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Very high fire danger in UK in 2022 at least 6 times more likely due to human-caused climate change

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Abstract

The UK experienced an unprecedented heatwave in 2022, with temperatures reaching 40 °C for the first time in recorded history. This extreme heat was accompanied by widespread fires across London and elsewhere in England, which destroyed houses and prompted evacuations. While attribution studies have identified a strong human fingerprint contributing to the heatwave, no studies have attributed the associated fires to anthropogenic influence. In this study, we assess the contribution of human-induced climate change to fire weather conditions over the summer of 2022 using simulations from the HadGEM3-A model with and without anthropogenic emissions and apply the Canadian Fire Weather Index. Our analysis reveals at least a 6-fold increase in the probability of very high fire weather in the UK due to human influence, most of which is driven by high fire conditions across England. These findings highlight the significant role of human-induced climate change in emerging UK wildfires. As we experience more hotter and drier summers as temperatures continue to rise the frequency and severity of fires are likely to increase, posing significant risks to both natural ecosystems and human populations. This study underscores the need for further research to quantify the changing fire risk due to our changing climate and the urgent requirement for mitigation and adaptation efforts to address the growing wildfire threat in the UK.

1. Introduction

The UK experienced an unprecedented heatwave in the summer of 2022, marked by record-breaking temperatures exceeding 40 °C for the first time, alongside prolonged dry conditions and widespread wildfires. This event, driven by a high-pressure system across Western Europe, drew hot air northward, caused severe heatwaves, prolonged dry periods and wildfires across the region and broke July maximum temperature records in Portugal, France and Ireland[4]. On 19 July 2022, a maximum temperature of 40.3 °C was recorded at Coningsby in Lincolnshire, closely followed by 40.2 °C in St. James's Park in London and 40.1 °C in Nottinghamshire (Kendon 2022) (figure S1). A remarkable feature of the event was the widespread extreme temperatures, with seven weather stations exceeding 40 °C and temperatures surpassing 39 °C as far north as North Yorkshire. New record daily maximum temperatures were recorded in Wales (37.1 °C) Hawarden, Flintshire) and Scotland (34.8 °C in Charterhall, Scottish Borders)[5]. Fires broke out in London and across England, including the Wennington grassland fire in East London, destroying 20 houses. This was one of 24 316 wildfires across England between June and August, a four-fold

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[4] https://climate.copernicus.eu/surface-air-temperature-july-2022, last accessed 05/08/2024.

[5] www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2022/record-high-temperatures-verified, last accessed 05/08/2024.

increase on the same period in the previous year[6,7]. The London Fire Brigade were reported to have said that this was their 'busiest day since World War 2' (BBC News, 2022)[8].

This heatwave occurred against the backdrop of ongoing UK climate warming. Observations show that extremely hot days have increased at a much greater rate than average temperatures, with days above 30 °C or 32 °C more than trebling in the most recent decade compared to 1961–1990 (Kendon *et al* 2024). Summers are projected to become increasingly hot and dry due to anthropogenic climate change, even under low-emission scenarios aligned with the Paris Agreement. By 2100, all areas of the UK are expected to be warmer, with hot summers becoming more frequent, and hot spells (two consecutive days above 30 °C) potentially occurring up to four times annually by the 2070s under a high-emissions scenario. The UK climate projections also indicate an overall summer drying trend in the future (Met Office 2022). Analysis conducted for the 3rd UK Climate Change Risk Assessment highlighted wildfire as an emergent risk to the UK, with a number of impacts and cascading risks potentially affecting many sectors (Belcher *et al* 2021, Betts *et al* 2021).

A rapid attribution study by the World Weather Attribution (Zachariah *et al* 2022) found that human-caused climate change made the 2022 heatwaves, which resulted in at least 13 deaths, at least 10 times more likely. Previously, Christidis *et al* (2020) likewise found that the likelihood of exceeding 40 °C in the UK to be around 10 times more likely because of anthropogenic climate change and becoming as frequent as every 3–4 years by 2100 under a high emissions scenario. However, to date, there has not been an attribution study of the contribution of climate change to the likelihood of increased wildfires over this period.

Attributing wildfires to human or natural causes is more complicated than other extreme events because the multiple meteorological, biological, physical, and social factors that drive fires. Meteorological and biological factors affecting flammability include fire weather (temperature, precipitation, relative humidity, wind), ignition (lightning), fuel (leaves, litter, trees, grasses, bark, twigs, shrubs, peat), and fuel dryness (soil moisture, fuel moisture). Topography (slope, elevation, aspect) and wind influence a fire spread. Social factors include direct ignition (accidental or deliberate), suppression, and land-use changes affecting fuel availability. Common approaches tend to attribute separate drivers like temperature (Gillett *et al* 2004), fuel moisture (Williams *et al* 2019) or vapour pressure deficit (Tett *et al* 2018) as proxies, or use a Fire Weather Index (FWI) to understand how climate change alters the likelihood of weather conditions that sustain fires once ignited.

