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River flow amplification under climate change: attribution and climate-driven storylines of the winter 2023/24 UK floods

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Abstract

Climate change is expected to alter the magnitude and frequency of river floods. Post-event analyses often assess the rarity of events from historical observations and a growing number of studies attempt to attribute the event's severity to anthropogenic warming. Recent studies also advocate for the creation of "what-if" event storylines to explore consequences if an observed event turned out worse. However, few studies have harmonised these different approaches when conducting retrospective analyses of hydrological extremes. Climate change attribution including river flows also remains rare. Here, a framework for post-event analyses of hydrological extremes is demonstrated using the winter half-year 2023/24 UK river flooding as a case study. Persistent high river flows were observed across the UK and Western Europe, following on from notable winter floods in 2013/14, 2015/16 and 2019/20. The 'ClimaMeter' analogue-based attribution suggests that a 6-month period with similar atmospheric circulation patterns to the observed winter half-year 2023/24 has become warmer and wetter (by an average 8.8%) in 1945-2021 compared 1850-1925. Monthly river flow reconstructions extended back to 1850 show that river flows during the analogue periods in the recent past have also become 13.5% higher. Applying the UNSEEN approach by pooling seasonal hindcasts show the potential for river flows to be 46% higher than the baseline in a worst-case storyline. Finally, hydrological simulations driven by a single model initial-condition large ensemble suggest that when accounting for internal variability, a robust climate signal in winter half-year river flows have emerged for some areas but may remain concealed until mid-21st century and beyond. Our results contribute to the use of storyline approaches in post-event analysis and highlights the changing risk of winter UK flooding. This framework can be applied to future hydrological extremes both in the UK and elsewhere to inform long-term planning for climate adaptation.

1 Introduction

A warming climate is expected to alter the timing, magnitude, frequency and spatial pattern of floods (Arnell and Gosling, 2016). Studies have also found an increase in widespread, spatially extensive floods in observations (e.g. Fang et al., 2024) and future projections (Griffin et al., 2024). The thermodynamic response of a warming climate is well understood as a warmer atmosphere holds more moisture following the Clausius-Clapeyron relationship. However, understanding the changing risk of these extremes is challenging under non-stationarity. In a sign of increasing hydrological volatility, floods also increasingly follow on or occur in conjunction with other weather and climate extremes, such as temporally compounding events resulting from windstorms clusters (Bevacqua et al., 2020).

Researchers often assess the statistical rarity of notable events and whether the event is part of a trend, such as analysis following successive UK river flooding across winters 2013/14 (Muchan et al., 2015), 2015/16 (Barker et al., 2016) and 2019-21 (Griffin et al., 2025; Sefton et al., 2021). Methodologies to detect river flow trends are widely used and some studies suggested the period since the 1990s was notably flood-rich across western and central Europe (Blöschl et al., 2020). However, river flows are highly variable, and most records are short (e.g. many UK gauging stations were installed in the 1960s/70s – Dixon et al., 2013). Identifying emerging trends from short observations is challenging as historical or near-term trends may oppose the long-term climate-driven trend given large climate variability (Chan et al., 2025; Deser and Phillips, 2023; Wilby, 2006). A growing number of studies also attempt to attribute the effects of anthropogenic warming by comparing the probability of an event class in climate model simulations of the present-day climate and a climate without anthropogenic warming (Stott et al., 2016) (e.g. World Weather Attribution: https://www.worldweatherattribution.org/). Attribution including river flows remains challenging as hydrological responses do not scale linearly with rainfall (Scussolini et al., 2024) and coarse climate model resolutions preclude detailed catchment simulations. Past probabilistic flood attribution has focused on short-duration river flow flood peaks (e.g. Gillett et al., 2022). In the UK, attribution for the autumn 2000 and winter 2014/15 floods using a hydrological model were uncertain and results ranged from no attributable risk to increased risk with climate change (Kay et al., 2011, 2018). This reflect the challenges with attributing events driven by strong atmospheric circulation anomalies and the uncertain response of atmospheric circulation to climate change (Shepherd, 2014).

A storyline approach has recently emerged for climate change attribution and exploring plausible worst-cases (Shepherd et al., 2018; Sillmann et al., 2021). For example, the ClimaMeter attribution approach (https://www.climameter.org/; Faranda et al., 2024) samples for events with similar atmospheric circulation patterns to the target event in historical observations or reconstructions. Unlike probabilistic attribution, ClimaMeter anchors attribution to the specificity of the target event, rather than aggregating across events with different dynamical drivers. It has been applied for heatwaves (Jézéquel et al., 2018), heavy rainfall (Thompson et al., 2024) and meteorological droughts (Faranda et al., 2023b) and recently extended beyond these more traditional variables to storm surges by coupling with impact models (Faranda et al., 2023a). The storyline approach also encourages more routine creation of “what-if” downward counterfactuals to enhance risk awareness (i.e. what if an observed event turned out worse?) (Kelder et al., 2025; Ommer et al., 2024). Worst-case storylines can be created by perturbing the event’s drivers to explore alternative versions of the event in space, time or magnitude (Chan et al., 2022; Heinrich et al., 2024; Lin et al., 2020). Unprecedented outcomes can also be sampled from initialised climate model simulations, following the UNprecedented Simulations of Extremes using ENsembles (UNSEEN) technique (Thompson et al., 2017, 2025). Kay et al. (2024) used initialised large ensemble simulations with a national UK hydrological model to show that in the worst-case storyline, river flows during the autumn and winter 2023/24 flooding could have been 42% higher.

Traditional standalone event reports and attribution studies are often separate pieces of analysis and seldom cover the same domain or time horizon. Few studies to date have attempted to harmonise the different approaches when conducting retrospective analysis of hydrological extremes. Here, we take the winter half-year 2023/24 UK river flooding as a case study to demonstrate a framework for analysing hydrological extremes that combines event attribution, "what-if" counterfactual storylines and appraises trend detectability in context of internal climate variability. The specific aims are to:

- Place the 2023/24 UK in the context of past climate change for both rainfall and river flows following the 'ClimaMeter' attribution approach;
- Quantify the present-day risk of high rainfall using the UNSEEN approach and explore worst case storylines of the 2023/24 river flooding;
- Investigate the effects of internal variability on winter half-year river flows using a single-model-initial-condition large ensemble and estimate when changes are statistically detectable beyond historical variability (i.e. Time of Emergence).

