Climate Risk Management 31 (2021) 100265

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Changing climate risk in the UK: A multi-sectoral analysis using policy-relevant indicators

N.W. Arnell [a,*], A.L. Kay [b], A. Freeman [a], A.C. Rudd [b], J.A. Lowe [c,d]

[a] *Department of Meteorology, University of Reading, United Kingdom*
[b] *UK Centre for Ecology and Hydrology (UKCEH), Wallingford, Oxfordshire, United Kingdom*
[c] *Met Office Hadley Centre, Exeter, United Kingdom*
[d] *Priestley International Centre for Climate, University of Leeds, United Kingdom*

ARTICLE INFO

Keywords:
Climate risk
Heatwaves
Floods
Droughts
Wildfire
Adaptation
Resilience
UKCP18

ABSTRACT

This paper presents a consistent series of policy-relevant indicators of changing climate hazards and resources for the UK, spanning the health, transport, energy, agriculture, flood and water sectors and based on UKCP18 climate projections. In the absence of explicit adaptation, risks will increase across the whole of the UK, but at different rates and from different starting values in different regions. The likelihood of heat extremes affecting health, the road and rail network and crop growth will increase very markedly. Agricultural and hydrological drought risks increase across the UK, as does wildfire danger. River flood risk increases particularly in the north and west. Demand for cooling energy will increase, but demand for heating energy will decline. Crop growing degree days will increase, benefiting the production of perennial crops. In general, the risks associated with high temperature extremes will increase the most in warmer southern and eastern England, but the rate of increase from a lower base may be greater further north and west. Reducing emissions reduces risks in the long term but has little effect over the next two or three decades.

The results provide evidence to support the development of national and local climate and resilience policy. Measures to enhance resilience are needed alongside policies to achieve net zero emissions by 2050. Resilience policy should recognise the variability in change in risk across the UK, and therefore different local priorities. Explicit choices need to be made about 'worst case' emissions scenarios as they can influence strongly estimated changes in risk: the increase in risk with RCP8.5 can be considerably higher than with a pathway reaching 4 °C by 2100.

1. Introduction

The UK Parliament passed the Climate Change Act in 2008, and in 2019 the government adopted an ambitious policy of achieving net zero emissions by 2050. The UK has completed two Climate Change Risk Assessments (in 2012 and 2017: HM Government, 2012; 2017) and published two National Adaptation Programmes (in 2013 and 2018). Several sectors – including flood, water resources and ecosystems management – have developed policies to adapt to a changing climate. A series of national climate projections has been produced since 1998, with the most recent projections released in 2018 (UKCP18: Lowe et al., 2018). Around 250 local authorities have declared 'climate emergencies'.

* Corresponding author.
E-mail address: n.w.arnell@reading.ac.uk (N.W. Arnell).

https://doi.org/10.1016/j.crm.2020.100265
Received 21 August 2020; Received in revised form 8 December 2020; Accepted 14 December 2020
Available online 17 December 2020

However, in 2019 the Committee on Climate Change produced a generally critical assessment of the UK's progress towards developing a climate resilient economy and society (Committee on Climate Change, 2019). It identified a lack of coordination between government departments and a low priority given to adaptation and resilience. A sequence of 'extreme' weather events – heatwaves and wildfires in 2018 and 2019, drought in 2018 and flooding and storms in 2018, 2019 and 2020 – highlighted how the UK was exposed to the types of events which can be expected to become more frequent with climate change. Meanwhile, the UK (with Egypt) leads the international Resilience and Adaptation Call for Action launched at the 2019 UN Climate Action Summit, and is hosting the COP26 UNFCCC climate negotiations in November 2021.

There is therefore an increasing interest in the UK in strengthening climate resilience measures in government at national and local levels. This interest is matched by the private sector. The Bank of England consulted in early 2020 on a 'climate change stress test' for the financial sector. However, in order to enhance resilience to climate risk it is necessary to understand the characteristics of those risks and how they may change in the future.

Climate risk is increasingly conceptualised as a function of climate hazard and resource, exposure and vulnerability (IPCC, 2010). Exposure represents the people, livelihoods, assets and ecosystems in places that could be adversely affected by hazard or change in climate resource, whilst vulnerability characterises the propensity to suffer harm or loss. Current and future climate hazard and potential climate resource are determined by the physical climate system and global greenhouse gas emissions, but exposure and vulnerability are influenced by socio-economic changes and by adaptation policy. Future climate risk is therefore a function of both climate and socio-economic changes.