The Canadian FWI is widely used to quantify fire risk based on meteorological conditions that influence fire ignition potential and spread. It integrates key factors such as temperature, precipitation, wind speed, and relative humidity to provide a robust estimate of fire danger. In regions like the UK which has ample fuel during dry spells, the FWI provides a useful estimate of the intensity and danger of wildfires once ignited. Higher FWI values correlate fire occurrence, fire spread (Perry *et al* 2022) and risk, with the potential for intense fire behaviour if fires are ignited (John and Rein 2024). Alternative fire metrics focus on outcomes such as burned area (Kelley *et al* 2021, Burton *et al* 2024a), are less relevant in areas like the UK due to smaller geographic extent (Jones *et al* 2024). Thus, FWI is a key tool for predicting fire risk from weather conditions, essential for operational use and climate change studies in the UK.

In this study, we quantify the contribution of anthropogenic climate change to the extreme fire weather conditions observed during the 2022 UK heatwave using the Canadian FWI to assess the likelihood of such conditions under different climate scenarios. We begin by outlining the attribution methodology and evaluate its application to the UK context. We then present results demonstrating how human-caused climate change has influenced extreme FWI conditions. Finally, we discuss the broader implications of these findings for wildfire risk and management in a warming climate.

2. Methods

2.1. FWI

We use the FWI, developed for operational use by the Canadian Forest Service within the Canadian Forest Fire Danger Rating System (Wagner 1987). The FWI is internationally used in multiple operational contexts, including the European Forest Fire Information System[9], the Global Wildfire Information System[10], and the Canadian Wildland Fire Information System[11], and as the basis for the Met Office Fire Severity Index[12] (Perry *et al* 2022). It is frequently used in attribution studies (Abatzoglou and Williams 2016, Kirchmeier-Young *et al* 2017, Kirchmeier-Young *et al* 2019, Barbero *et al* 2020, Goss

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[6] https://nationalemergenciestrust.org.uk/wildfires-growing-risk/, last accessed 05/08/2024.

[7] www.forestryjournal.co.uk/news/23236807.firefighters-tackled-nearly-25-000-wildfires-summer-2022/, last accessed 05/08/2024.

[8] www.bbc.co.uk/news/uk-england-london-62236018, last accessed 05/08/2024.

[9] https://forest-fire.emergency.copernicus.eu/, last accessed 02/06/2024.

[10] https://gwis.jrc.ec.europa.eu/, last accessed 02/06/2024.

[11] http://cwfis.cfs.nrcan.gc.ca/, last accessed 02/06/2024.

[12] www.metoffice.gov.uk/public/weather/fire-severity-index/#?tab=map&fcTime=1711281600&zoom=5&lon=−4.00&lat=55.74, last accessed 05/08/2024.

et al 2020, Du et al 2021, Van Oldenborgh et al 2021, Krikken et al 2021, Li et al 2021, Touma et al 2021), including the World Weather Attribution study of the Canada's 2023 wildfires (Barnes et al 2023). Recently, the FWI technique we apply here was used in the State of Wildfires 2023–24 report (Jones et al 2024).

FWI equations can be found in Wagner (1987). Here, we calculated FWI using HadGEM3-A climate model output (hereafter HadGEM3; Ciavarella et al 2018), described in Jones et al (2024) and with code from Kelley et al (2024). FWI is calculated using drought indices, including the Build Up Index and Initial Spread Index, which combine to produce the Fine Fuel Moisture Code, the Duff Moisture Code and the Drought Code (Wagner 1987). To calculate the index, we used daily maximum temperature (as a proxy for noon values, following Perry et al 2022), daily mean wind speed, daily mean relative humidity, and 2 d average precipitation. The latter serves as a proxy for the standard 24 h accumulated precipitation due to the absence of sub-daily precipitation data in available model outputs.

For the attribution analysis, we use HadGEM3s large ensemble simulations (Ciavarella et al 2018). This atmosphere-only model uses observed sea surface temperatures (SSTs) and sea ice boundary conditions, producing ensemble statistics that retain a degree of ocean influence; for example, near-surface air temperatures can correlate significantly with observations. Therefore, we can see the ensemble as exploring a wide range of climate variability conditional on the boundary conditions. A limitation is that this approach only uses a single model, so will not capture the diversity of climate and model uncertainty from a multi-model ensemble.

Following Jones et al (2024), our analysis focuses on the 90th percentile of FWI over the UK during June, July, and August (JJA). For the 2022 attribution analysis, we use two sets of large ensembles, with 525 members of historical forcing (with natural and anthropogenic forcing present), and 525 members of natural-only forcing (solar irradiance and volcanic activity only) taken from Ciavarella et al (2018). The all-forcing simulations (ALL) include historical emissions of well-mixed greenhouse gases, aerosols, and transient land use change, all of which are held constant at 1850 levels in the natural-only simulation (NAT). An estimate of the changes in SSTs and sea ice fields due to anthropogenic influence, based on results from phase 5 of the Coupled Model Intercomparison Project (CMIP5), is removed in NAT (Christidis et al 2013). Specifically, the anthropogenic influence in SSTs is taken from the difference between multi-model means of the ALL and NAT experiments, while the change in sea ice fields is derived from a linear relationship between observed SST and sea ice. We calculate 90th percentile FWI for JJA for both ALL and NAT. We then use ERA5 reanalysis data to calculate the FWI over JJA 2022 (referred to as 'observed FWI'), providing the observed fire severity across the UK during this period. The 0.25°resolution observed ERA5 FWI was regridded by linear interpolation to match the $0.56^\circ \times 0.83^\circ$ model grid. These ERA5 2022 90th percentile JJA values are later used to assess how frequently the ALL and NAT experiments exceed these FWI thresholds in the attribution analysis.