1.1 Winter half-year 2023/24

The winter half-year (Oct 2023-Mar 2024) was exceptionally wet across the UK (Figure S1). Central, eastern England and northeast Scotland saw their highest total winter half-year rainfall since 1836 (Figure 1a) and winter 2024 is one of the wettest on record. Consequently, many catchments registered their highest average winter half-year and winter (Dec-Feb) river flows (Figure 1b) (Hannaford et al., 2024). Flood impacts were widespread with transportation disruptions, property flooding and loss of agricultural crops (Magee et al., in prep). A clustering of storms brought exceptional rainfall accumulations, with 12 named storms in the 2023/24 storm season (nine within the winter half-year), the highest since the naming system began in 2015 (Met Office, 2024). Clarke et al., (2024) found that extreme rainfall due to Storm Babet in October 2023 has become more likely and intense across Ireland with climate change. Storm Ciarán in November 2023 was comparable to the Great Storm of 1987, but impacts in the UK were muted as it followed a southerly track with strongest impacts felt across northern France (Winter et al., 2024). Attribution of the 2023/24 storm season showed rainfall on stormy days has increased by 30% relative to pre-industrial, with a 6-25% increase in winter half-year rainfall (Kew et al., 2024).

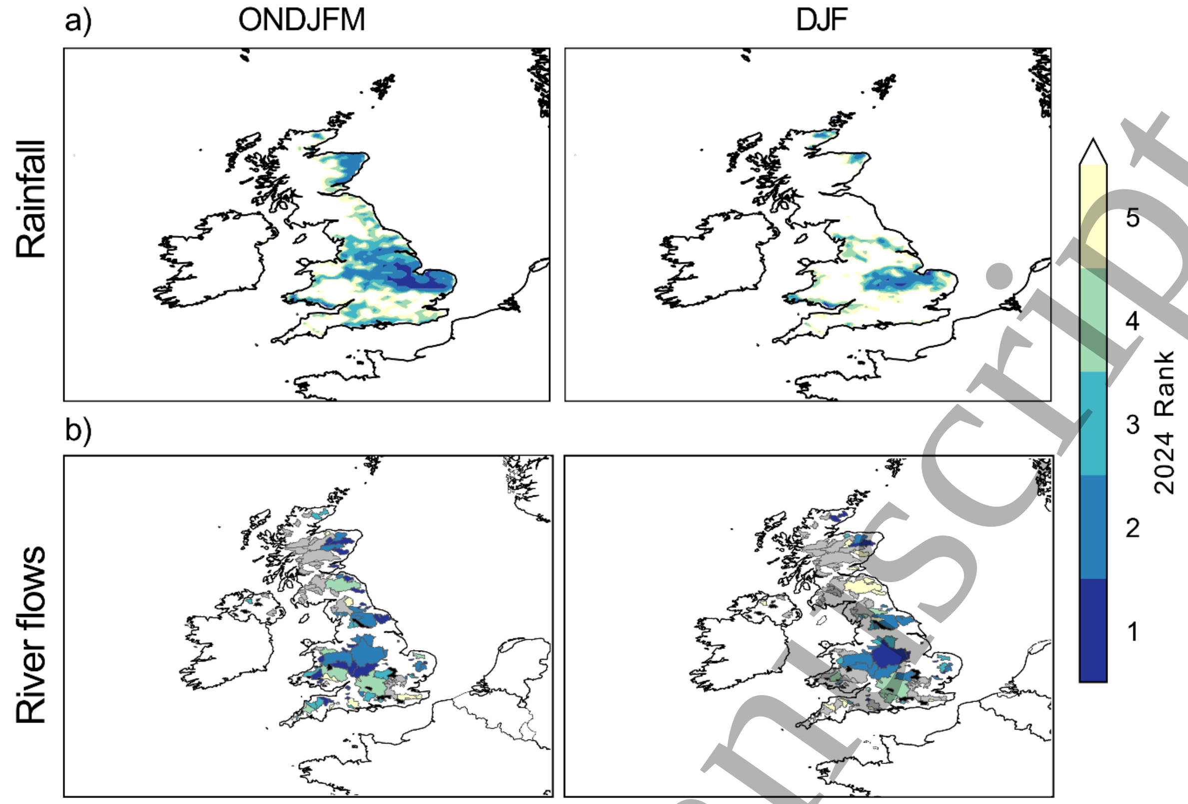

Figure 1 Ranking of the winter half-year (ONDJFM, left) and winter (DJF, right) 2023/24 a) total rainfall and b) mean river flows. Note that the period of record for rainfall and river flows are different. Rainfall ranking is calculated over the 1836-2023 period using the HadUK-Grid 1km dataset. River flow ranking is calculated separately for each catchment according to their period of record. Catchments coloured in grey indicate that the rank of 2023/24 is not within the top five for these two periods.

2 Methods and data

Figure 2 shows a schematic of the various observational and modelled data, methodological steps, and outputs of this study. The methods are described further below.

