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Learning from the 2018 heatwave in the context of climate change: are high-temperature extremes important for adaptation in Scotland?

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Abstract

To understand whether high temperatures and temperature extremes are important for climate change adaptation in Scotland, we place the 2018 heatwave in the context of past, present, and future climate, and provide a rapid but comprehensive impact analysis. The observed hottest day (d), 5 d, and 30 d period of 2018 and the 5 d period with the warmest nights had return periods of 5–15 years for 1950–2018. The warmest night and the maximum 30 d average nighttime temperature were more unusual with return periods of >30 years. Anthropogenic climate change since 1850 has made all these high-temperature extremes more likely. Higher risk ratios are found for experiments from the CMIP6-generation global climate model HadGEM3-GA6 compared to those from the very-large ensemble system weather@home. Between them, the best estimates of the risk ratios for daytime extremes range between 1.2–2.4, 1.2–2.3, and 1.4–4.0 for the 1, 5, and 30 d averages. For the corresponding nighttime extremes, the values are higher and the ranges wider (1.5- >50, 1.5–5.5, and 1.6- >50). The short-period nighttime extremes were more likely in 2018 than in 2017, suggesting a contribution from year-to-year climate variability to the risk enhancement of extreme temperatures due to anthropogenic effects. Climate projections suggest further substantial increases in the likelihood of 2018 temperatures between now and 2050, and that towards the end of the century every summer might be as hot as 2018. Major negative impacts occurred, especially on rural sectors, while transport and water infrastructure alleviated most impacts by implementing costly special measures. Overall, Scotland could cope with the impacts of the 2018 heatwave. However, given the likelihood increase of high-temperature extremes, uncertainty about consequences of even higher temperatures and/or repeated heatwaves, and substantial costs of preventing negative impacts, we conclude that despite its cool climate, high-temperature extremes are important to consider for climate change adaptation in Scotland.

1. Introduction

Climate change adaptation is essential alongside mitigation given existing climate change (IPCC 2018), and urgent given the implementation time of measures. Prioritising limited resources for adaptation measures requires a thorough understanding of both the projected climate changes and the expected impacts. In the United Kingdom, and Scotland specifically, the relevance of adaptation measures in general has been politically acknowledged (The UK Government 2008, The Scottish Government 2009, 2014, 2019), and efforts were made to inform projected changes in regional climate (Lowe *et al* 2019).

High-temperature extremes can have significant impacts on the environment and society

(Smith *et al* 2014). Globally, adaptation measures to cope with temperature extremes are therefore important, especially in regions where present-day temperatures are close to physiological limits to human heat tolerance. It remains unclear, however, whether high-temperature events need to be considered in Scotland, where temperatures are climatologically moderate but might show substantial relative changes in frequency and magnitude of its extremes (O'Neill and Tett 2019).

The societal impact of high temperatures can be understood by analysing observed impacts of extreme events on people, ecosystems, and infrastructure. The year 2018 is a good case study for Scotland, since it had anomalously high summer temperatures (Met Office 2018), and anecdotal evidence suggested substantial heatwave-related societal and economic impacts. To understand the relevance of temperature extremes for adaptation in Scotland, we place observed temperatures in the context of past, present, and future climate and identify the observed impacts of the 2018 heatwave. Specifically, we show the observed temperatures and discuss how anomalous they are; analyse the contribution of anthropogenic forcings to the risk of these temperature extremes; evaluate impacts they had in Scotland; and assess future changes in the likelihood of these events.

2. Data and methods

2.1. Observational climate/weather data

We characterise observed temperatures during summer 2018 using near-surface daily minimum (nighttime) and maximum (daytime) temperature from the European gridded observational dataset (E-OBS), version 19.0e spanning 1/1/1950–31/12/2018 at 0.25° resolution (Haylock *et al* 2008, European Climate Assessment & Dataset (ECA&D) 2019). We further use daily minimum and maximum temperature observed at the stations at Eskdalemuir (WIGOS station identifier (World Meteorological Organization (WMO), 2015): 0-20000-0-03162; MIDAS source ID (Met Office 2012): 1023) and Auchincruive (MIDAS source ID: 1005). The atmospheric circulation is shown using daily sea level pressure data at 0.75° resolution from the ERA-Interim reanalysis (Dee *et al* 2011, European Centre for Medium-Range Weather Forecasts (ECMWF) 2018).

2.2. Climate model data

To analyse the anthropogenic contribution to the observed temperatures, we use simulations from the HadGEM3-GA6 model, which is the atmospheric component of the Met Office's Global Environment Model version 6 (HadGEM3-A hereafter; Walters *et al* 2017). The model has a horizontal resolution of 0.55° × 0.9° (N216; corresponding to about 60 km at mid-latitudes), and the system (based on Christidis *et al* 2013) has been evaluated for event attribution studies for Europe (Ciavarella *et al* 2018, Vautard *et al* 2018). To study the sensitivity of the results to the climate model used, we use simulations from weather@home (short: W@H; Massey *et al* 2015, Guillod *et al* 2017)—a nested model setup within the distributed computing platform climate*prediction*.net (Allen 2016). This is a global atmospheric model (HadAM3P) at 1.25° × 1.875° resolution driving a regional model (HadRM3P) at 25 km resolution over a European domain (Guillod *et al* 2017, 2018).