The 525 member present-day ensemble, taken from Ciavarella et al (2018), were branched from a smaller 15 member historical ensemble of longer simulations. The larger ensemble is designed for event attribution, while the longer simulations of the smaller historical ensemble allow comparison to validate the model's skill at reproducing observed trends in fire weather and to calculate a bias correction term that we applied to the present-day ensemble. We therefore calculated 90th percentile FWI for this 15-member 1960–2013 HadGEM3 historical ensemble and compared against FWI calculated using ERA5 reanalysis data (C3S, 2024) over JJA for the period 1960–2013 (figure 1).

2.2. Bias correction

The modelled FWI has a positive bias for the UK compared to ERA5 (figure 1(a)). Given this bias, we apply a bias correction to ensure the event threshold for JJA 2022 lies at the same percentile in the model distribution as the ERA5 distribution. After evaluating the individual variables in the FWI, we found that each variable is slightly biased compared to ERA5 (figure S2), and we, therefore, apply a bias correction to the final FWI, as per Jones et al (2024), rather than bias-correcting each variable individually. This choice was also made by Jones et al (2024) to preserve the inherent physical relationships among the interconnected meteorological variables; for example, precipitation affects humidity, which subsequently influences temperature and other variables. By correcting the FWI as a whole, we maintain the integrity of these relationships, ensuring a more coherent representation of fire weather risk. While other studies, such as Son et al (2021), have addressed similar issues by bias-correcting individual variables, our study requires that the FWI distribution aligns with the distribution of observed FWI (see 'Probability ratio' section). This alignment is essential for accurately assessing the probability of the observed FWI event in 2022 with and without anthropogenic influence. Given that the FWI is a nonlinear combination of its respective drivers, this necessitates a bias correction of the FWI itself to achieve reliable threshold matching for our analysis.

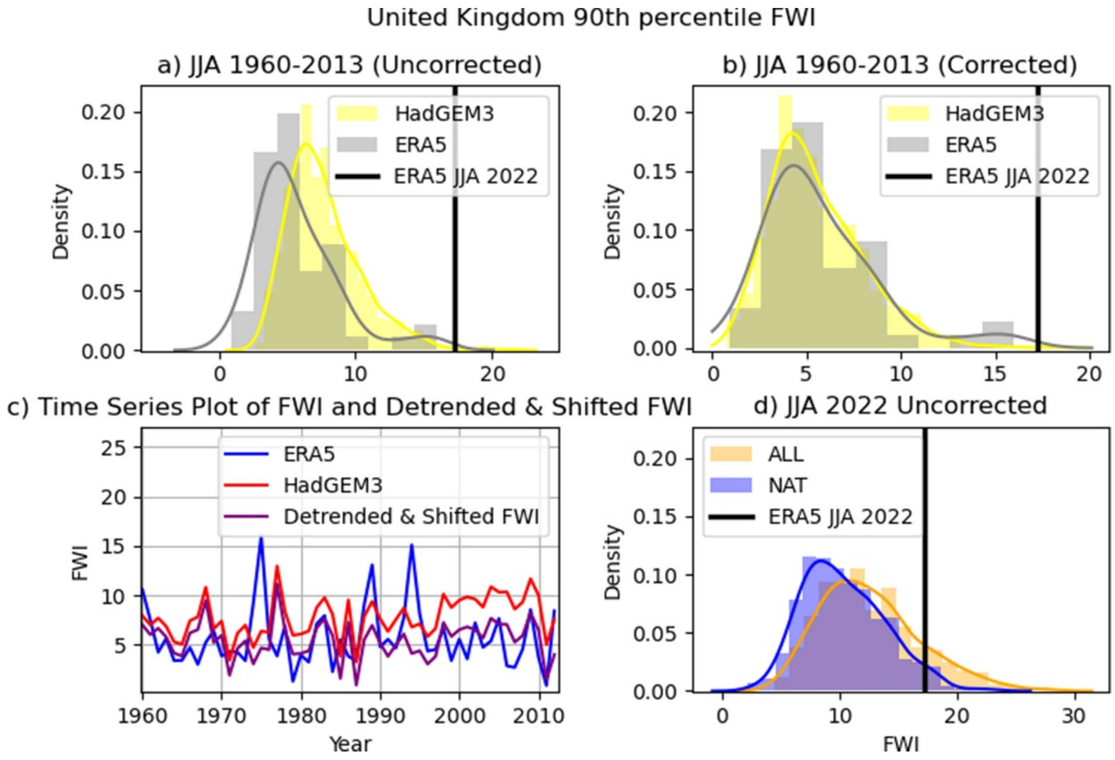

Figure 1. Bias correction for the UK. Historical ensemble of HadGEM3 (yellow) compared to ERA5 (grey) 90th percentile of FWI for the historical period (JJA 1960–2013), shown as probability density before correction (a) and after correction (b), and one member shown as a time series (c, where HadGEM3 is shown in red, ERA5 in blue and adjusted HadGEM3 in purple). HadGEM3 ensemble for 2022 shown before bias correction (d). ERA5 2022 event is shown as a black vertical line on all probability density plots. The bias correction method is outlined in Jones *et al* (2024) and described in full in 'bias correction' in the methods.