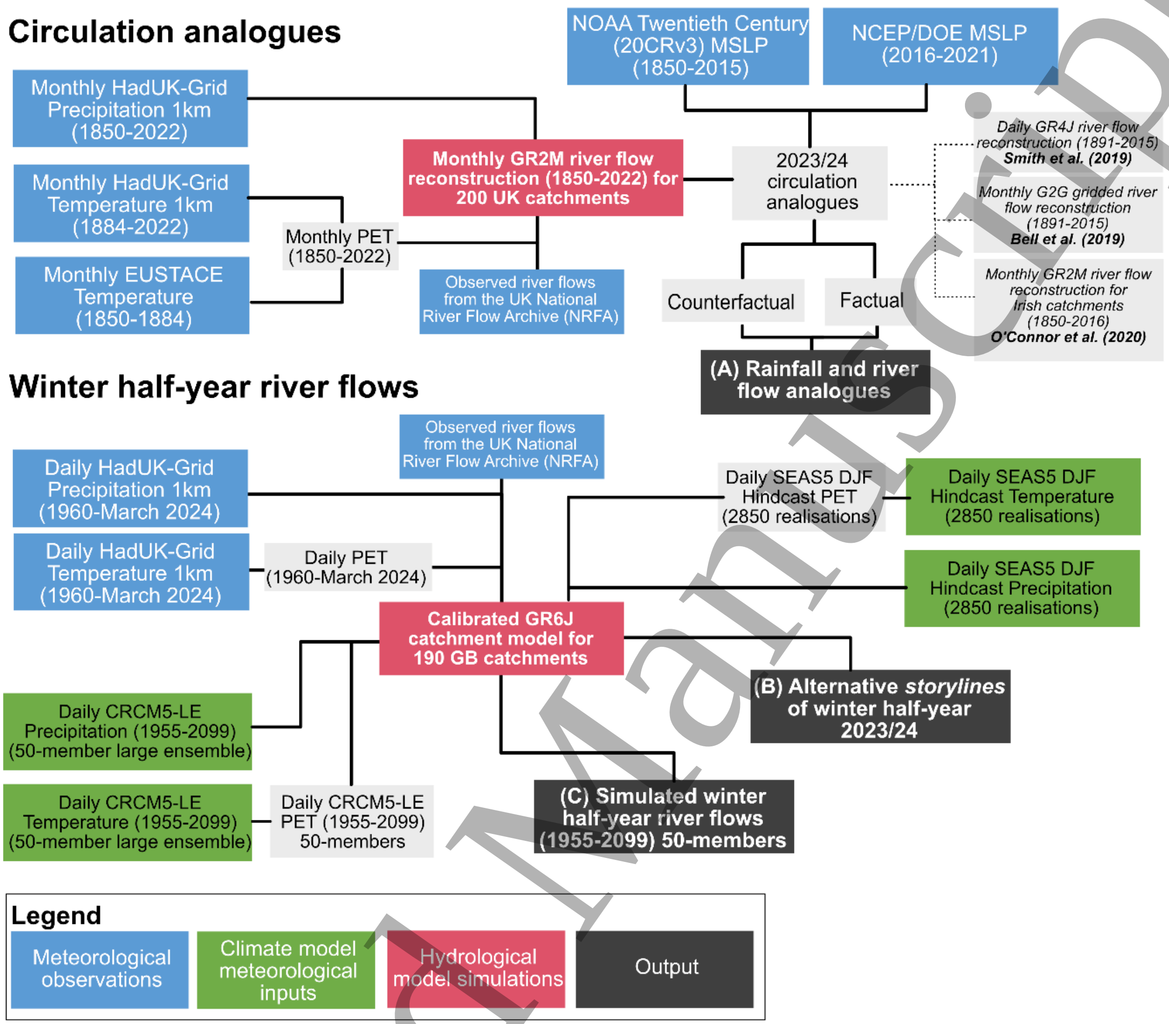

Figure 2 Schematic diagram of the datasets and methodology involved in this study.

2.1 Circulation analogue attribution

The ClimaMeter approach aims to place the high rainfall and river flows over winter half-year 2023/24 in context of historical climate change. Atmospheric circulation analogues with similar mean sea level pressure (MSLP) patterns to the observed winter half-year 2023/24 are sampled from the recent past (factual: 1945-2021) and a more distant past with less anthropogenic warming (counterfactual: 1850-1925). MSLP data over 1850-2021 is obtained by combining the NOAA Twentieth Century (20CRv3) (1850-2015) and the NCEP/DOE (2016-2021) reanalysis for the Euro-North Atlantic region (70°W-30°E, 20°-80°N) (further details in the supplementary Section S1). A 6-months backwards rolling average is applied to MSLP (i.e. SLP-6) with the observed winter half-year 2023/24 event described by SLP-6 ending March 2024. The SLP-6 analogues most similar to winter half-year 2023/24 are sampled from the factual and counterfactual periods. Similarity is defined by the top 30 SLP-6 maps with the lowest Euclidean distance compared with SLP-6 of the observed winter half-year 2023/24. This follows established methods for selecting circulation analogues as outlined in Faranda et al. (2024) and Jézéquel et al. (2018). The effect of climate change is estimated by comparing the rainfall and temperature between analogues in the counterfactual and factual periods.

Monthly river flow reconstructions for 200 UK catchments (Figure S2) for the 1850-2021 period are conducted to consider possible river flows during the analogue periods. Attribution of the persistent high river flows over a 6-months period is achieved by comparing the average river flow anomalies during analogue periods between the counterfactual and factual periods. Previous UK river flow reconstructions cover 1891-2015 (Smith et al., 2018), but not the full 1850-2021 period. High-resolution gridded monthly meteorological observations from the HadUK-Grid dataset for the mid-19th century have been improved after data rescue and digitisation (Hawkins et al., 2023). Correspondingly, we created monthly river flow simulations using the GR2M hydrological model, driven by 1km HadUK-Grid rainfall (1850-2021) and monthly potential evapotranspiration (calculated using the McGuiness-Bordne temperature-based approach using gridded temperature from the EUSTACE dataset from 1850-1883 and 1km HadUK-Grid temperature from 1884-2021). The calibration of the GR2M model follows that of O'Connor et al. (2020) and is further described in section S2.1. Reconstructions for 51 Irish catchments using GR2M from O'Connor et al. (2020) are included for a comprehensive view across the British and Irish Isles. GR2M performs well with observations across most catchments (Figure S3; Section S3) and reconstructed flows correspond well with existing reconstructions over the 1891-2015 period (Figure S4), revealing flood-rich periods prior to the instrumental record. The 6-months analogue selection window considers river flow response time and maximises the sample size available for analogue selection. However, antecedent conditions for each analogue are different, possibly under-estimating changes for slow-responding (e.g. groundwater-dominated) catchments. Thus, results are compared with an additional sensitivity test where monthly GR2M simulations are initialised with observed data up until September 2023, then ran forwards with rainfall and PET from each 6-months analogue period, keeping antecedent conditions constant.

