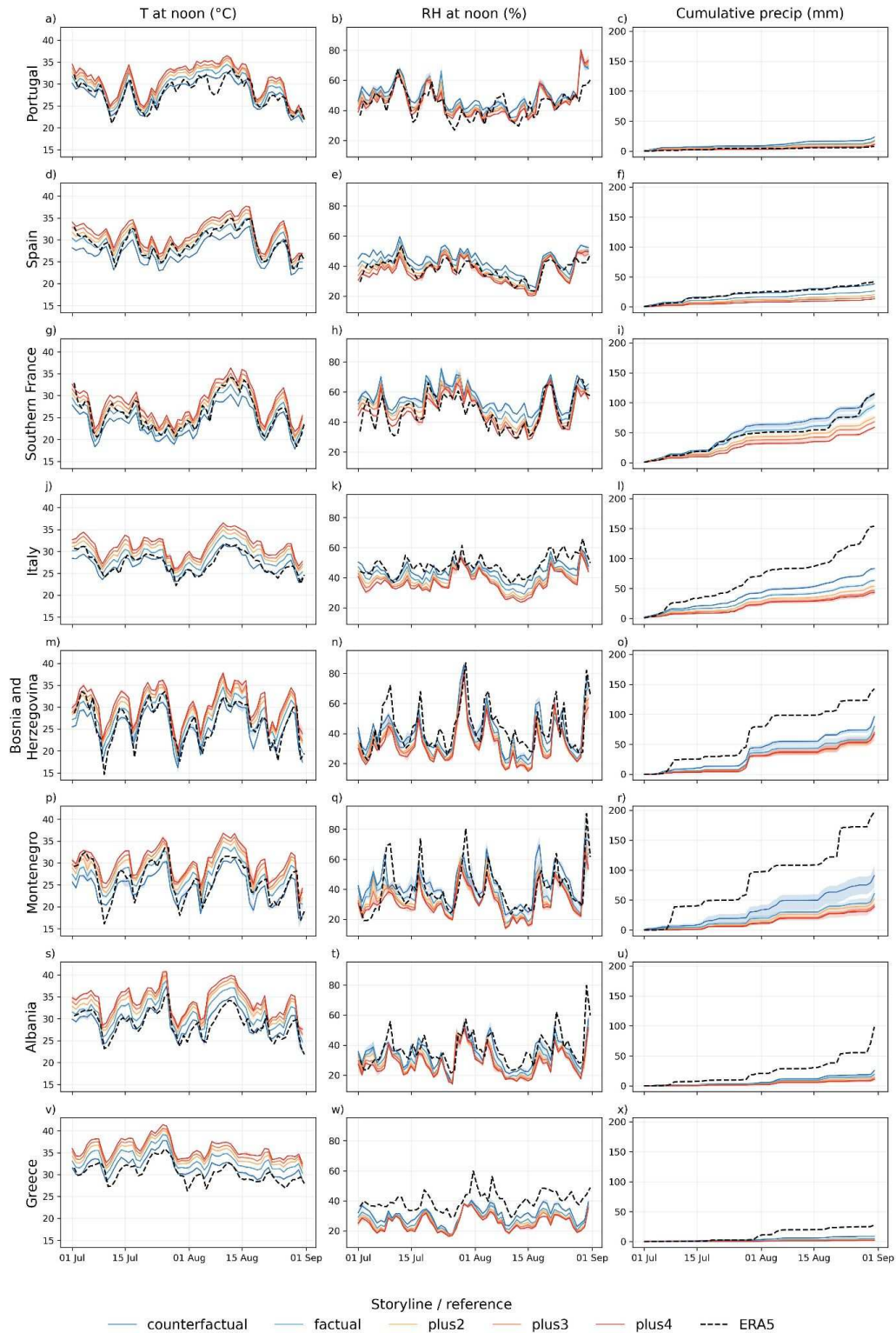
241

242 Precipitation provides insight into the increasing divergence between ERA5 and ECHAM6 towards the
243 eastern Mediterranean. The cumulative precipitation totals show progressively larger differences between
244 the two datasets from west to east, beginning in Italy and peaking in Montenegro, while remaining
245 noticeable through to Greece. For Greece, it should be noted that precipitation amounts are close to zero
246 across all storylines, meaning that small absolute differences can appear as relatively large signals. For
247 Montenegro, the analysis is further limited by the small sample size, as only seven ECHAM6 grid cells
248 represent the country, requiring careful interpretation.