The bias correction method compares the time series and distribution of the modelled and observed FWI and applies a simple linear regression to find the bias correction required for the 2022 model output. Our correction adjusts the trend, absolute value and mean-variance while maintaining inter-annual variability, and the model successfully reproduces the observed distribution after applying the correction (figures 1(b) and (c); figures S3–6). For reference, the distribution for 2022 before bias correction is also shown (figure 1(d)), and the range of the ensemble time series is shown in figure S7.

We bias-corrected the HadGEM3 2022 large ensemble based on a bias assessment of the 15 historical members from 1960–2013 vs. ERA5 observation-driven FWI, using a linear regression on *fwi* transformed using:

$$fwi_* = \log\left(\exp\left(fwi\right) - 1\right) \tag{1}$$

to remove the physical bound at 0. We use this instead of a straight log transformation as it ensures numerical stability at higher values, which is crucial when dealing with extreme FWI values. It also preserves the extreme tail of the FWI distribution, allowing us to accurately capture and analyse critical events associated with high fire risk.

We perform a linear regression on ERA5 and on each historical member to obtain the basic regression parameters:

$$fwi_* \sim fwi_{*,0} + \Delta_{fwi} \times t \tag{2}$$

where t is time, and $t = 0$ is set to our target year, 2022. Δ_{fwi} is the rate of change, or trend, of fwi_* and $fwi_{*,0}$ is the estimated fwi_* for when $t = 0$ (i.e. 2022). Our bias correction is based on present-day warming levels, considering the additional warming from 2013–2022 (assuming the same trend from 1960–2013 continues to 2022). This is likely conservative, given that warming rates may have increased rapidly in the last 10 years.

Similar to the method presented in Christidis *et al* (2020), we generate the bias-corrected 2022 ensemble by correcting each of the 525 present-day ensemble members against each of the 15 historical members (creating an ensemble of 7875 members) and iterate over all possible pairs:

$$fwi_{\text{corrected}} = \left(fwi_{*i} - fwi_{*0,j}\right) \times \sigma_{\Delta}\left(fwi_{*\text{era5}}\right) / \sigma_{\Delta}\left(fwi_{*j}\right) + fwi_{0,*\text{era5}} \tag{3}$$

$$\sigma_{\Delta}\left(fwi_{*}\right) = sdev\left(fwi_{*} - \Delta_{fwi} \times t\right)$$

where i is a present-day ensemble member, and j is a historical member.

We finish by applying the inverse of the transformation from equation (1):

$$fwi_{\text{corrected}} = \log\left(\exp\left(fwi_{*,\text{corrected}}\right) + 1\right). \tag{4}$$

2.3. Probability ratio (PR)

We use the ERA5 2022 FWI for our event threshold in each region on our bias-corrected ensemble. We use this threshold to calculate the PR of the event occurring with and without climate change. To calculate the PR, we find the number of ensemble members that exceed the 2022 ERA5 90th percentile FWI value in the bias-corrected ALL simulation and divide this by the number of members that exceed the same value in the bias-corrected NAT simulation (equation (5)), randomly sampling 90% of the data without replacement 10 000 times to give the probability of exceeding the observed 2022 FWI value in a world with and without climate change plus uncertainty bounds for the 5–95th percentile

$$\text{PR} = \text{p}\left(\text{ALL}\right) / \text{p}\left(\text{NAT}\right). \tag{5}$$

The return time is calculated as the inverse of the probability of exceedance, also bootstrapped 10 000 times:

$$\text{RT} = 1/\text{p}\left(\text{ALL}\right). \tag{6}$$

2.4. Evaluation

We evaluate the HadGEM3 FWI simulations against ERA5 reanalysis to assess model performance following the procedure outlined in Burton *et al* (2024b)(see evaluation supplement for details and figures S7–11). In summary, the simulations reproduce key spatial patterns of ERA5-driven FWI across the UK, capturing regional variations such as high FWI in southeast England and lower values in northwest Scotland. Meteorological drivers, including temperature, precipitation, wind speed, and humidity, are well-simulated and align closely with ERA5 observations. Temporal trend analysis reveals substantial uncertainty in the direction of observed trends, with HadGEM3 simulations capturing a wide range of plausible FWI trends that spanned possible observational trends.

This evaluation demonstrates the model's ability to assess fire weather risk under climate change. Additionally, clear differences in the likelihood of extreme FWI events between ALL and NAT distributions emerge even without bias correction (figure 1). Applying bias correction and PR methods, therefore, serves mainly to align thresholds between model outputs and observed conditions. This dual approach enables us to more precisely quantify how climate change influences fire risk relative to the conditions seen in 2022.