For each model, we compare large-ensemble experiments representing the actual with those representing a counterfactual, 'natural' climate. Both ensembles, Historical2018 and Natural2018 hereafter (referred to as 'HistoricalExt' and 'HistoricalNatExt' in Ciavarella *et al* 2018), are pre-conditioned on the state of the ocean during 2018 by prescribing estimates of observed sea surface temperatures (SST) and sea ice coverage (SIC) as boundary conditions for the atmospheric models (see supporting information (SI)). For HadGEM3-A, we also use analogous Historical2017 and Natural2017 simulations to examine the role of SST and sea-ice variability. To estimate biases of the extreme indices from HadGEM3-A and W@H, respectively, we use the historical 15- and 170-member ensembles described in Ciavarella *et al* (2018) and Sparrow *et al* (2018) that include both anthropogenic and natural forcings and span 1/1/1960–30/12/2013 and 1/1/1986–30/12/2017, respectively.

To assess projected changes in the likelihood of 2018 temperatures, we use the perturbed parameter ensembles (PPEs) provided by the UK Met Office as part of the UK Climate Projections 2009 and 2018 (UKCP09 and UKCP18, respectively). Members of PPEs are derived from slightly different model variants between which a range of parameters are varied to represent uncertainty in physical processes that are not resolved in the model. The initial-condition ensembles used for the event attribution, in contrast, are derived from the same model variant and only represent internal atmospheric variability. The UKCP18 12-member PPE for 1980–2080 is based on the coupled HadGEM-GC3.1 model that uses version 7.1 of the atmospheric model (Murphy *et al* 2018, Walters *et al* 2019) and assumes emissions following the Representative Concentration Pathway (RCP) 8.5 (Moss *et al* 2010). The UKCP09 11-member PPE for 1950–2099 is based on the coupled HadCM3 model (Hadley Centre for Climate Prediction and Research 2008, Murphy *et al* 2009) and uses the A1B scenario (Nakicenovic and Swart 2000, Murphy *et al* 2009). A1B lies between RCP4.5 and RCP 8.5 in terms of the anthropogenic radiative forcing since pre-industrial over the twenty first century, and is very close to RCP8.5 until 2050 (Collins *et al* 2013).

2.3. Return period and event attribution method

We calculate area means over land between 53.5°–61° N; 10°W–2°E for daily maximum and minimum

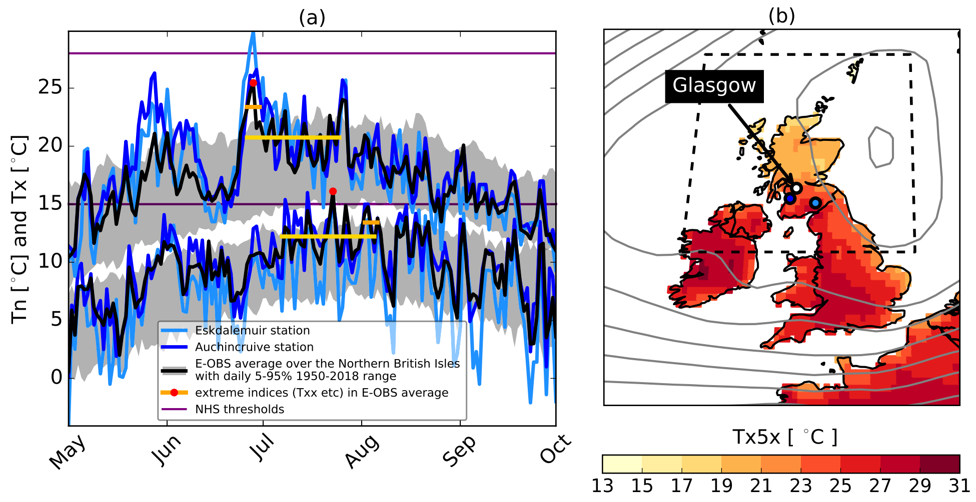

Figure 1. Observed 2018 temperatures. (a) Time series of (top) maximum and (bottom) minimum daily temperatures at the Scottish weather stations (blue) Eskdalemuir and (dark blue) Auchincruive as well as (black) the gridded observational dataset E-OBS averaged over the Northern British Isles (NBI; land areas within the dashed box in (b). Also shown are where the E-OBS area-means have the (red dot) single-hottest day, the (orange line) hottest 5 d period, and the (yellow line) hottest 30 d period, which are the extreme indices used in figures 3–4. The purple lines at 15°C and 28°C indicate the temperature thresholds that might be relevant for health impacts if sustained over at least two consecutive days (Public Health England *et al* 2019). (b) Spatial map of (colour shading) daily maximum temperature from E-OBS and (contour lines; for numbers see figure S1(a)) sea level pressure (SLP) from reanalysis data (ERA-Interim), both averaged over the 5 d period with the highest maximum temperature in 2018 (late June; upper orange line in (a)). The blue dots indicate the location of the weather stations used in (a).