2.2 Alternative storylines of winter half-year 2023/24

It is valuable for risk awareness and adaptation to imagine how events could have turned out worse. The potential of even higher rainfall and river flows over winter 2023/24 is examined by sampling for extremes within initialised simulations. The SEAS5 seasonal hindcast (Johnson et al., 2019) provides 2850 simulated winters over the 1982-2020 period (i.e. pooled simulations initialised in September, October and November - 38 years x 25 ensemble members x 3 lead times) (further described in section S3.1). A simple bias adjustment factor was applied to match the monthly mean observed rainfall and temperature. Statistical tests in Thompson et al. (2017) are applied to compare the statistical moments of simulated rainfall with observations to ensure that simulated rainfall is statistically indistinguishable with observations (section S3.2). The presence of ensemble member dependence and model drift between lead times could reduce effective sample size (Kelder et al., 2022). The credibility of winter rainfall from SEAS5 was confirmed in Chan et al. (2024), showing that ensemble members can be treated as independent and that there was no evidence of model drift in the hindcast ensemble.

The large sample of winter weather sequences from SEAS5 is used to drive the GR6J hydrological model to explore plausible storylines over winter 2023/24 (Section S2.2). GR6J is a widely used daily hydrological model for both forecasting and climate change projections and was calibrated for the same 200 catchments as in section 2.1, showing satisfactory model performance over the winter half-year 2023/24 (Figure S5 and S6). For exploring alternative storylines of the winter 2023/24, GR6J is used as a daily time-step enables more detailed simulation of temporal flood dynamics. Simulations also benefit from the availability of daily meteorological observations from the HadUK-Grid 1km dataset over the winter half-year 2023/24. All 2850 bias-adjusted hindcast weather sequences are treated as individual realisations of plausible winters, following that of Chan et al., (2024) and Kay et al., (2024). For each catchment, GR6J is initialised from 1961 until November 2023, accounting for wet antecedent catchment conditions in autumn 2023, then run forwards using each SEAS5 winter. Hydrological model parameter uncertainty can be large when simulating individual events (Brigode et al., 2013). To estimate this, the top 20 parameter sets from calibration are used to simulate river flows from each of the 2850 SEAS5 winters.

2.3 Time of Emergence

Single-model-initial-condition large ensembles (SMILEs) can be used to estimate the timing when changes are estimated to exceed the range of internal variability (i.e. Time of Emergence ToE) as they explicitly quantify internal variability. The CRCM5-LE large ensemble, a 50-member SMILE dynamically downscaled over Europe (Leduc et al., 2019), is used to drive the GR6J hydrological model to estimate ToE for winter half-year river flows into the 21st century. Details of CRCM5-LE can be found in Section S3.3. Simulated river flows by GR6J, with the same calibration strategy as previously noted, are taken from Chan et al., (2025) which applied the ToE framework for low flows in Great Britain. The ToE for each catchment is obtained following the approach in Faghih and Brissette (2023). For each catchment, average winter half-year river flows over the 1981-2010 period are calculated for each ensemble member. The range of internal variability is defined as ±1 standard deviation of the average flow across all 50 ensemble members. The average for each ensemble member is then computed over successive overlapping 30-year periods (e.g. 1982-2011, 1983-2012….2068-2098). The ToE is defined as the middle year of the 30-year period where the ensemble mean difference in winter half-year flows relative to the baseline period exceeds internal variability.

3 Results

3.1 Circulation analogue attribution

The top 30 SLP-6 analogues for both counterfactual (1850-1925) and factual (1945-2021) periods exhibit low pressure centred over the British Isles and high pressure over Greenland (Figures 3a-c), a pattern that is expected to bring cyclonic conditions and higher UK rainfall (e.g. Richardson et al., 2018). The analogues also show a deepening of the low pressure in the factual period (Figure 3d). Analogue quality, the average Euclidean distance of the circulation pattern of the observed event from its closest 30 analogues, shows that the observed 2023/24 circulation pattern was relatively unusual although analogues in the factual period are slightly more similar to the observed event (Figure S7a). Analogues in both periods are generally found in winter half-year months (Figure S7b).

Analogues are associated with positive rainfall anomalies, particularly for England and northeast Scotland (Figures 3e-h) – consistent with the spatial pattern of the observed event. Temperatures have warmed by >1°C, with greatest warming across southeast England (Figures 3i-l). UK rainfall averaged across the analogues is 8% higher in the factual period with spatial variations (e.g. 14% higher for East Midlands) (Table S3). This increase in rainfall exceeds the rate of the Clausius-Clapeyron relationship, suggesting dynamical and atmospheric circulation influences. The dependence of analogues on modes of natural variability suggest that El Niño may have played a larger role for analogues in the factual period (Figure S8c) but no such dependence on the Atlantic Multidecadal Variability was found (Figure S8d). An El Niño phase is more likely to be associated with cyclonic days and wet UK winters (Fraedrich and Müller, 1992).

River flows during analogue events in both factual and counterfactual periods match the spatial pattern of observed river flow anomalies over winter half-year 2023/24 (Figure 3m-o). However, observed anomalies are much greater than the analogue mean, highlighting the event's severity. River flow anomalies are on average 13.5% higher in the factual period (Figures 3p), with the greatest increase for catchments in the East Midlands (+26%), followed by Yorkshire and Humber (+22%) (Table S4). For the Republic of Ireland, events similar to winter half-year 2023/24 had 9.9% higher flows in the factual period. Larger changes in river flows compared to rainfall highlight the non-linearity in catchments' response to rainfall, which can exceed changes in rainfall of a given magnitude. Keeping the antecedent conditions prior to October 2023 constant yields very similar results, with river flows on average +12.5% higher than in the counterfactual period (regional statistics in Table S5). For the post-1891 period, existing river flow reconstructions provide an opportunity to test the results' sensitivity to different periods and hydrological models. The choice of an alternative counterfactual (1891-1940) and factual (1966-2015) period and simulations by different models show consistent changes with higher flow anomalies in the factual period but differences in river flows are slightly higher (e.g. for Scotland) (Figure S8 and Table S6).

In summary, a six-month period with a similar atmospheric circulation pattern to the winter half-year 2023/24 has become wetter and warmer with higher river flows, attributable to anthropogenic climate change since 1850 and potentially exacerbated by natural variability associated with El Niño.