3. Results

3.1. Fire weather conditions in 2022

In JJA 2022, daily maximum temperatures across the UK were higher than the long-term mean with southern and eastern England seeing a 2 °C–2.5 °C anomaly, Scotland 0.5 °C–1.5 °C, Wales around 0.8 °C–2 °C, and Northern Ireland 0.5 °C–1 °C relative 1991–2020 (figure S1). Precipitation was just 50%–80% of the average summer rainfall. Southern England, northern Scotland, and Wales experienced lower wind speeds. Relative humidity in southern and eastern England decreased by 10%–40%. On 19th July, the heatwaves peak, some of the hottest locations in eastern England recorded temperatures up to 18 °C above the long-term average, with southern England 6 °C–16 °C warmer. Rainfall was minimal across the UK, except for northern Scotland. Relative humidity dropped significantly in southern and eastern England, while Northern Ireland showed no significant anomalies.

3.2. Impact of climate change

In the UK, ALL forcing simulations show a distinct shift to higher FWI values, with more of the distribution in higher ranges than NAT (figure 2). The 90th percentile of bias-corrected FWI in the JJA 2022 ERA5 data—the vertical black line in figure 2, falls within the 'very high' FWI category (tables S1 and S2). A greater proportion of ALL exceeds this threshold compared to NAT, indicating a higher probability of experiencing very high fire weather, as seen during JJA 2022, in a climate modified by human influence. The shift in FWI distribution between ALL and NAT indicates a substantial increase in the likelihood of

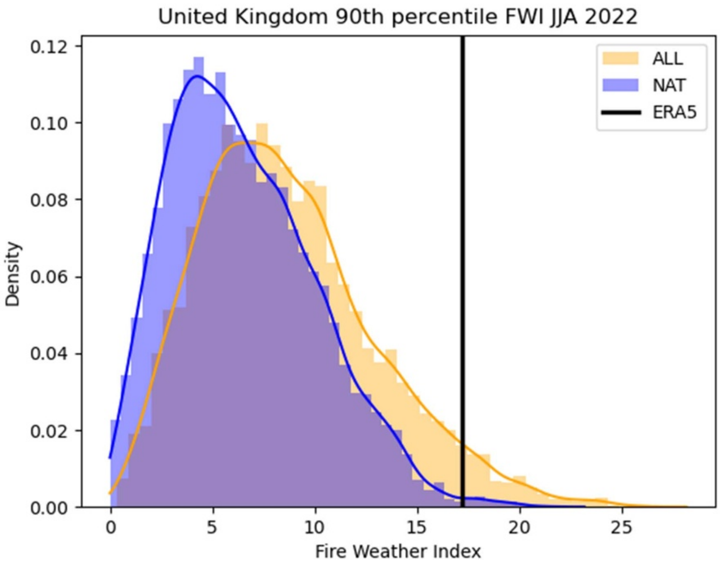

Figure 2. Distribution of 90th percentile of FWI for the UK JJA 2022 in ALL (ORANGE), NAT (BLUE) and ERA5 event threshold (black line).

experiencing extreme fire weather under anthropogenic climate change.

3.3. Meteorological drivers of high FWI

Relative humidity, precipitation, and temperature are strong predictors of our bias-corrected FWI's 90th percentile (figures S12 and 13). Relative humidity exhibits the strongest correlation with FWI ($R^2 = 0.536$), followed by precipitation ($R^2 = 0.431$) and maximum temperature ($R^2 = 0.429$). Wind speed has minimal correlation with FWI and is unlikely to significantly influence fire weather independently. High FWI values in ERA5 2022 are linked to relative humidity below 68.78% (68.13%–69.26%, 90% confidence interval), with the 1.14%–2.29% of ensemble members experiencing such dry conditions directly translating to the likelihood of all forcings resulting in 2022 conditions driven solely by relative humidity. Similarly, maximum temperatures exceeding 22.53 °C (22.09 °C–23.2 °C), experienced by 1.14%–2.29% of ensemble members, and precipitation below 0.31 mm d^{-1} (0.09–0.53 mm d^{-1}), experienced by 0.38%–1.71% of ensemble members, can likewise be associated with 2022 FWI conditions, highlighting that dry and hot conditions drive fire weather extremes. In NAT simulations, no ensemble members exceeded the thresholds related to 2022 ERA5 FWI values for individual meteorological drivers. This implies that, without climate change, individual meteorological extremes were inadequate for producing FWI comparable to 2022. However, rare combinations of slightly elevated temperatures, reduced humidity, and low precipitation in some NAT ensemble members led to a few FWI values exceeding the threshold. This highlights the importance of compounding effects rather than singular variable extremes in driving fire weather risk without anthropogenic climate influences.

3.4. Regional variations in fire weather attribution

There is a notable increase in the probability of elevated FWI across UK regions attributable to anthropogenic climate change (figures 3 and S14), driven by increases in temperature and changes in precipitation patterns (figures S9 and 10)—characteristic of anthropogenic climate change. England exhibits the highest FWI values (19.72), significantly contributing to the UK's overall elevated FWI levels. Although Wales experienced a larger increase in high-fire weather probability, England's ratio (6.25–10.49) remains substantial due to its higher baseline FWI. This was driven by higher temperatures and drier conditions in the ALL simulations compared to NAT (figures S9 and 10), which would have led driven evaporative demand, reducing soil moisture and drying vegetation, further amplifying fire risk. In Wales, high-fire weather was 8.9–15.4 times more likely because of human emissions—the most significant across regions (figure 3; table S1). This increased probability was largely driven by warmer temperatures and drier conditions in ALL simulations vs. NAT., with some areas seeing temperature rises up to 1.5 °C in summer (figure S9) and reduced rainfall and humidity. Higher wind speeds also promote more intense fire spread. Scotland shows a 5.0–11.4-fold increase (figure 3). Areas in the east of Scotland, which are typically warmer and drier (figures S9 and 10), see a more pronounced FWI response. The west is drier and warmer throughout JJA in ALL vs NAT (figure S9), but exhibits varied precipitation responses extreme FWI (figure S10).