temperature both for E-OBS and all model data. This region includes the Northern British Isles (NBI hereafter; see box in figure 1) and is purposefully chosen to be larger than the immediate area of interest in order to avoid selection bias. For E-OBS, HadGEM3-A, and W@H, we weight the regional means by area size; for UKCP09 and UKCP18, we use non-weighted means on the original rotated grid. For the model data, we use only grid boxes with at least 75% land fraction in the models' native grids. We then calculate the annual summer (June to September, JJAS) maxima of daily (x) data as well as of 5 d (5x) and 30 d (30x) centred running means for both maximum (Tx) and minimum (Tn) near-surface temperature, resulting in the extreme indices Txx, Tx5x, Tx30x; Tnx, Tn5x, and Tn30x. For each model, we correct for the difference in the observed and simulated mean of each index during 1/1986–12/2009. For the UKCP datasets, we correct this bias for each PPE member separately. Correcting for the mean of the distribution as done in previous studies (e.g. Holmes *et al* 2017) has disadvantages, e.g. could increase the mismatch in the tail of skewed distributions (figure 3(d)). However, there is no clear evidence that other methods would be more appropriate, and this method has the advantage of simplicity and transparency.

We obtain return periods of the observed 2018 values in the 1950–2018 period by fitting a generalised extreme value (GEV) distribution (Sparrow *et al* 2018) to the E-OBS data.

The contribution of anthropogenic forcings to the likelihood of 2018 temperatures is estimated by comparing the Historical2018 and Natural2018 ensemble experiments. For each ensemble, we derive GEV fits to the distributions of the extreme indices to get the likelihood of exceeding a given threshold. We then calculate the risk ratio as a function of a threshold's return period in E-OBS by dividing both values. Bootstrapping (Efron and Tibshirani 1993, 1000 replications) gives the uncertainty in the GEV fits for Historical2018 and Natural2018 separately, and the uncertainty in the risk ratios is calculated from each combination of these 2 × 1000 distributions.

2.4. Identifying observed impacts

To understand the impacts of the hot weather on Scotland, we performed a media analysis and interviewed individuals representing sectors that were potentially impacted. We used thematic content analysis (Bryman 2016) to examine patterns in the media coverage and interview transcripts. Using a coding scheme, we thus identified both positive and negative impacts, including alleviated negative impacts and unexploited positive impacts (table 1). To increase rigour and consistency two co-authors (JH & MM) independently coded all interviews and articles and reconciled divergent interpretations.

The media analysis consisted of querying Scottish publications in the LexisNexis database (LexisNexis 2019) for the keywords ('heatwave' or 'hot' or 'heat' or 'warm' or 'temperature') and ('health' or 'water' or 'air' or 'soil' or 'infrastructure' or 'agriculture') and ('Scotland') during 1/5/2018–1/11/2018. We removed duplicate articles, resulting in the selection of 223 articles, of which we discarded 65 because they did not discuss impacts in Scotland, leaving 158 articles from 16 news sources for analysis (table S1 is available online at

Table 1. Coding schedule and counts for impacts in Scotland reported in the media and in the interviews. Each mention of an impact in the media coverage and interview transcripts was assigned one of these six codes.

Negative impacts	Positive impacts
[code] count—definition	**[code] count—definition**
[N1] $n = 68$—*Minor negative impact.* A negative impact occurred causing minor disruption, delays, costs etc. These were not considered severe and the response was within normal operating procedures (e.g. business continuity plans). There are only minor cost/resource implications.	*[P1]* $n = 27$—*Minor positive impact.* A positive impact occurred that led to minor benefits. Although these were recognised, they were not considered unusual or significant in terms of normal operations.
[N2] $n = 55$—*Alleviated (avoided) negative impact.* A negative impact occurred that required a response to mitigate against disruption, delays, damage etc. By implementing extraordinary/special measures the consequences were effectively managed to avoid the worst impacts, although typically with significant cost/resource implications.	*[P2]* $n = 6$—*Unexploited (missed) positive impact.* There was potential for a positive impact, but benefits were not realised due to a lack of preparation, capacity, resources etc. There was a missed opportunity of what could have been a significant benefit.
[N3] $n = 71$—*Major (significant) negative impact.* A negative impact occurred causing disruption, delays, loss, damage etc. Any measures taken were not sufficient to avoid significant consequences. There will be cost/resource implications during the event and associated with recovery.	*[P3]* $n = 19$—*Major (significant) positive impact.* A positive impact occurred that led to recognised benefits. There were sufficient planning, resources, capacity etc in place to realise the main benefits. These benefits were significant/notable in the context of normal operations.

stacks.iop.org/ERL/15/034051/mmedia, see also table S2 available in the supplementary data.)

Using our professional networks and snowball sampling—whereby participants help identify and recruit further participants—we conducted 25 short semi-structured interviews with individuals working in three sectors identified by the Climate Ready Clyde Climate Change Risk and Opportunity Assessment (England *et al* 2018): natural environment and assets (12); infrastructure (5); and people and the built environment (8). Each interview lasted 10–30 min and asked whether and how the interview partners' organisations were affected by the heatwave, and if so, whether and how they responded to these impacts.