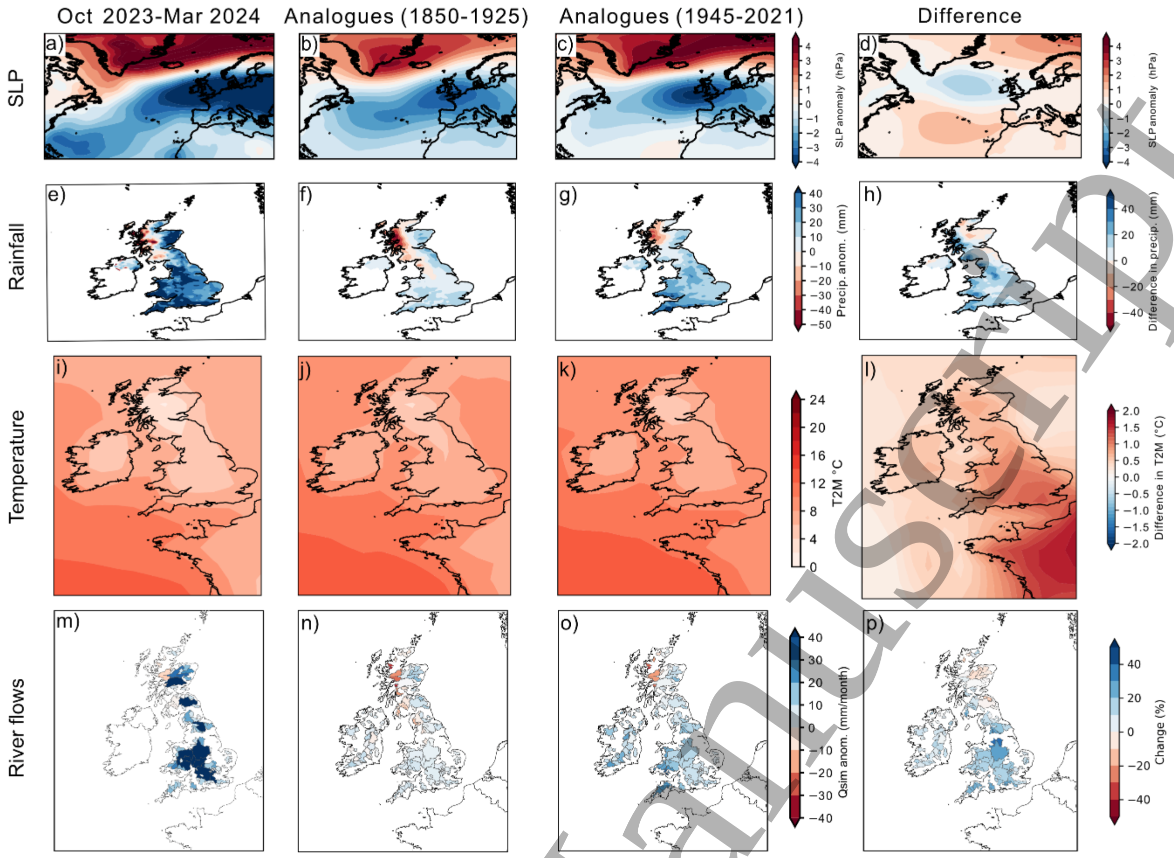

Figure 3 Results from ClimaMeter circulation analogue-based attribution. The observed sea level pressure, rainfall, temperature and simulated river flows anomalies over the winter half-year 2023/24 (Oct 2023 to Mar 2024) are shown in panels (a), (e), (i) and (m), respectively. Panels (b-d) show mean sea level pressure of the top 30 analogues found for the counterfactual (1850-1925) and factual (1945-2021) periods and the difference between the two periods. Panels (f-h) show mean rainfall anomalies associated with the top 30 analogues for the counterfactual (1850-1925) and factual (1945-2021) periods and the difference in rainfall between the two periods. Panels (j-l) show mean temperature of the top 30 analogues for the counterfactual (1850-1925) and factual (1945-2021) periods and the difference between the two periods. Panels (n-p) show mean river flow anomalies of the top 30 analogues for the counterfactual (1850-1925) and factual (1945-2021) periods and the difference in total runoff between the two periods. River flow reconstructions for the 51 catchments in the Republic of Ireland are taken from O'Connor et al. (2020).

3.2 Potential for unprecedented extremes

In this section, the potential of more extreme rainfall and river flows is examined by following the UNSEEN approach using the SEAS5 hindcast archive. The robustness and credibility of the SEAS5 simulated rainfall assessed via model fidelity tests shows that bias-adjusted simulated winter rainfall in SEAS5 can be considered statistically indistinguishable from observations for large parts of the UK in December and January (Figure S9). However, almost all regions fail the test in February with the variability in the modelled rainfall lower than the observations. This was also found in Kelder et al. (2022) and Kay et al. (2024), the latter with a different set of initialised hindcasts. The present-day chance of exceeding observed rainfall for winter 2023/24 is shown in Figure 4a-c. On average, there is a 18%, 52% and 21% chance of exceeding the observed December, January and February rainfall, respectively, with significant regional variations (Table S7). Observed February 2024 rainfall is particularly hard to beat with a very low chance of exceedance across England and considerable uncertainty in the magnitude of unprecedented rainfall (e.g. for East of England: Figure 4d-f). February 2024 was the wettest since 1836 for several regions, hence a low chance of exceedance, but estimates could be underestimated as simulated February rainfall in SEAS5 exhibits lower variability compared to observations.

Daily river flow simulations initialised in November 2023 with all 2850 SEAS5 winters show the potential of significantly higher river flows than observed, including higher n-day maxima river flows (defined as the highest average flows over a period of 14-, 30- and 60-days across 2023/4. In the worst case, n-day maxima could be at least 1.5 times higher than the baseline winter 2023/24 event (Figure 5a). The proportion of storyline simulations breaking the observed 14-day maxima flows is higher compared to exceeding the observed average winter half-year river flows, especially across catchments in Wales and southern England (Figure 5b; Table 2 for all regions). Averaged across all regions, 7.2-8.3% of all winters in the SEAS5 hindcasts result in higher average winter flows relative to the baseline. Autumn 2023 was wet across the UK, with parts of the Midlands receiving over 1.5 times the average rainfall (Met Office 2023). The combination of wet antecedent conditions at the end of November in conjunction with the wettest SEAS5 winter suggests winter flows could be 41.3-48.9% higher than the already exceptionally high flows in the baseline.