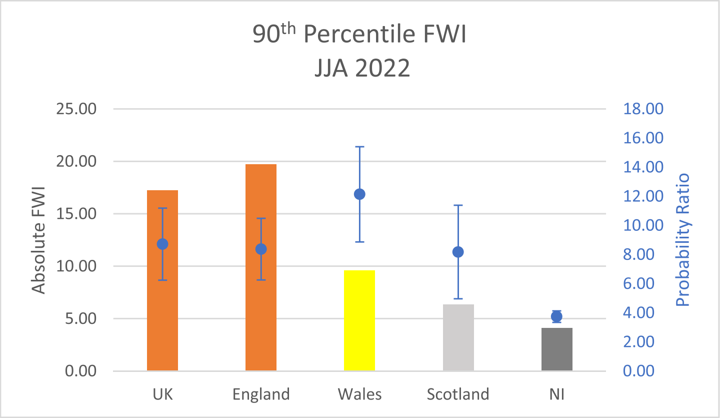

Figure 3. Absolute observed FWI from ERA5 (bars, left axis), and probability ratio (point and whiskers, right axis) for increase in 90th percentile of FWI due to climate change for the UK and individual countries (NI = Northern Ireland). The colours used for the bars relate to the FWI category (see table S2); low (dark grey); moderate (light grey); high (yellow), very high (orange). The PR range bars indicate the 5th–95th percentiles across the ensemble, with the point showing the central value of this range.

Northern Ireland sees a modest elevation of 3.3–4.1, driven by warmer temperatures (0.8 °C–1.2 °C), with minimal changes in wind speed or humidity. Northern Ireland also has high variability in precipitation anomalies, with some areas showing slight decreases (0–0.2 mm d^{-1}). Despite these shifts, stable wind and humidity conditions limit the FWI increase compared to other UK regions.

The UK as a whole faces an overall increase of 6.2–11.2. While the PR increases the most for Wales, it is absolute FWI is lower than in England, and therefore an increased probability of high fire weather has a disproportionate impact on England, the primary driver of the nation's increased fire weather risk.

3.5. Return times for extreme fire weather

Return times in ALL simulations are much lower than in NAT in all regions (figure 4). For example, the UK's median return time for FWI's 90th percentile is 24 years with ALL forcing versus 192 years with natural only. England's return times are similar, seeing very high fire weather occurring every 19 years in a climate warmed by anthropogenic emissions versus 154 years in a climate without human influence. Northern Ireland's return times are lower, at 7 and 25 years, while Scotland's is much higher, at 53 and 375 years. Some NAT ensemble members report return times of more than 1000 years in Scotland, therefore a potentially low likelihood of high-fire weather occurrence under natural conditions.

4. Discussion

4.1. Anthropogenic influence on UK fire weather

This study demonstrates a significant increase in the likelihood of extreme fire weather across the UK due to anthropogenic climate change, as indicated by our FWI analysis. The bias correction applied to the HadGEM3-A model ensures closer alignment with observed data, addressing systematic discrepancies and enhancing the reliability of our findings. A multi-model ensemble could provide a broader range of climate outcomes. However, including potentially less realistic model outputs without weighting schemes (Liu *et al* 2022, Burton *et al* 2024a) risks diluting the robustness of the analysis. By focusing on HadGEM3-A, we isolate anthropogenic influences and demonstrate the model's capability to distinguish fire weather patterns driven by human emissions from those under natural conditions, even prior to bias correction.

While our ensemble does capture large-scale patterns in meteorology and fire weather, small residual biases in absolute meteorological values remain. This suggests that bias correction should be standard in event or season-specific attribution studies on climate impacts, particularly in small-scale regions like the UK. Bias-correcting FWI directly preserves the relationships among meteorological variables, ensuring a robust assessment of extreme fire weather conditions. Yet, this approach limits the ability to quantify the contribution of individual fire weather drivers, and studies using HadGEM3-A to explore this would require separate bias correction of these drivers (Son *et al* 2021).

4.2. Predictability of fire weather

Our findings emphasise the predictability of fire weather risk based on both individual meteorological variables and their combined extremes. Temperature and relative humidity consistently emerge as strong predictors of FWI across ALL and NAT simulations (figures S12 and S13), demonstrating their reliability for forecasting fire weather. Nevertheless, our simulations' most extreme FWI values cannot be fully attributed to a single variable, and interacting extremes in multiple variables are therefore required in shaping the riskiest fire weather conditions.