3. Results

3.1. How anomalous were the 2018 temperatures?

Averaged over the NBI, day- and nighttime temperatures exceeding the 1960–2018 95% range were observed on days in spring, early summer, and July 2018 (figure 1). The daytime temperature peaks in June and July recorded in station observations from Western Scotland are even more pronounced. Daily maximum temperature in Eskdalemuir was 29.9 °C on 28/6/2018, which was the highest on record (spanning 1/1/1954–29/6/2019). The minimum temperature was 15.8 °C, which was the 4th-highest following 16.7 °C, 16.3 °C, and 16.0 °C on 25/8/1959, 9/8/2004, and 10/8/2004, respectively.

Daily maximum temperature (*T*x) thus exceeded the threshold of 28°C in Eskdalemuir, and minimum temperature (*T*n) that of 15°C repeatedly in station data and even in the large-area mean. These thresholds were not exceeded for two days in a row as would be considered critical by the health system for triggering heatwave action in the climatologically most similar English region (Public Health England *et al* 2019). Note however, that the station data, which are also the basis of the E-OBS dataset, are sparse, and the urban centre of Glasgow is expected to have had higher temperatures than those measured at the rural station sites due to heat island effects (Mitchell 1961, Emmanuel and Krüger 2012, Goddard and Tett 2019).

The hottest day and the warmest night of summer 2018 in the NBI occurred in different months, with above-average minimum temperatures throughout July (figure 1(a)). In terms of the 1 d, 5 d, and 30 d period with the highest values for daily minimum and maximum temperatures separately, comparison with the baseline climate (1950–2018) shows that the daytime extremes were moderately rare (return periods of about 5–15 years; grey lines in figures 2 and S2). Some of the nighttime extremes, in contrast, were more rare: The return period for the single-warmest night has a best estimate of >30 years, and the warmest 30 d period was even rarer and the second-hottest ever.

The high temperatures in the early summer were preceded by low rainfall in May across Scotland (<50% of 1981–2010 average), with average to low rainfall in June and July (Met Office 2019). During the hottest 5 d period (Tx5x) in late June, a high-pressure system was located over the Northern UK and the North Sea (figures 1(b); S1), causing high temperatures (figure 1(b)) and sunshine (>150% of 1981–2010 average of sunshine duration; Kendon *et al* 2019) especially around the Irish Sea.

3.2. How much has anthropogenic forcing changed the risk of extreme temperatures?

We performed an event attribution study using the CMIP6-generation global climate model HadGEM3-A, and compared the results with those from the very