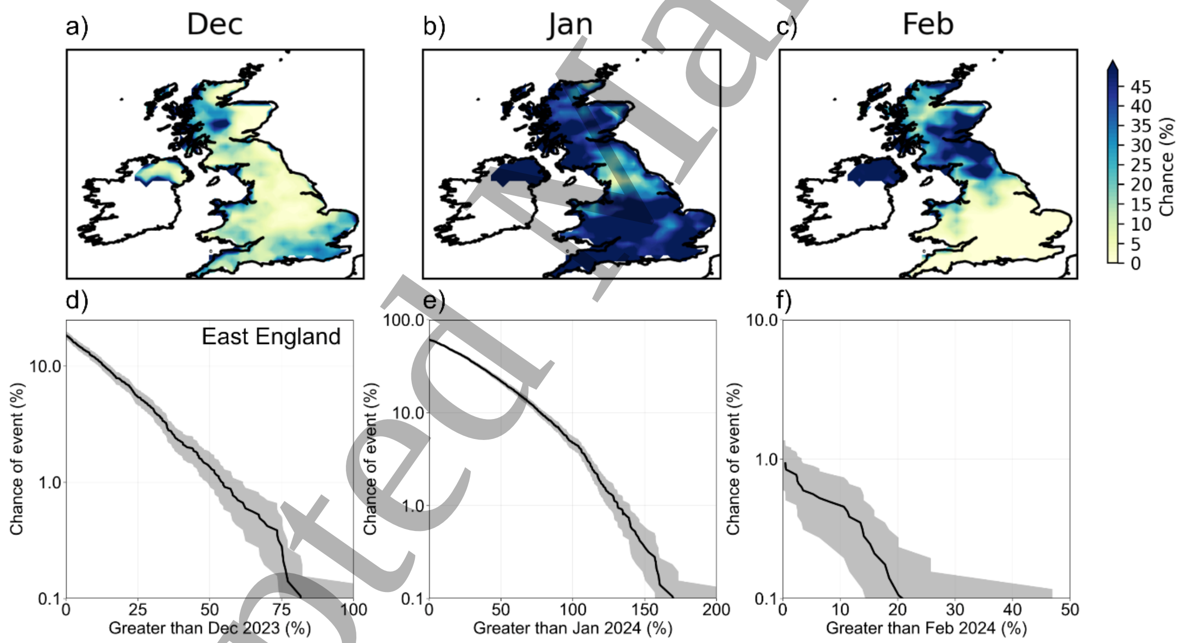

Figure 4 The UNSEEN estimates of the chance of exceeding the observed December 2023, January 2024 and February 2024 rainfall for the UK (a-c) and over East of England (d-f). The grey shading on panels (d-f) shows the confidence interval from 10,000 sub-samples of model simulations (2.5th and 97.5th percentiles).