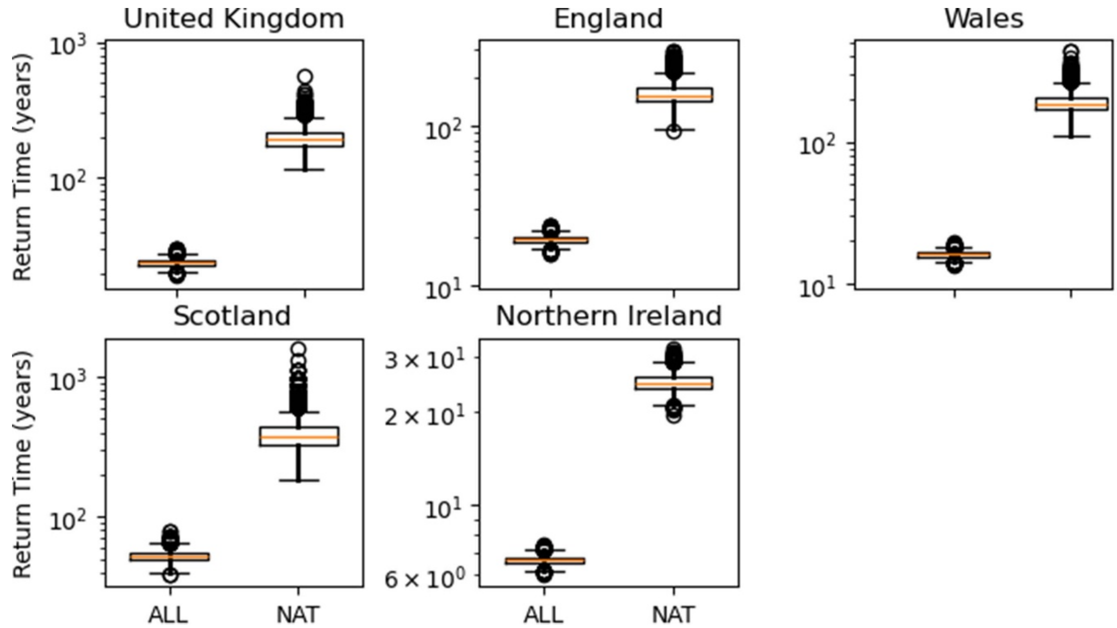

Figure 4. Return times for 90th percentile of FWI in ALL and NAT for UK and individual countries (using log scale). The box represents the median (red line) and interquartile range (box), with whiskers extending to the farthest data point lying within 1.5× the inter-quartile range from the box. Flier points are those past the end of the whiskers.

The bias-corrected FWI distributions align well with ERA5 reanalysis (figures 1 and S3–S6), illustrating the ensemble's capacity to reproduce observed fire weather patterns. Furthermore, the ensemble captures a range of trends and uncertainties in ERA5-based FWI for 1960–2013 (figures 1–2 and S11), with some members reflecting positive trends and others mixed or negative trends. This variability showcases the ensemble's ability to represent trend differences but also points to the potential benefits of refining the ensemble through weighting against observational data (e.g. Kelley *et al* 2021, Burton *et al* 2024a).

4.3. Future directions

This study highlights the utility of the FWI as a critical metric for assessing fire weather risks and guiding adaptation strategies. The FWI provides actionable insights for fire management practices, such as promoting fire-safe behaviours and implementing fuel-reduction strategies. However, while the index relies on daily maximum temperatures, mean wind speed, and relative humidity, finer-scale factors—such as higher night-time temperatures or hourly fluctuations in wind and humidity—may also significantly influence fire risk during extreme heatwaves. Future iterations of the FWI could incorporate higher temporal resolution data to improve fire risk assessments under extreme climate conditions, though that would take the index away from operational use.

Attribution of observable fire activity metrics, such as burnt area or active fires, could provide additional insights and reflect how burning in the UK responds to slower-changing factors like land use, vegetation type, and human activities, which are not directly captured by the FWI (figure S15). These factors could be considered in conjunction with fire weather metrics to achieve a comprehensive understanding of fire risk under changing climate conditions. However, these more observable fire metrics are more challenging for robust attribution in smaller regions like the UK due to their stochastic nature (Barbosa *et al* 2024, Jones *et al* 2024).

4.4. Implications

Historically, large wildfires have played a minimal role in shaping UK ecosystems, although human fire use has been common practice for centuries. The temperate, often wet climate typically suppressed large-scale fires. However, increasingly hotter and drier recent summers have led to more favourable fire weather conditions and more frequent, larger, and intense fires, particularly on moorlands. This presents new challenges for land management and fire suppression efforts.

Notable incidents such as the 2019 Marsden Moor fire in Yorkshire, which burned 700 hectares and took four days to extinguish[13], underscore the growing severity of these events. Similarly, the 2018 Saddleworth Moor fire in Greater Manchester, which necessitated the evacuation of 50 homes and scorched seven square miles, remains one of the largest fires in recent memory. The 2020 fires on

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[13] www.nationaltrust.org.uk/visit/yorkshire/marsden-moor/our-work-to-protect-marsden-moor-from-fires, last accessed 05/08/2024.