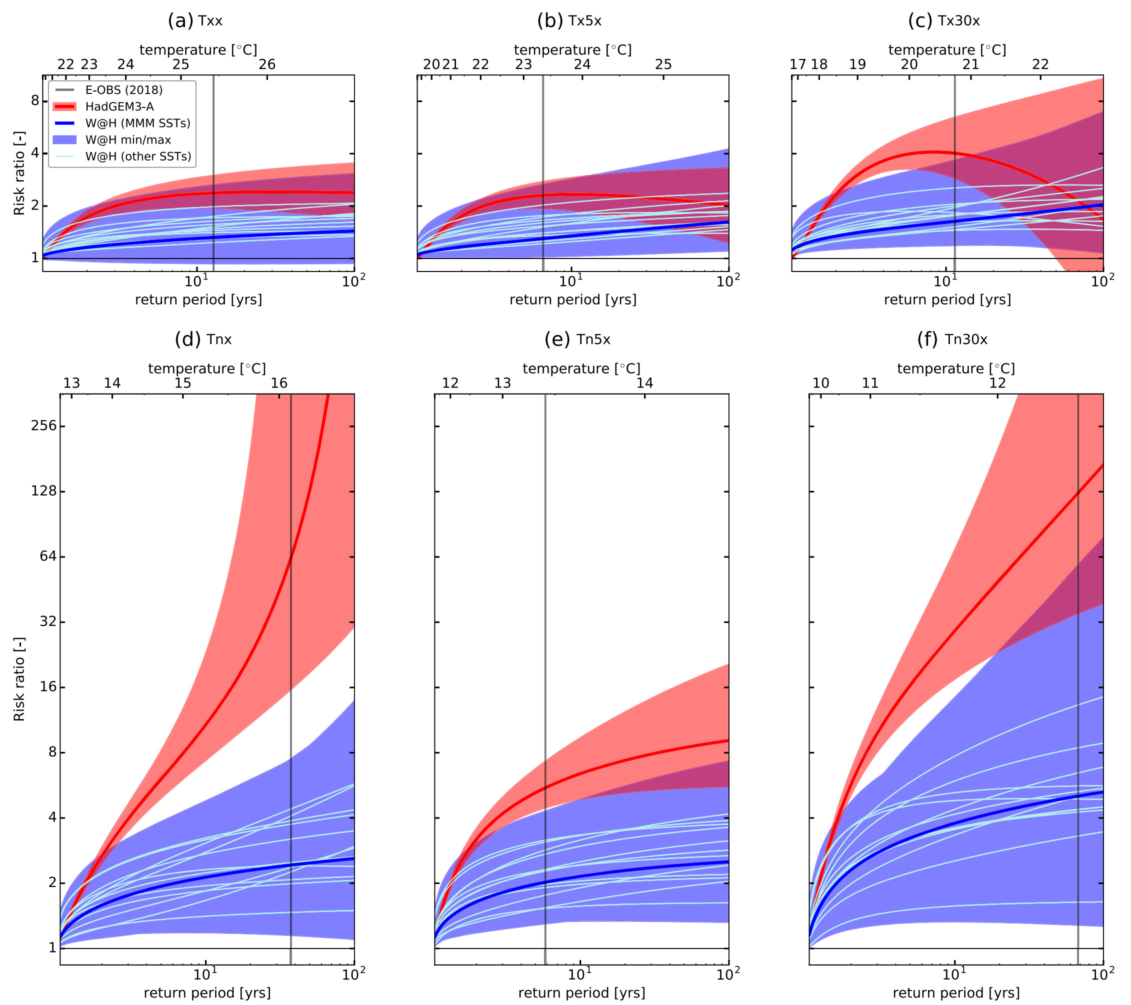

Figure 2. Risk ratios for high-temperature extremes over the NBI due to anthropogenic forcings. The summer maxima of (a), (d) daily, (b,e) 5 d mean, and (c), (f) 30 d mean of (a)–(c) maximum temperature and (d)–(f) minimum temperature are shown. The *x* axes show the (top) temperature index values and the (bottom) corresponding return periods in the 1950–2018 observations (figure S2), with the value of the 2018 observations indicated by the vertical grey line. The (lines) best estimates for the risk ratios for the (red) HadGEM3-A model and (blues) the W@H system for different SST patterns are shown. The W@H experiment with the MMM SST pattern is highlighted with thick blue lines, while the other experiments are shown as thin, faint blue lines. Shadings represent uncertainty bounds (90% confidence) for HadGEM3-A (red) and minimum and maximum of the respective bounds from each individual W@H SST experiment (blue).

large ensemble W@H system (figure 2). Both models show that anthropogenic forcings and the ensuing SST warming and sea-ice reductions have made all extreme temperature indices over the NBI more likely (risk ratios >1) at the 90% confidence level over many return times.

The magnitude of these risk ratios varies substantially between both models, with the estimates derived from HadGEM3-A consistently higher than those from W@H; for Tnx and Tn30x, which were particularly rare in 2018 (section 3.1 and figure S2), the 90% confidence ranges do not even overlap (figure 2). Model validation is difficult since the common historical period, for which both W@H data (1986–2017) and HadGEM3-A data (1960–2013) are available, is only 24 years. This is very short, causing uncertainties in the observed distributions of temperature indices to be large. We tentatively conclude, however, that W@H has larger biases than HadGEM3-A, both in the mean (which we correct for) and the tail of the distribution (figure 3)[6]. This suggests that the higher risk ratios derived from HadGEM3-A might be more realistic than the lower ones from W@H, which gives a conservative estimate. For multi-day daytime extremes in the HadGEM3-A ensemble the uncertainty range widens and the best estimates of the risk ratio fall for return periods above 10 years (figures 2(b)–(c)). This is because the HadGEM3-A distribution is narrow and rare events are far in the tail of the distribution (figure S3) for which few events are simulated giving large uncertainties. For W@H, this is less of an issue due to the wider distribution and larger ensemble size.

[6] The warm bias in W@H is thought to be partly related to land-surface biases (Guillod *et al* 2017) that are a common issue also in other models (Davin *et al* 2016, Donat *et al* 2018, Ukkola *et al* 2018). The W@H bias is smallest over Britain and Ireland than over any other European region (Guillod *et al* 2017).