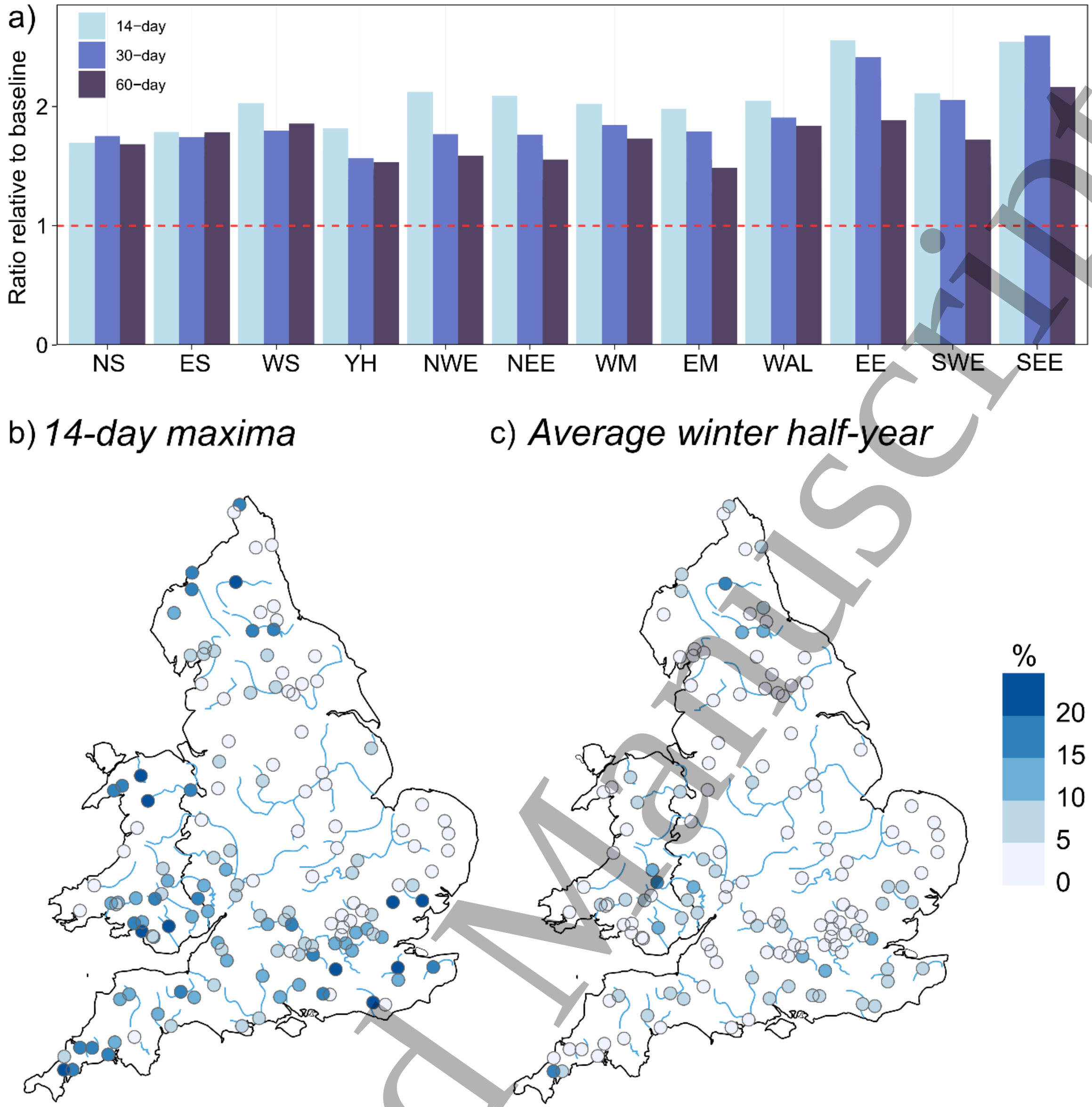

Figure 5 a) Maximum deviation of n-day (14, 30 and 60-day) maxima river flow in the worst-case storyline expressed as a ratio relative to the baseline winter half-year 2023/24 event for all UK regions as shown by the horizontal red dashed line (abbreviations of UK regions shown in Figure S2 in the supplement). Proportion of SEAS5 storyline simulations exceeding the baseline for b) 14-day maxima river flow and c) average winter half-year 2023/24 river flows across England and Wales. England & Wales is visualised here as river flooding from the observed event was most severe for these constituent countries of the UK.

Table 1 Percentage of simulations (%) exceeding the average winter river flows in the baseline (simulated river flows over the observed winter 2022/23) and the maximum change in river flows (%) relative to the baseline averaged across all catchments in each region. The uncertainty range represents hydrological model parameter uncertainty (i.e. the maximum and minimum value across the top 20 parameter sets)

Region	**% of simulations exceeding baseline**	**Maximum change in mean river flows relative to baseline (%)**
North Scotland	15.3 (14.3 – 16.1)	43.5 (41.1-45.5)

East Scotland	13.1 (12.6 – 13.8)	39.8 (36.9-42.6)
West Scotland	21.2 (20.4 – 21.7)	59.5 (55.7-63.1)
North East England	6.5 (6.2 – 7)	41.0 (36.5 – 44.3)
North West England	3.0 (2.8 – 3.3)	41.7 (38.4 – 44.2)
Yorkshire & Humber	2.0 (1.9 – 2.2)	32.1 (30 – 34.3)
East Midlands	1.7 (1.5 – 1.9)	26.3 (24 – 28.3)
West Midlands	5.9 (5.6 – 6.3)	57.7 (52.6 – 61.6)
Wales	5.9 (5.6 – 6.5)	49.2 (46 – 51.3)
East of England	4.4 (3.6 – 5.1)	48.1 (40.1 – 57.6)
South East England	7.8 (6.9 – 8.8)	59.1 (52.2 – 66.1)
South West England	6.1 (5.4 – 6.8)	45.4 (41.6 – 48.5)

3.3 Time of Emergence

The timing of a robust climate-driven signal (Time of Emergence, ToE) may not be statistically detected given short observational records and the influence of internal climate variability superimposed on a climate-driven trend. In this section, the ToE for winter half-year mean river flows is estimated using the 50-member CRCM5-LE SMLE. Figure 6a shows, for six regions in Great Britain (GB), the difference in winter half-year river flows in successive 30-year periods with the average winter half-year river flows over the baseline period. Winter half-year river flows are projected to increase with climate change for all regions but the timing of when the ensemble mean exceeds estimated internal variability varies between regions. Catchments in some parts of northern Scotland have an early ToE where a robust climate change signal of increasing winter half-year flows has already emerged or may emerge imminently (e.g. within the next decade) (Figure 6b). However, there are several regions (e.g. North West England and Wales) where the estimated ToE for some catchments is towards late 21st century, suggesting a robust climate change signal is not estimated to emerge for several decades. This could relate to the large variability (i.e. noise) in flows across the ensemble members in these flashy catchments but could also be related to climate model-related uncertainty. Chan et al. (2025) found earlier ToE, within the next two decades, across some GB catchments for high flows (5th percentile of the flow duration curve – Q5), suggesting that uncertainty in rainfall changes for the shoulder months (i.e. October, November and March) due to internal variability could conceal a robust climate-driven trend.

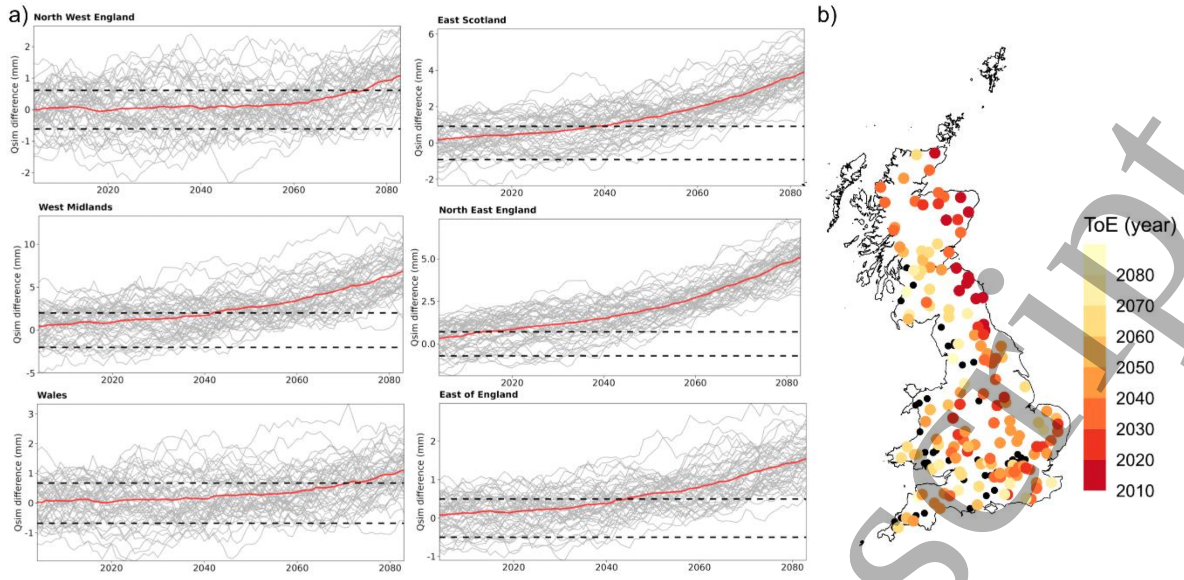

Figure 6 Panel (a) shows winter half-year simulated river flows in successive 30-year periods relative to the mean winter half-year river flows over the baseline (1981-2010) period for each of the 50 ensemble members of the ClimEx SMILE (individual lines) for six regions in Great Britain. The ensemble mean is shown by the red line and the dashed horizontal lines represent the estimated range of internal variability over the historical period. Panel (b) shows an estimation of the time of emergence for all catchments in Great Britain, defined as the middle year of any 30-year period where the ensemble mean change (red line in panel a) exceeds internal variability (dashed horizontal lines in panel a). Black dots are catchments where the ToE is not estimated to be reached within the 21st century.