Darwen Moor and in Wareham Forest which burned areas of 500 hectares[14] and 200 hectares[15] respectively, resulting from human ignitions (i.e. through disposable BBQs) further exemplifies the increasing frequency of large fires occurring as a result of human ignitions. October 2021 saw over 100 moorland fires reported within 4 d, a five-fold increase from the previous year[16]. The Sutherland peatland fire in Scotland lasted for 6 d in 2019, impacting over 5300 hectares and releasing between 174 and 294 kilotons of carbon—twice Scotland's carbon emissions during that period[17]. These trends highlight a troubling escalation in fire activity that poses significant risks to both natural and human systems.

The implications of these fires are concerning given the ecological and conservation significance of UK moorlands, such as Marsden Moor, designated as Sites of Special Scientific Interest, Areas of Outstanding Natural Beauty, and crucial conservation sites. Moorlands peat stores large amount of carbon. When burned, they disrupt habitats and release carbon into the atmosphere, worsening global warming. The fires also deteriorate air quality, adversely affecting human health. (Forestry Commission 2023).

Urban areas are not immune to these trends, as demonstrated by 2022's major fire incidents in London and Norfolk, which damaged infrastructure and posed significant risks to lives and livelihoods. In the UK, many fires ignite at the rural–urban interface (Perry *et al* 2022). Between 2009/10 and 2020/21 the UK Fire and Rescue Services dealt with over 360 000 wildfires in England, with 54.4% in urban and garden areas (Forestry Commission 2022). Here, we show England is driving high FWI in the UK, concerning as England's population density is approximately four times that of Scotland and three times greater than Wales (Office for National Statistics (ONS) 2024). Higher density raises risks to lives and increases fire frequency due to more ignition sources. While England may average a smaller burned area than Scotland[18] (figure S14), the increased fire weather danger could heighten risks to human life in urban environments.

Climate change will very likely increase fire significance in the UK (Perry *et al* 2022), with potentially profound implications for impacts and risks across many sectors (Belcher *et al* 2021, Betts *et al* 2021) necessitating a proactive approach to managing this evolving threat. To reduce wildfire risks in vulnerable areas, strategies such as engaging the public through awareness campaigns can re-educate people on fire safety, highlighting the significance of safe outdoor cooking and the importance of vigilant reporting of any activities that could lead to fire ignition. International collaboration is also vital for the UK, which historically has not experienced large wildfire incidents and thus possesses limited experience in this domain. Engaging with global partners and proactively establishing measures to prepare for and mitigate increasing fire risk in the future (Hamilton *et al* 2024).

5. Conclusion

We explored the 2022 UK high-fire weather during the JJA heatwave in the context of climate change. Using a large attribution ensemble, we found that FWI was higher in a world warmed by anthropogenic climate change than in a world with natural-only forcing for the UK and each UK country. Overall, anthropogenic forcing has increased the likelihood of experiencing high fire weather conditions more than 6-fold. This indicates that human influence likely contributed to the high-fire weather experienced across the UK in JJA 2022.

The recent upsurge in fire incidents across the UK marks a significant departure from historical trends and signals a critical shift in the region's environmental challenges. The examples of Marsden Moor, Saddleworth Moor, and the London fires of 2022 highlight the growing destructive nature, intensity and frequency of fires driven by hotter and drier summer conditions as the climate changes. This trend suggests that fires are becoming an increasingly important factor in the UK's ecological and socio-economic landscape.

As the UK is already seeing hotter and drier summers and faces the prospect of ongoing trends even in the lowest emissions scenarios, fires are becoming an emerging threat. This study has shown that climate change increased the likelihood of experiencing very high fire weather conditions in 2022, giving an indication of what we might see moving forward. The contribution of climate change to high fire weather conditions means that when fires do ignite, they have the potential to be larger, more intense, and harder to manage. It is imperative to develop and implement effective fire prevention and mitigation measures. The experiences of recent years serve as a stark reminder of the urgent need to adapt to a changing climate and its associated risks, and mitigate further warming through reducing our carbon emissions.

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[14] www.lancsfirerescue.org.uk/news-and-events/wrapped-fire-engines-added-to-lancashire-fleet, last accessed 05/08/2024.

[15] www.bbc.co.uk/news/uk-england-dorset-58479215, last accessed 05/08/2024.

[16] www.theguardian.com/environment/2021/oct/12/moorland-fires-reported-in-england-carbon-dioxide, last accessed 05/08/2024.

[17] www.copernicus.eu/en/media/image-day-gallery/peatland-wildfire-sutherland-scotland-uk, last accessed 05/08/2024.

[18] www.gov.scot/publications/provision-analyses-scottish-fire-rescue-service-sfrs-incident-reporting-system-irs-data-relation-wildfire-incidents/pages/8/, last accessed 05/08/2024.

Data and code availability statement

Code and figures for the analysis in this paper can be found at: DOI: 10.5281/zenodo.13224259. The historical (1960–2013) HadGEM3 data are available through CEDA (Dataset Collection Record: EUCLEIA: European Climate and weather Events: Interpretation and Attribution (ceda.ac.uk)). The 2022 data are available on request from the Met Office.

The data that support the findings of this study are openly available at the following URL: https://catalogue.ceda.ac.uk/uuid/99b29b4bfeae470599fb96243e90cde3/.

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