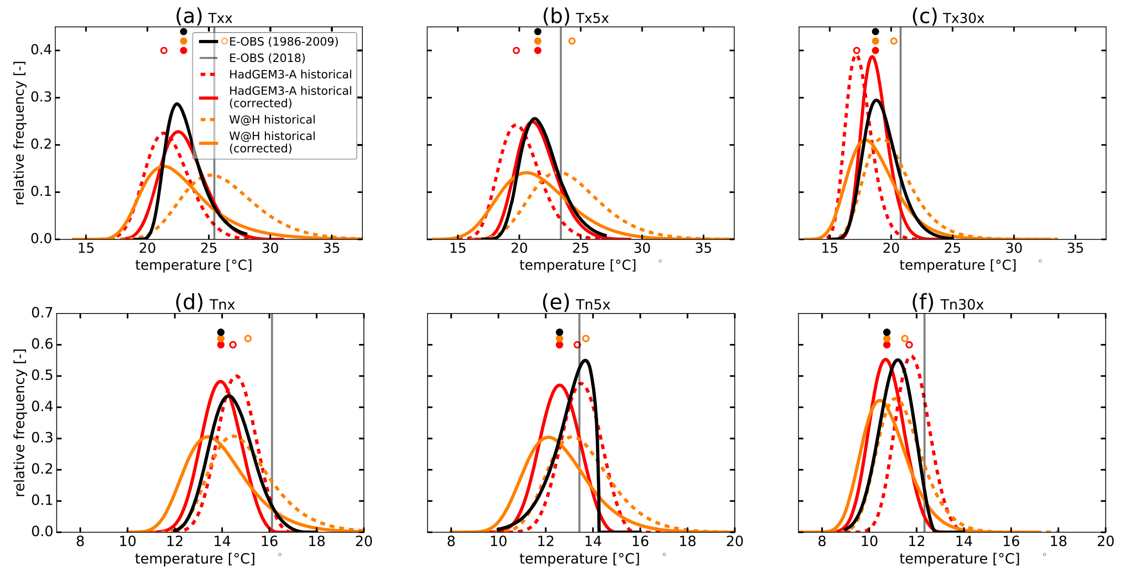

Figure 3. Simulated and observed distributions of high-temperature extremes over the NBI for 1986–2009. Shown are the GEV fits to the simulated distributions from the (red) HadGEM3-A model and the (orange) W@H system before (dashed line) and after (solid line) correcting their means with respect to that from (black) E-OBS observations. The means before and after correction are shown as empty and filled circles, respectively. The observed 2018 values are shown as vertical grey lines.

Compared with the inter-model differences, the effect of assuming different patterns of SST change since 1850 in the W@H model on the risk ratios is smaller, but still considerable especially for long periods of warm nights (figure 2(f)). Similar to Sparrow *et al* (2018), results differ in the first order because of the different global-mean SST changes rather than pattern differences (figure 2), with the experiments that assume a larger global-mean change since pre-industrial times showing higher risk ratios (not shown).

Regardless of model and SST pattern, the risk ratios for the nighttime extremes are higher than those for the daytime extremes. For the hottest single day, 5 d mean, and 30 d mean, the best estimates of the risk ratios range within 1.2–2.4, 1.2–2.3, and 1.4–4.0 respectively (figures 2(a)–(c)). For the corresponding nighttime extremes, the ranges are 1.5- >50, 1.5–5.5, and 1.6- >50 (figures 2(d)–(f)).

In addition to anthropogenic forcings, natural climate variability might have contributed to the observed 2018 temperature extremes. This is tested by comparing results from the ensembles forced with SST and SIC patterns from 2017 rather than 2018. For daytime extremes the distributions are similar with no significant differences between the two ensembles (risk ratio uncertainty range includes 1 and best estimate is close to 1; figures S4(a)–(c)). For short-duration nighttime extremes (Tnx and Tn5x) the risk is significantly larger in 2018 than in 2017 at all timescales, but not for Tn30x representing longer periods (figures S4(d)–(f)). Both 2017 and 2018 were neutral in terms of El-Niño-Southern Oscillation (Blunden 2016, World Meteorological Organization (WMO), 2019), though they differed in their Atlantic SST patterns and sea ice: In addition to anomalously cold SSTs south of Greenland in both June 2017 (NCEI 2019a) and 2018 (NCEI 2019b), June 2018 was also cool in the eastern sub-tropical Atlantic, while June 2017 experienced warm anomalies more uniformly. More detailed analysis is needed to understand the mechanisms by which year-to-year SST variability can drive the changes in the risk of nighttime extremes.

3.3. Which impacts occurred in Scotland?

Our assessment provides a nuanced picture of the impacts of the hot weather experienced in Scotland in summer 2018. We coded 194 instances of negative impacts, of which 55 were alleviated (code N2), while 68 constituted minor and 71 major negative impacts (codes N1 and N3, respectively). There were considerably fewer positive impacts reported (52 coded): 27 minor, 19 major, and 6 unexploited positive impacts (P1, P2 and P3 respectively). We summarise the results below, and provide the full detail of both media analysis and interviews in the SI (tables S1 and S2).

There was extensive media coverage of people enjoying the warm weather with busy beaches, parks, and swimming pools and an increase in staycations (P1, P2). This provided an associated boosts in the sale of garden furniture, barbecues, and fans, and benefited outdoor recreation businesses and ice cream sales (P1, P3). Meanwhile, foreign holiday operators and indoor recreation businesses suffered (N1), as did fashion retailers who reported profit drops due to lowers sales of coats and jumpers (N1). Blue algae prevented outdoor swimming in some lochs[7] (N1) and there were negative impacts related to increases in pests (wasps, jelly fish, mosquitoes; N1), while there was a reported drop in midge and tick numbers (P1).

Rural businesses had difficulties coping with the hot weather, with many reports of feed shortages and the early sale of livestock at unfavourable prices (N3); lower pea, broccoli, potato and cauliflower yields due to water shortages and pests (N3); and soft fruit ripening too quickly and left to rot unpicked (N3), in part due to a lack of available labour (P2). Some negative impacts could also be avoided, e.g. by increasing supplementary feed (N2), while in wetter parts of Scotland the warmer and drier weather resulted in an excellent grass harvest for silage (P3). A larger number of wild fires caused damage to newly planted trees and local biodiversity (N1, N3) but could generally be contained by sustained intervention (N2). There was however a significant impact on grouse numbers due to lack of food, water, and weak health, and on wild salmon and trout due to oxygen depletion affecting shooting and angling businesses (N3). There were also reports of losses in the seafood sector with harvests stopped several weeks early due to early spawning of mussels and oysters (N3).