There are two broad ways of characterising the future climate risks. One is to seek to estimate the future impacts - for example in human health or economic terms – but this requires assumptions not only about how climate will change in the future but also how the economy and society will develop and adapt to climate change. The other approach calculates a series of indicators which are related to impacts and consequences but do not in themselves measure them (Vallejo, 2017; Mäkinen, et al., 2018). The European Environment Agency (2017) distinguishes between indicators representing aspects of the climate, environmental and social systems. The first two sets are general indicators of climate hazard and resource, but most of the third set reflect the combined effects of changes in hazard and resource and changes in exposure and vulnerability. However, the indicators are calculated with different data sets and climate projections, and are mostly taken from published literature. The UK Adaptation Sub-Committee (ASC) developed a set of 182 indicators covering risks and adaptation actions (Committee on Climate Change, 2015). 79 of these relate to the implementation of policy, reflecting the ASC's concerns with monitoring action on adaptation, but the rest represent climate risk (three characterise 'opportunities'): 58 characterise change in exposure and vulnerability, and 39 measure 'realised impact' in order to monitor the actual experience of climate impacts.

This paper therefore presents a series of indicators of changes in climate risk, calculated in a consistent way across the UK at a range of spatial scales, using UKCP18 climate projections. The indicators are based on measures of climate hazard and climate resource. All are either specific current triggers for policy action (such as the implementation of an adverse weather plan or release of a warning), or are proxies used by policymakers in particular sectors to assess the impact of climatic variability and change. Whilst exposure and vulnerability are not explicitly incorporated – except in some of the weightings as outlined below - most of the indicators are based on current policy-relevant thresholds or critical values. They can therefore be interpreted as indicators of climate risk in the absence of adaptation or changes in risk appetite as represented by changes in the thresholds.

There have been a number of quantitative national and regional assessments of climate change risks across the UK (Table 1), but these have all concentrated on specific sectors and have used different projections and approaches. This study therefore represents the first attempt to produce consistent indicators across sectors, using the same underlying climate data and climate projections. The paper is explicitly not an *assessment* of future climate risks in the UK: in formal risk assessment terms it is an *analysis* of risks. Risk assessment

Table 1
National-scale studies of climate change risks in the UK.

Sector	Indicators	Domain	Reference
Agriculture	Five agri-climate indicators	UK	Harding et al. (2015)
	Winter wheat yields and production	UKGreat Britain	Cho et al. (2012), Harkness et al. (2020)
	Spring barley yields	UK	Yawson et al. (2016)
	Grassland productivity	Great Britain	Qi et al. (2018)
	Potato productivity	England and Wales	Dacacche et al. (2012)
	Milk yields	Great BritainUK	Dunn et al. (2014), Fodor, et al. (2018)
	Land suitability	Scotland	Brown et al. (2011)
Transport	Temperature-related impacts on rail network	Great Britain	Palin et al. (2013)
Health	Temperature-related mortality	UK	Hajat et al. (2014), Vardoulakis et al. (2014)
	Heat waves	UK	Sanderson and Ford (2016)
Energy	Solar radiation	UK	Burnett et al. (2014)
Infrastructure	Subsidence hazard	Great Britain	Pritchard et al. (2015)
Water	Seasonal river flows	Great Britain	Prudhomme et al. (2012)
	Water resource availability	UK	HR Wallingford (2015)
	Groundwater recharge under barley crops	UK	Yawson et al., (2019)
	Drought indicators	Great Britain	Rudd et al. (2019)
	River flood indicators	Great Britain	Bell et al. (2016)
	River flood indicators	UK	Sayers and Partners (2015)

These studies all produce national-scale maps or totals, mostly UKCP09 climate projections.

involves evaluating risks against specified criteria. These depend on context and need to be defined by stakeholders: they may vary regionally. However, the results can be interpreted by users in terms of critical change thresholds to inform an assessment.