249

250 Despite differences between ECHAM6 and ERA5, all countries exhibit a decrease in precipitation under
251 climate change. The precipitation signal is robust for Portugal, Spain, southern France, and Italy. In
252 contrast, robustness is harder to establish in regions with very low precipitation totals, such as Portugal,
253 Albania, and Greece.

254



255

256 Figure 6 Country-mean time series of Fire Weather Index (FWI) components for each storyline, shown
 257 with ensemble mean (line) and member range (min-max envelope). Columns show (a) near-surface
 258 temperature at noon (°C), (b) relative humidity at noon (%), and (c) cumulative precipitation from noon to
 259 noon (mm).

The temporal evolution of vapour pressure deficiency (VPD) closely follows that of near-surface temperature (See supplementary Figure S2), indicating that VPD variability is largely temperature-driven under these dry summer conditions. Relative humidity remains low and comparatively less variable. As a result, VPD does not provide substantially independent information beyond temperature for this period and is therefore shown in the Supplement.

3.3 Trends

Figure 7 shows the change in temperature, precipitation, and FWI per degree of global warming, based on the July and August 2025 averages. The temperature response exhibits different spatial patterns between the two months. In July, increases exceeding 1.25 °C per degree of global warming are rare, whereas in August these elevated warming rates extend over a much larger area across south-eastern Europe.

Notably, the strongest reductions in precipitation (Figure 6c-d) are not located directly along the Mediterranean coastline, but are instead found further north, particularly over northern Spain, southern France, and northern Italy. It is important to note, however, that regions such as Greece and Portugal experience very little precipitation during these months, making it difficult to detect a robust climate-change signal in these areas. Relative humidity is not shown, as no statistically robust or spatially coherent signal could be detected per degree of warming.

The spatial pattern of FWI change closely follows that of temperature, consistent with the country-based component analysis (Figure 6). Nevertheless, reductions in precipitation also contribute to the FWI signal in certain regions.

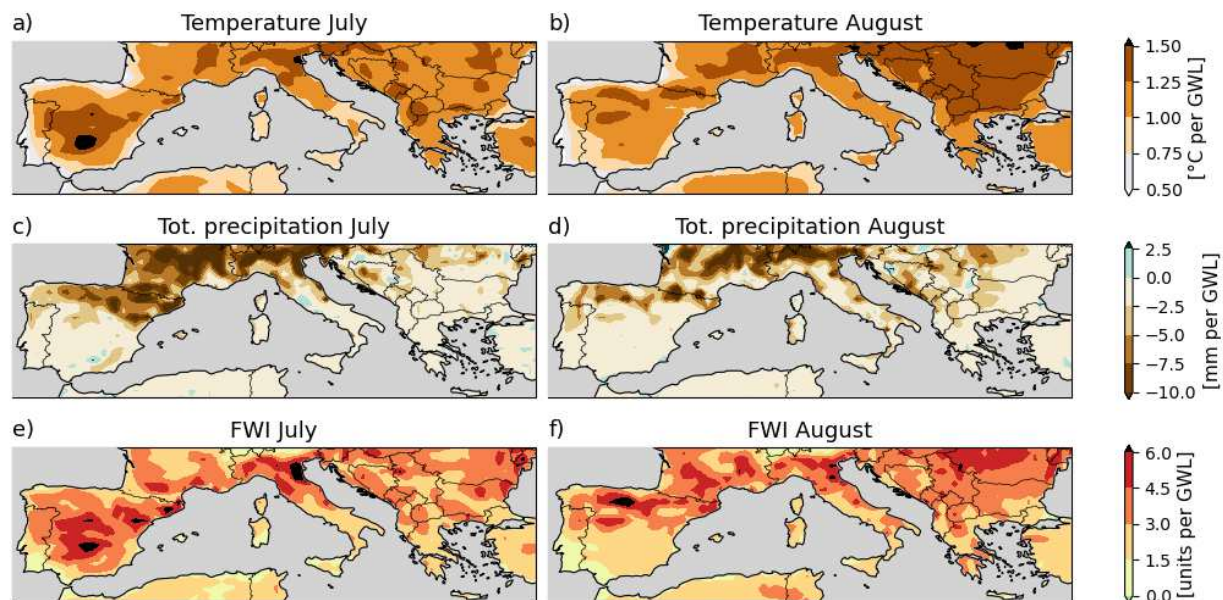


Figure 7 Trend per degree warming for July 2025 (left) and August 2025 (right) for near surface temperature at noon (a and b), total daily precipitation from noon-noon (c and d), and fire weather index (e and f).