4 Discussion and conclusion

This study demonstrates a framework for post-event analyses of hydrological extremes that combines event attribution, "what-if" storylines and the use of large ensemble simulations to appraise climate-driven trend detectability. Taking the winter half-year 2023/24 UK river flooding as a case study, ClimaMeter attribution shows that events with similar atmospheric circulation patterns has become wetter (by an average 8.8%) since 1850, consistent with probabilistic attribution of the winter 2023/24 storm season (Kew et al., 2024). UK winters in the last decade were 9% (24%) wetter than 1991-2010 (1961-1990) (Kendon et al., 2024). Monthly river flow reconstructions extended back to 1850 show that average river flows during analogue events is higher in the factual period (1945-2021) by 13.5%, highlighting the non-linearity of river flow response to rainfall. The 6-months analogue selection period is designed to capture longer-term extremes, as the main driver of UK river flooding is saturation excess, where high flows occur after a series of rainfall events, rather than a singular largest rainfall event or snowmelt-driven (Berghuijs et al., 2016; Kay, 2016). However, a limitation of the ClimaMeter approach is the reliance on historical observations/reconstructions so the years available for analogue selection is limited. Analogue quality for the winter half-year 2023/24 suffers given limited sample size, especially if circulation patterns of the observed event are rare. Spectral nudging simulations (e.g. Athanase et al., 2024) or sampling for analogues within climate model simulations in pre-industrial, present-day and future climates could complement these results. Additionally, our study did not attribute changes to individual flood peaks as river flow reconstructions at finer temporal resolution would be required. Uncertainty in the quality of the rainfall observations in the early 19th century, such as comparatively poor gauge density despite data rescue efforts, a lack of standardisation and biases related to under-catch of snowfall (Murphy et al., 2020), may further impact attribution results.

Alternative storylines of winter 2023/24 showed the potential for river flows to be ~46% higher in the worst-case, reflecting the compound occurrence of extreme winter rainfall with already high observed antecedent wetness in Autumn 2023. This is consistent with findings in Kay et al. (2024) using a different hindcast dataset and hydrological model. The creation of event storylines contributes to calls for routine exploration of how observed events could have turned out worse (Sillmann et al., 2021; Woo, 2019) and adds to the use of the UNSEEN technique to constrain the present-day potential of hydrological extremes (e.g. Brunner and Slater, 2022). Additional storylines, such as shifting rainfall fields to maximise rainfall accumulations in certain locations (e.g. Goulart et al., 2024; Merz et al., 2024), ensemble boosting to generate potentially worse event severity and footprint (Thompson et al., 2025) or even higher antecedent conditions in Autumn 2023 could be further extensions. Considering human influences (e.g. land use change) and socio-economic impacts (e.g. properties at risk of flooding) could potentially further contribute to impact-based attribution (Perkins-Kirkpatrick et al., 2024).

Finally, large ensemble simulations suggest an increasing trend in winter half-year river flows across the 21st century. However, internal climate variability masks early detectability of a c statistically significant climate-driven signal, although earlier signals are detectable for some catchments (e.g. central England and northern Scotland). This is consistent with previous studies showing that climate variability may conceal climate-driven trends in river flows (e.g. Wilby, 2006; Chan et al., 2025). The use of alternative SMILE simulations for hydrological modelling is subject to on-going work to consider climate model uncertainty. Robustness could also be enhanced with the use of alternative hydrological models.

In summary, we have demonstrated a framework for post-event analysis of hydrological extremes using the winter half-year 2023/24 UK river flooding as a case study. A major advantage is that the framework goes way beyond standard event reporting that typically uses relatively short hydrological observations alone. Here, we combine extreme event attribution, “what-if” storylines and the use of initial-condition large ensembles. Additionally, the framework makes use of publicly available meteorological datasets (both observations and climate model simulations) in conjunction with open-source hydrological models (i.e. *airGR* R package). The methodology can potentially be applied to other hydrological extremes and other environments. However, while portable in principle, applications in other regions need to consider the wide variability in hydrological regimes. Regions or events dominated by other flood generation mechanisms (e.g. snowmelt) may require alternative process representation or hydrological model structures. High resolution and long meteorological observations are a key requirement for driving river flow reconstructions, but such datasets may not be readily available for all regions. However, internationally, there are many initiatives underway to extend and improve meteorological datasets, such as the C3S Data Rescue Service. Despite these constraints, there is clear potential for the framework presented here to be applied to other events in other regions, to assist disaster risk reduction and climate change adaptation.

5 Data availability

Observed river flow data for UK catchments can be obtained from the National River Flow Archive (NRFA) (https://nrfa.ceh.ac.uk/data/). Reconstructed monthly river flows for all 200 UK catchments for the 1850-2021 period using the GR2M hydrological is available at (DOI: https://doi.org/10.5281/zenodo.14982949). Daily river flow reconstructions for 303 UK catchments for the 1891-2015 period are available from Smith et al., (2018) (https://doi.org/10.5285/f710bed1-e564-47bf-b82c-4c2a2fe2810e). UK rainfall and temperature data is available from the HadUK-Grid dataset (Hollis et al. 2019) and accessible via CEDA (https://catalogue.ceda.ac.uk/uuid/5a248096468640a6bfb0dfda8b018ac5/). Rainfall and temperature data for the CRCM5-LE is publicly available on the ClimEx website (https://www.climex-project.org/data-access/). River flow simulations across Great Britain driven by the CRCM5-LE is available from (https://doi.org/10.5281/zenodo.13990611). Daily SEAS5 hindcasts are available from the Climate Data Store (CDS) (https://doi.org/10.24381/cds.181d637e, Copernicus Climate Change Service, Climate Data Store, 2018).

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