Different users have different requirements for climate risk information (Table 2). High level climate policy users are concerned with developing national and international climate mitigation policy, and for assessing the priorities for adaptation and resilience policy against other policies. This group needs information on indicators which map onto high-level priorities across a range of sectors, for different emissions pathways, at a coarse spatial resolution and highlighting long-term trends. Most of the few studies of the effect of reductions in emissions on risks (e.g. Arnell et al., 2013; O'Neill et al., 2018) have taken a global perspective, and there is currently little information on how international climate policy would affect risks in the UK. Users developing sector adaptation and resilience policy and guidance require indicators tailored to sector requirements and mapping directly onto policy issues. These users will need a range of indicators for a sector, across multiple locations and regions, and at a spatial resolution that is influenced by variability in the exposure of the sector to change. Local authority users use climate indicators to help set priorities for local climate policy and to highlight the significance to their area of climate change (for example in the context of a declaration of climate emergency). A fourth user community is interested in monitoring climate trends, and here the primary requirements are for indicators that can be calculated with both observed and projected data, and that highlight long-term trends rather than short-term variability. A fifth community is concerned with developing specific adaptation and resilience measures for specific locations.

This paper focuses on high level climate policy users, concentrating on a subset of indicators calculated as part of a more comprehensive analysis. It provides information about the potential consequences of climate change in terms directly relevant to policymakers who are developing national and local mitigation and adaptation policies and plans. Specifically, the paper addresses two questions:

(i) what are the risks with high emissions through the 21st century and across sectors, and how do they vary across the UK?
(ii) what are the effects of reductions in global greenhouse gas emissions on risks in the UK?

The paper concludes by drawing implications for the development of climate resilience policy in the UK.

2. Methods, indicators and scenarios

2.1. Overview

The approach involves the calculation of a series of policy-relevant indicators of climate risk using UKCP18 climate projections. These indicators were assembled through discussions with stakeholders and from the literature. It uses the delta method to apply different types of UKCP18 climate projections to observed HadUK-Grid climate data (Met Office, 2018a, 2018b; Hollis et al., 2019), and therefore the natural variability is derived from the observational period. The reference period against which climate change is compared is 1981–2010, and all indicators are expressed as averages or likelihoods over a 30-year period. The indicators are calculated

Table 2
Policy areas and requirements for climate risk indicators.

Policy area	Policy topics	Indicator requirements
High level climate policy	• Climate mitigation policy • Prioritisation of adaptation and resilience	• Relevant to high-level policy priorities • Multi-sectoral • Different emissions pathways • Coarse spatial resolution • High-level trends • Long time horizon
Sector adaptation and resilience policy	• Adaptation and resilience strategy • High-level guidance	• Relevant to sector priorities • Sector-specific indicators • Variable spatial resolution, at multiple locations • "worst-case" projections • Variability and trend • Spatially-coherent projections of indicators
Local authority climate policy	• Prioritisation of climate change • Local adaptation and resilience policy	• Relevant to local priorities • Multi-sectoral • Fine spatial resolution • Different emissions pathways
Monitoring climate change	• Monitoring trends and progress	• Relevant to exposed sectors • Measurable • Can compare observations with projections • Identifies long-term trends
Specific adaptation and resilience measures	• Design of site-specific measures	• Directly-related to design parameters • Fine spatial resolution • "worst-case" and/or "best-case" projections

at a fine spatial resolution (1 × 1 km or 12 × 12 km) and then averaged to the regional and national scales. This section explains the indicators and methods used.

2.2. Indicators of climate risk

Climate presents both a hazard and a resource. 'Climate hazard' here means the occurrence of some discrete event which has damaging or adverse consequences. Examples include hot and cold spells, floods, droughts, and windstorms. 'Climate resource' is a characteristic of climate that allows or constrains some activity. Examples include the seasonal cycle in temperature affecting heating and cooling energy demands and the seasonal cycle in temperature and rainfall affecting crop growth. Climate risk therefore represents both the occurrence of discrete hazardous events and the potential for the climate resource to vary from expected values.

In general terms, seven potential characteristics of climate hazard or resource can determine climate risk: magnitude, duration, frequency, likelihood, variability, timing, and spatial extent (Table 3). The first six can be calculated at a point and then averaged or summed over an area. The seventh is explicitly an aggregation over an area. This framing can be used to inform the development and selection of indicators.