285 The SPEI12 index was analysed to assess longer-term moisture conditions (Supplementary Figure S4).
286 While differences between the storyline simulations are present, the overall signal reflects relatively moist
287 antecedent conditions following a wet spring in 2025. As a result, the long-term drought index does not
288 directly capture the conditions that were most relevant for the extreme fire season.

289

290 3. Discussion

291 For both July and August, FWI shows a robust increase across the Mediterranean region under climate
292 change, with the largest relative increases occurring in regions that would otherwise experience low to
293 moderate fire weather conditions. This indicates both an intensification and a spatial expansion of
294 fire-conducive conditions. The country-based time series analysis shows that this increase is consistent
295 across all regions when comparing the counterfactual and factual storylines, although the response to
296 higher levels of warming is not uniform. Spain, Italy, and southern France exhibit a clear increase in FWI
297 across all storylines, whereas countries along the eastern Adriatic and parts of south-eastern Europe
298 show greater variability and overlap between ensemble members, indicating a less robust signal. This
299 variability can be attributed to both low precipitation amounts, which limit the detectability of a climate
300 signal, and the small number of grid cells representing some countries, which increases uncertainty in the
301 country-mean estimates.

302 Building on this, the thermodynamic attribution of the Mediterranean summer of 2025 shows that the
303 climate change signal in fire weather is primarily driven by temperature. This is consistent with the
304 generally dry conditions of the Mediterranean summer, where thermodynamic effects dominate over
305 hydrological variability. However, the response is not spatially uniform. Further inland, reductions in
306 precipitation and relative humidity also contribute to increases in the Fire Weather Index, highlighting a
307 more regionally differentiated response. While the storyline simulations indicate reduced seasonal
308 precipitation, climate change can still intensify short-duration rainfall extremes, as demonstrated by recent
309 Mediterranean flash-flood events. This contrast across timescales highlights that sub-daily precipitation
310 extremes may increase even when the seasonal mean declines.

311 The interpretation of precipitation changes in the Mediterranean region is complicated by the fact that
312 different studies capture different aspects of the climate response. Large-scale observational and
313 model-based analyses show no long-term trend in mean precipitation³⁷, reflecting the multi-year to
314 decadal variability and competing influences acting on the region. At the same time, storyline studies
315 indicate a tendency towards reduced precipitation at seasonal scales, particularly in winter³⁸, and
316 similarly in the present analysis for the summer of 2025, where a reduction in precipitation is found inland
317 of the Mediterranean. In contrast, event-based analyses demonstrate that precipitation intensity can
318 increase under climate change, as shown for the 2024 Valencia flood, where subdaily extremes were
319 amplified through thermodynamic processes³⁹. These findings are not contradictory, but instead reflect
320 the combined influence of dynamical and thermodynamic processes, as well as differences in spatial and
321 temporal scale. The reduction in precipitation found in the storyline simulations reflects the
322 thermodynamic response under the specific circulation patterns of the 2025 summer, as the large-scale
323 dynamics are constrained by the nudging. Thermodynamic effects alone can lead to reduced
324 precipitation, while not excluding the possibility of increased precipitation intensity under different
325 conditions. This illustrates that seasonal-scale drying and extreme precipitation intensification can occur
326 simultaneously under warming.

327 3.1 Role of antecedent conditions and non-climatic influences

In addition to these meteorological drivers, antecedent conditions likely played an important role in shaping the 2025 fire season. The spring of 2025 was relatively wet, with above-average precipitation²³, most likely promoting vegetation growth across large parts of the Mediterranean region. As a result, wildfire intensity during the summer was influenced not only by meteorological conditions but also by increased fuel availability. This indicates that fire activity was not solely driven by moisture deficits but by compounding preconditions⁴⁰. Because the spring was unusually wet, long-term drought indicators such as SPEI12 do not fully capture the processes that shaped the 2025 season, underscoring the need for event-specific diagnostics.

Beyond environmental controls, human influences remain important for understanding fire activity. Anthropogenic factors such as land management practices and human-caused ignitions may have contributed to the severity and extent of the 2025 fire season^{28,41}. While these factors are not explicitly quantified in the present study, they are known to play a dominant role in European wildfire activity, where most ignitions are human-caused⁴². As this study focuses on the influence of climate change on meteorological conditions conducive to fire, these processes are not represented, but should be considered when interpreting observed fire impacts.

