Human influence and persistent low pressure are estimated to make extreme May rainfall in the United Kingdom, as in year 2021, about 1.5 and 3.5 times more likely, respectively.

HadUK-Grid rainfall observations (Hollis et al. 2019; Fig. 1a) indicate that in 2021 the United Kingdom had its second wettest May since 1836. The month was characterized by heavy downpours and prolonged wet spells that amassed an average of about 120 mm of rain. New records were set locally, for example in Wales, where the observed rainfall was about 30 mm higher than the previous record of 183.8 mm. Wet conditions were favored by persistent low pressure over the United Kingdom linked to a southern shift of the jet stream. The sustained heavy rains were also accompanied by record low maximum temperatures in parts of the country, but the warm last week of May meant that the month, as a whole, was not one of the coldest on record. Our study assesses 1) how human-induced climate change alters the likelihood of extreme May events in the United Kingdom with a mean rainfall above that in 2021 and 2) the influence of the atmospheric circulation on such events.
Observations, CMIP6 data, and circulation

Using HadUK-Grid data we compute May mean rainfall anomalies averaged over the United Kingdom during the period 1836–2021, represented by the black time series in Fig. 1a. Anomalies are defined relative to 1901–30, an early baseline that is less affected by human influence than more recent decades. Early baselines enable attribution analyses to account for the bulk of the anthropogenic effect (Eyring et al. 2021). The strong influence of variability seen in the observed time series would mask, to some extent, any long-term change signal. There is, however, a small positive trend over the observational period, consistent with increases in spring rainfall in northern Europe linked to greenhouse gas emissions (Christidis and Stott 2022a).

For the attribution analysis we utilize data from nine state-of-the-art climate models (supplemental material) that participated in phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al. 2016). We employ 52 simulations of the actual world that include all external forcings (ALL) and 56 simulations of a hypothetical “natural” world (NAT) that only include the effect of natural forcings. The ALL simulations start in 1850 and are extended to the end of the twenty-first century with the “middle-of-the-road” emissions scenario Shared Socioeconomic Pathway 2-4.5 (SSP2-4.5; Riahi et al. 2017), which enables us to assess future

Fig. 1. (a) Time series of May rainfall anomalies in the United Kingdom relative to 1901–30 produced with HadUK-Grid data (black) and CMIP6 simulations with (red) and without (green) human influence. The observed anomaly in May 2021 is marked by the black dashed line. (b) Spatial pattern of the Z500 anomaly relative to 1961–90 in May 2021 constructed with data from the NCEP–NCAR reanalysis. The yellow box marks the United Kingdom area. (c) The estimated likelihood of a Z500 anomaly pattern over the United Kingdom similar to May 2021 in the natural climate (green), the first half (red), and second half (dark red) of the twenty-first century. The bars mark the 5%–95% uncertainty range, and the white horizontal line marks the best estimate of the probability.
changes in rainfall extremes. The NAT simulations cover the period 1850–2020. Natural forcings include changes in volcanic aerosols and the solar irradiance, while the additional anthropogenic forcings in the ALL experiment correspond to changes in greenhouse gases, aerosols, ozone, and land use. Time series of May rainfall anomalies in the United Kingdom constructed with the ALL and NAT simulations are illustrated in Fig. 1a (red and green lines, respectively). The models suggest that exceedances of the observed anomaly in 2021 are rare, though still possible, in the NAT climate, but they become increasingly more frequent in the ALL climate. We apply a set of common evaluation tests against HadUK-Grid (Christidis et al. 2013), which indicate that the models perform well in simulating historical trends, variability, and the distribution of rainfall anomalies (supplemental material).