The warm weather and drought led to a reported 30% increase in water demand, and it required major effort from the national utility company to maintain supply by increasing pumping from reservoirs, distributing water with 30 tankers, and encouraging consumers to lower consumption (N2). Nevertheless, private water supplies ran dry causing discomfort to many (N1) and significant disruption to several businesses (N3). There were also reports of whisky distilleries closing for longer periods than normal due to low stream flow in rivers used for cooling (N3).

The weather also directly affected infrastructure and the built environment. There are many reports of complaints from workers, students, and patients that buildings were too warm (N1), and of higher electricity bills due to cooling (N2, N1). The roof of the Glasgow Science Centre and asphalt on roads around the country were reportedly melting (N1) and there was disruption to rail services due to buckling rails and signalling faults (N1). Rails were painted white to reduce heating and trains had to run at lower speeds to maintain a reduced service (N2).

Finally, the extended warm and dry weather also impacted on Scotlands cultural heritage. Dry soils and low water levels revealed previously unrecorded archaeology, including ancient settlements, burial sites, and waterways (P3), and the remains of a stone drovers' bridge was revealed when levels of a 60 year old reservoir dropped. There were also concerns that Scottish children would not be able to play the traditional game of conkers in the autumn due to heat stress preventing fruiting of horse chestnut trees (N1).

[7] Lakes.

While these findings confirm a diversity of heatwave impacts, the information available through our rapid assessment does not allow us to distinguish to what extent these impacts are due to extreme temperature alone. For example, many of the most negative impacts, e.g. on agriculture and water supply, were exacerbated by low rainfall throughout spring and summer. Nevertheless, the assessment provides strong evidence of negative impacts, along with examples of positive impacts—many related to recreation and retail—and existing adaptive capacity to cope with extreme temperatures. Furthermore, several of the interviewed stakeholders suggested increased adaptation needs if more than one summer with 2018 temperatures occurred in a row.

3.4. How likely are these temperatures in the future?

We assess the relevance of these impacts for adaptation to *future* climate change using the UK climate projections UKCP09 and UKCP18. Rather than extrapolating the impacts to events with even higher temperatures and/or a longer duration, we focus on the projected change in frequency of summers with 2018 temperatures. Both projections agree on an increase in the likelihood of all temperature extremes (figure 4).

There are substantial differences between the two projection datasets, with UKCP18 consistently showing higher likelihoods than UKCP09 from about 2040. A comparison of projected summer temperature change over Northern Scotland by Lowe *et al* (2019) suggests that these might be explained to similar extents by the different models and emission scenarios (see Section 2). With UKCP09 based on the same model as W@H, its smaller projected probabilities for 2020are consistent with the lower risk ratios derived for W@H (section 3.2); and the UKCP09's PPE members, representing variants of the model, tend to also have larger biases than the UKCP18 ones with distributions wider than observed in 1986–2009 (not shown).

Regardless of dataset and extreme index, the projections show a substantial increase in the likelihood of 2018 temperatures between the present day and 2050. By 2050, two out of three summers are projected to have at least one 5 and 30 d event with nighttime temperatures higher than in 2018, and one out of three summers at least one 1 and 5 d event with such daytime temperatures. Towards the end of the century, every summer might have extremes as hot as in 2018; for nighttime extremes, this could be reached by 2080.

4. Discussion and conclusion

In summer 2018 Scotland experienced anomalously high temperatures, and a range of impacts of this *heatwave* were reported by news media. This study

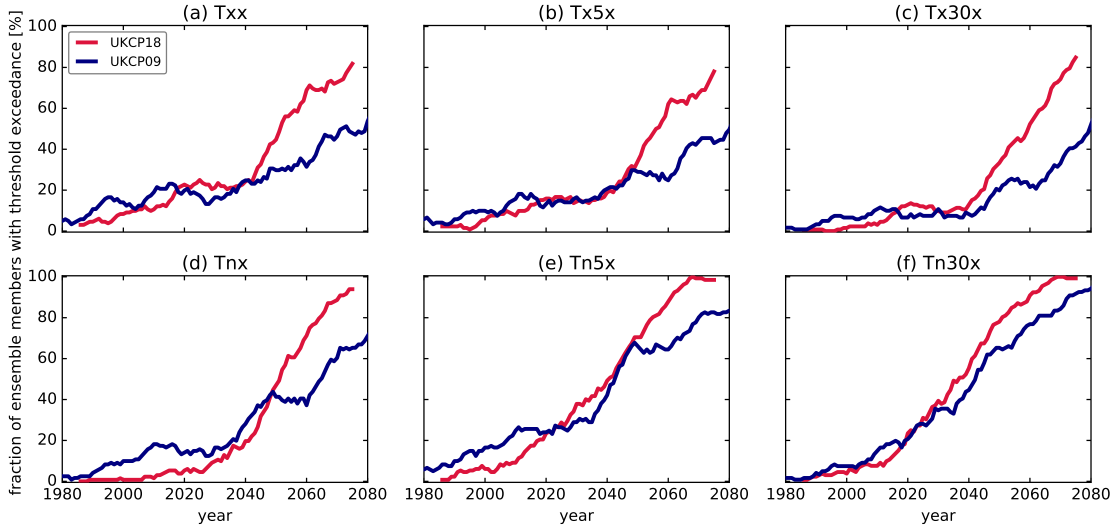

Figure 4. Projected likelihood per year of temperature extremes over the NBI hotter than those observed in 2018. Shown are the fractions of ensemble members from the (red) UKCP18 and (blue) UKCP09 regional perturbed physics ensembles that after bias correction are high or higher than the observed 2018 values of the extreme indices (abbreviations as in figure 3) as 11 year running means. This is interpreted as the likelihood of a summer with at least one period (lasting 1, 5, or 30 d) with temperatures as high or higher as in 2018.

places the 2018 heatwave in the context of past, present, and projected future climate, and provides a rapid but comprehensive analysis of the heatwave impacts to understand the need for Scotland—as a climatologically colder country—to invest in adaption measures to cope with high-temperature extremes.