3.2 Robustness and consistency of the fire weather signal

A comparison between the ECHAM6 factual storyline simulations and both CEMS daily output and ERA5-based estimates shows good agreement in the large-scale spatial patterns of FWI. Despite the presence of regional biases, particularly along a west–east gradient, the overall structure of fire weather conditions is consistently represented across datasets. Focusing on Southern Europe, the bias patterns between ERA5 and MPI-GE are consistent with those reported for the EURO-CORDEX ensemble⁴³, with a coherent positive bias in southeastern Europe and Italy, and a more heterogeneous pattern with locally varying bias signs over the Iberian Peninsula. The agreement with independent modelling frameworks provides confidence that the identified fire weather patterns and their associated climate change signal are robust.

At the same time, interpretation at smaller spatial scales remains sensitive to model resolution. Smaller countries, such as Montenegro and Albania, are represented by only a limited number of grid cells, which can lead to increased variability and larger deviations from higher-resolution datasets such as ERA5. This highlights that small-country estimates must be treated cautiously due to sampling limitations.

The response across different warming levels further highlights characteristics of the applied storyline framework. Warmer climate states show smaller incremental increases in the climate signal compared to the transition from counterfactual to present-day conditions, resulting in a more conservative estimate of climate change effects. This attenuation reflects the storyline setup, in which only SSTs and greenhouse gases are modified, while uncertain drivers such as aerosols remain fixed. This likely reflects the construction of the storyline set-up, in which only SSTs and greenhouse gas concentrations are modified, as these have well-established anthropogenic signals. Other factors, such as aerosols, exhibit more uncertain and model-dependent responses and were therefore not included.

3.3 Interpreting fire weather changes in a conditional attribution framework

The patterns expressed per degree of warming are specific to the meteorological conditions of July and August 2025 and should not be interpreted as general climate change responses. Rather than providing projections, this analysis aims to quantify how climate change influenced a specific event, and how that same event would manifest under different thermodynamic conditions.

Notably, the counterfactual simulations show regions with extreme FWI values, indicating that the Mediterranean climate is inherently conducive to fire weather. Climate change acts to intensify, rather than initiate, such conditions. At the same time, potential contributions from changes in atmospheric dynamics cannot be assessed within the conditional attribution framework applied here. Furthermore, once FWI values reach the extreme category, additional increases become difficult to interpret, as the index does not further differentiate levels of severity within this range. This limitation underscores that FWI saturates in highly fire-prone regions, constraining interpretation of additional intensification.

An interesting behavior emerges when comparing the regions where the FWI increases the most under global warming with those where fire weather is currently most intense and where wildfires occur. In regions where fire weather already peaks, precipitation is already extremely low, leaving little room for further intensification. As a result, fire weather in these areas cannot become substantially more extreme under additional warming. In contrast, regions where fire weather is not currently prevalent are more susceptible to large increases in FWI. This spatial contrast reflects that already precipitation-limited regions have limited headroom for further increases in fire weather severity.

3.4 Outlook

Future work should extend conditional attribution of fire weather towards a more impact-oriented framework. While the Fire Weather Index provides a physically meaningful intermediate metric between atmospheric conditions and wildfire activity, it does not directly translate to realized impacts such as burned area, emissions, or economic damage. Bridging conditional attribution approaches with impact-based models therefore offers a key opportunity to better understand how climate change influences not only fire-conducive conditions, but also their societal and ecological consequences. Because FWI captures only atmospheric drivers and not vegetation dynamics or human ignitions, integrating impact-based models will be essential to translate meteorological changes into realised wildfire outcomes.

Such an approach would enable the assessment of how the same extreme event translates into tangible impacts under different climate states, providing more actionable information for risk assessment and adaptation planning. Integrating analog-based methods into the highly conditioned storyline framework would enable a combined attribution approach⁴⁴ that both physically quantifies the influence of anthropogenic warming and assesses its associated likelihood, while also capturing potential changes in large-scale atmospheric dynamics. Expanding this framework across regions and events, and integrating additional processes such as vegetation dynamics and human influences, would further strengthen the link between physical climate attribution and real-world wildfire impacts.

4. Method

We apply the spectrally nudged storyline analysis to conditionally attribute the thermodynamics of the Mediterranean summer 2025 fire weather to climate change. Fire weather is defined according to the Canadian Fire Weather Index. This is the first study that applies a conditional attribution to fire weather. The analysis is applied to the Mediterranean region (34.5-47N, 10W-30E), as a systematic country-based analysis for the Mediterranean Sea neighboring states for which extensive forest fires were reported through the Global Wildfire Information System (GWIS): Portugal, Spain, Southern-France, Italy, Bosnia and Herzegovina, Albania, Montenegro, and Greece.