Besides external climatic forcings, the role of the prevalent cyclonic conditions during the event is also assessed in this study. Figure 1b shows the mean 500 hPa geopotential height (Z500) anomaly pattern in May 2021 constructed with data from the NCEP–NCAR reanalysis (Kalnay et al. 1996). The pattern features a north–south wave train with a low pressure center over the United Kingdom, contributing to the markedly wet conditions during the month, as we will demonstrate later. We assess the likelihood of such persistent low pressure systems under different climatic conditions by identifying simulated May circulation patterns similar to the one in 2021, i.e., cases for which the correlation coefficient of the Z500 anomaly pattern over the reference United Kingdom region is greater than 0.6 (Christidis et al. 2018). The pattern probability is computed as the fraction of months with high correlation patterns, and the associated 5%–95% uncertainty range is estimated with a bootstrapping procedure that randomly resamples the modeled months and recalculates the pattern probability from alternative samples (Christidis et al. 2013). We find (Fig. 1c) that the reference circulation pattern becomes more frequent under the influence of anthropogenic forcings, with its likelihood increasing by 18% during the first half of the twenty-first century and 23% during the second (best estimates) relative to the natural world. This suggests that a change in May rainfall in the United Kingdom due to human influence would have some dynamical contribution due to changes in circulation.

**Unconditional attribution**

In an unconditional framing, extreme events are defined relative to a threshold, without accounting for the precise conditions under which they develop. Wet extremes in our analysis are characterized by May rainfall anomalies higher than the one observed in 2021 (+52 mm). We adopt the risk-based attribution approach (Stott et al. 2016), whereby the anthropogenic effect on extreme events is assessed by comparing their likelihood derived from simulated data with and without anthropogenic forcings. We first construct the distributions of United Kingdom’s May rainfall illustrated in Fig. 2a. The distribution representing the natural world utilizes all simulated data from the NAT experiment (56 simulations × 171 years), assuming the NAT climate is largely stationary. The distributions of the present-day climate and the climate of the late twenty-first century are constructed with data from the ALL simulations extracted from the 30-yr periods 2007–36 and 2071–2100, respectively (52 simulations × 30 years). The overall increase in the global mean near-surface temperature is estimated to be around 1.2°C for the present-day climate, as computed with HadCRUT5 observations (Morice et al. 2021), and around 2.7°C for the late century following the SSP2-4.5 (IPCC 2021). Figure 2a shows a shift of the distribution toward wetter conditions relative to the natural climate, expected to increase the likelihood of extreme events with anomalies higher than the 2021 value (marked by the dashed vertical line).

Estimates of the return time (inverse probability) of extremely wet months are illustrated in Fig. 2b. Extreme probabilities are calculated with the generalized Pareto distribution and associated uncertainties are again computed with a simple Monte Carlo bootstrap procedure.
(Christidis et al. 2013). The models indicate that the return time progressively decreases and by the end of the century it is about 43% smaller than in the natural world. We find a moderate increase in the present likelihood relative to the natural world of 1.5 (best estimate), although the associated uncertainty range also includes values less than unity, suggesting that the likelihood increase is not statistically significant. (Fig. 2c). The risk ratio is estimated to further increase by the end of the century by a factor of 1.8 with an associated uncertainty that is now above unity.

**Circulation effect**

As in previous work (Christidis et al. 2018; Christidis and Stott 2022b), we assess the effect of circulation by comparing the present-day likelihood of extremes developing under similar and different conditions to the ones during the actual event (Fig. 1b). Figure 2d shows the rainfall distributions corresponding to months with high and low Z500 pattern correlations, constructed with data from the ALL simulations in the period 2007–36. The presence of persistent low pressure leads to a considerable shift of the distribution toward higher rainfall and is estimated to increase the likelihood of extremes 3.5 times (uncertainty range 1.3–8.1). A similar increase in the likelihood is estimated for the natural climate.
Discussion

Our analysis indicates that the likelihood of extreme May rainfall accumulations in the United Kingdom is on the rise under the influence of anthropogenic forcings. The CMIP6 models suggest a modest, though nonsignificant, increase in the likelihood in the current climate, which, however, nearly doubles by the end of the century. Such extremes become several times more likely in years with persistent low pressure during the month. As the hydrological cycle intensifies in a warming climate (Allen and Ingram 2002), rainfall extremes are also expected to increase (Alexander 2016), though regional changes can be complex and are determined by the interplay between thermodynamical and dynamical effects (Seager et al. 2010). We find that the increase in United Kingdom’s May rainfall may indeed have a dynamical contribution, but this needs to be further investigated with a more detailed analysis. The thermodynamic contribution is expected to be more prominent. Keeping the focus on the overall anthropogenic response, we find evidence of more frequent rainfall extremes, which adds to the scientific basis for United Kingdom’s adaptation planning.

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References