The observed hottest day, 5 d, and 30 d period of 2018 and the 5 d period with the warmest nights averaged over the Northern British Isles (NBI) corresponded to 1950–2018 return periods between 5 and 15 years. The warmest night and the 30 d period with the warmest nights were more unusual with return periods of more than 30 years. The Eskdalemuir station measured its highest temperature on record, and in population centres such as Glasgow, urban heat island effects will likely have increased nighttime temperatures, too. It is unclear whether temperature thresholds that might be relevant for health impacts were locally crossed. An open question remains as to whether significant changes in percentile thresholds, as assessed commonly in scientific studies (Seneviratne *et al* 2012), are meaningful in terms of impacts in colder countries such as Scotland. Absolute temperature thresholds that seem meaningful based on impacts in other parts of the UK with similar infrastructure (e.g. South East England), are historically too rare to allow an assessment of the anthropogenic contribution to changes in their likelihood in colder Scotland.

Anthropogenic climate change has made all high-temperature extremes more likely. Higher risk ratios were found for experiments from the CMIP6-generation global climate model HadGEM3-A compared those from the very large ensemble weather@home. From larger biases in the simulated distribution during 1986–2009, we tentatively concluded that the higher risk ratios from HadGEM3-A might be more realistic, while the W@H experiments provide a conservative estimate. Compared to the inter-model differences, the effect of assuming different SST and sea-ice pattern change since pre-industrial times was found to be of secondary importance. The risk ratios from both models were higher for nighttime than for daytime extremes. While the reasons for this are not clear yet, possibly larger changes in nighttime extremes -as also visible in the future projections shown here- might have to be considered in adaptation planning especially in urban areas, where the effectiveness of typical countermeasures like the introduction of high-albedo materials or tree canopy (Stone *et al* 2012, Seto *et al* 2014, Emmanuel and Loconsole 2015) depends on daytime temperatures (e.g. Imran *et al* 2019).

These findings are based on model simulations that include a variety of anthropogenic changes since pre-industrial times; we have not disentangled the contribution from various forcings, nor whether the attributed contribution is just by means of a shift to higher temperatures or due to other factors, too. Those other factors could include an anthropogenic impact on the frequency of circulation patterns that favour higher temperatures over the NBI. The circulation can itself be considered a driver of temperature variations including extremes—our comparison with simulations for 2017 instead of 2018 suggested that higher short-duration nighttime extremes were more likely in 2018, which may indicate an additional role for natural climate variability. A more thorough analysis of this was beyond the scope of the study, but a follow-up study investigating potential changes in the dynamic drivers of temperature extremes over the region is underway. Besides, there may be other non-anthropogenic drivers that warrant further investigation.

The assessment of observed impacts of the 2018 heatwave provides a nuanced picture of impacts across sectors. Major negative impacts were identified, especially on rural sectors, while transport and water infrastructure just about alleviated most impacts by implementing costly special measures to avoid significant consequences. Unsurprisingly, there was widespread media reporting of positive impacts related to outdoor recreation and related retail opportunities (e.g. barbecues and ice creams). The media coverage is, however, likely to have inherent biases, and may over-represent major impacts, as they are considered more newsworthy. It should also be noted that the observed impacts are not caused by temperature extremes in isolation, and that for some sectors dry weather throughout spring and summer has exacerbated the observed impacts (e.g. due to dry soils and lower water levels). Overall, these results suggest that despite widespread disturbances, Scotland could cope with the impacts of the 2018 heatwave.

However, given the substantial increased in the likelihood of future temperature extremes similar to the 2018 heatwave (figure 4), it would be wrong to suggest that Scotland should ignore extreme temperatures in its adaptation planning. Multiple interviewed stakeholder noted that repeated summers with extreme temperatures would greatly exacerbate negative impacts, and it is unclear from our analysis how close different sectors were to more severe impacts. Furthermore, there are many lessons to be learned from the negative impacts—and the costs of alleviating impacts—to conclude that despite its cool climate, extreme temperatures are important to consider for climate change adaptation in Scotland.

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Data availability statement

The data that support the findings of this study are either openly available or available from the corresponding author upon reasonable request as follows. All observational and reanalysis as well as UKCP model data are available from the sources referenced in sections 2.1 and 2.2. The W@H data are available upon request from the authors. HadGEM3-A data are available from CEDA and from the C20C+ project. Full transcripts of the interviews can also be made available in a form that preserves anonymity of the interviewees upon request.

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