4.1 Spectrally Nudged Storylines

411 This highly conditioned attribution methodology ^{45,46} addresses how specific events would unfold under
 412 alternative climate conditions, under the assumption that the same weather patterns persist. Based on
 413 the approach proposed by van Garderen et al. ⁴⁷, five storylines are simulated to represent the 2025
 414 summer under: counterfactual (pre-industrial: 1850-1920), factual (present), and future +2K, +3K, and +4K
 415 warming levels (with respect to pre-industrial) conditions. Because of the causal nature of this
 416 methodology, all differences in the factual and future storylines relative to the counterfactual storyline can
 417 be directly attributed to anthropogenic global warming.

418 We use the atmospheric general circulation model ECHAM6 (the atmospheric component of MPI-ESM at
 419 T255 using 95 levels ^{48,49}, which includes the coupled land surface and vegetation model JSBACH. To
 420 keep the large-scale circulation close to the observed one, all simulations are spectrally nudged ⁵⁰
 421 towards NCEP-NCAR Reanalysis 1 ^{51,52}. The nudging is applied to vorticity and divergence only at large
 422 spatial scales (about 1000km; using a plateau-shaped profile above the 750-hPa level up to 3 hPa),
 423 letting regional processes close to the surface free to evolve.

424 All five storylines share the same atmospheric dynamics, differing only in the thermodynamical
 425 background prescribed by the sea surface temperature (SSTs) and greenhouse gas (GHGs) emissions,
 426 which define the targeted warming level. For the factual storyline, the SSTs pattern corresponds to the
 427 NCEP SSTs of the simulated period. Meanwhile, for counterfactual and future warming levels, a
 428 climatological SST cooling and warming pattern (10-year mean SSTs surrounding the global warming
 429 levels of each storyline in ECHAM6 CMIP6 simulations, MPI-ESM1.2-HR) is respectively added to NCEP
 430 SSTs. Similarly, GHGs concentrations are imposed using 1890 emission levels for the counterfactual
 431 storyline, while factual and future storylines use concentrations from RCP4.5 ⁵³ at their corresponding
 432 periods. These two variables, SSTs and GHGs, are used as boundary conditions because they are
 433 strongly linked to anthropogenic forcing with high certainty ^{1,47}. To account for model and initial-condition
 434 variability, each storyline counts on five members, initialized with a one-week lag during their spin-up
 435 simulations.

436 When working with spectrally nudged storylines, it is worth noting that they should not be considered
 437 future projections. While these storylines prescribe weather situations that may not fully represent future
 438 atmospheric states due to potential shifts in atmospheric dynamics ⁴⁴, they nonetheless constitute a
 439 rigorous framework for attributing extreme events. Their use is valuable for understanding complex
 440 physical interactions influenced by global warming on a specific event ⁵⁴, thereby advancing
 441 process-based understanding beyond what purely statistical methods can provide.

442 4.2 Fire Weather Index

Fire Danger Class	FWI
Low	< 11.2
Moderate	11.2 - 21.3
High	21.3 - 38.0
Very High	38.0 - 50.0
Extreme	50.0 - 70.0
Very Extreme	> 70.0

443

444 Table 1: *Fire Danger Classes for different Fire Weather Index Values in Europe as used by the European*
445 *Forest Fire Information System (EFFIS)*
446 (<https://forest-fire.emergency.copernicus.eu/about-effis/technical-background/fire-danger-forecast> ,
447 accessed: 25 March 2026).

448 We compute the Canadian Forest Fire Weather Index (FWI), following van Wagner ³², using the
449 implementation provided by the xclim Python package (v0.57.0, xclim.indices.fire.cffwis_indices). The
450 FWI considers the key meteorological variables influencing fire weather - surface air temperature, relative
451 humidity, and wind speed at local noon (12:00), as well as accumulated precipitation over the preceding
452 24 hours. It captures how these conditions influence fuel moisture across different timescales, from
453 rapidly responding surface fuels to longer-term drying of deeper layers, as well as the potential rate of fire
454 spread driven by wind and surface conditions, yielding a dimensionless indicator of the meteorological
455 component of fire danger.

456 Although originally developed for boreal forest conditions in Canada, the FWI has been shown to
457 correlate strongly with burned area in Europe ^{3,55} and is widely used for fire danger assessment, including
458 operational applications by the European Forest Fire Information System (EFFIS).

459 **Data availability statement**

460 Spectrally Nudged Storylines are available upon request.

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592

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600

601 **Competing interests**

602 Authors declare that they have no competing interests.

603

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