These characteristics of hazard and resource are frequently expressed in terms of thresholds, but in two different ways. One way incorporates a threshold into the definition of the hazard or resource – for example a temperature threshold used to define a growing season or accumulated temperatures. Such a threshold may be physically-based, or may be a policy or practical choice (for example the comfort temperature thresholds used to define heating degree days). The other way defines a *critical* threshold – beyond which there is some challenging event - and expresses hazard or resource in terms of exceedance of this threshold. Such a critical threshold could be physically-based but is usually based on some operational or policy target, such as an alert level. Critical thresholds discretise impacts, although in practice there is often a continuous relationship between climate and impact. A third type of threshold defines the significance or importance of a particular impact or change in impact. This type of 'critical significance' threshold must be defined by users, based on their tolerance of risk and change in risk. For example, a health care manager may believe that a 20% chance of a heatwave is tolerable, but that if the likelihood rises above 20% then plans and measures would need to be revised. Similarly, an increase in cooling degree days of 50 might represent a threshold triggering a change in building standards. These critical significance thresholds will depend on local context, and are not considered in this analysis.

Table 4 summarises the indicators of changes in hazard and resource presented in this paper (with more detailed information provided in Supplementary Material). These are a subset of a wider set, selected to characterise different dimensions of climate change risk. The indicators do not necessarily map directly onto actual impact because most are based on critical policy or alert thresholds and therefore discretise impacts. In all cases, it is assumed here that these critical thresholds do not change over time. In practice, adaptation and other policy changes will mean that these thresholds will change.

Two indicators represent the effects of climate change on health and well-being. One is based on the heat-health alert temperature thresholds which initiate the Heatwave Plan for England (PHE, 2019; Sanderson and Ford, 2016). This plan specifies emergency measures which are implemented in the health and social care service on receipt of a heat-health alert warning to address the health risks associated with excessive heat. The 'amber alert' temperature thresholds vary across England. Different policies apply in Wales, Scotland and Northern Ireland, so there are no specific temperature thresholds for these regions and here values for neighbouring regions were used as an indication of risk. The 'Met Office heatwave' (McCarthy et al., 2019) is primarily designed for public communications purposes, and again thresholds vary by county across the UK from 25 to 28 °C. Both of these indicators can be expressed as numbers of events per year ('frequency'), as length of heatwave ('duration'), or indeed in terms of dates, but here are expressed as the annual likelihood of experiencing at least one event. The consequences of high temperatures for mortality and ill-health vary continuously (see e.g. Vardoulakis et al., 2014), and in practice adverse effects will occur at temperatures below the critical thresholds used in the heat-health and heatwave alerts.

The two energy indicators are proxies for heating and cooling energy demand, based on thresholds used in building management (Azevedo et al., 2015; Carbon Trust, 2012; Wood et al., 2015). Demands are related to heating and cooling degree days, but the precise relationship depends on building characteristics. The indicators are calculated using the same algorithms as in the Met Office annual State of the Climate Report (Kendon, M et al., 2019), with thresholds of 15.5 °C and 22 °C for heating and cooling degree days respectively.

Table 3
A categorisation of potential climate risk indicators.

Characteristic	Description	Example
Magnitude	Size of an event or variable	Average annual maximum temperatureAnnual heating degree daysT-year return period flood magnitude
Duration	Length of event or the time conditions are within a specific range	Growing season durationLength of heatwave
Frequency	Number of times an event occurs	Average annual number of days above X°C
Likelihood	The chance of an event or condition occurring	Annual likelihood of having a heatwave
Variability	Variation in the magnitude or frequency of an event or condition from year to year	Standard deviation of the number of days above X°C
Timing	When an event or condition occurs	Start of growing season
Extent	Area(s) affected by an event or condition	Proportion of region affected by a heatwave

Table 4
Summary of climate risk indicators.

Indicator	Definition	Reference	Specific metric used	Regional weighting
Health and well-being				
Activation of Heatwave Plan for England (“Amber alerts”)	Maximum and minimum temperatures above region-specific thresholds for at least two days	PHE (2019)	Annual likelihood of at least one alert threshold reached	2011 population
Met Office heatwave	Maximum temperature above region-specific thresholds for at least three days	McCarthy et al. (2019)	Annual likelihood of at least one heatwave threshold reached	2011 population
Energy use				
Heating degree days	Heating degree days relative to 15.5 °C	Carbon Trust (2012), Azevedo et al. (2015)	Average annual value	2011 population
Cooling degree days	Cooling degree days relative to 22 °C	Azevedo et al. (2015)	Average annual value	2011 population
Transport				
Transport network risk: 26 °C	Maximum temperature above 26 °C	Chapman (2015), RSSB (2013)	Mean number of days/year	Length of railway network
Rail network risk: 30 °C	Maximum temperature above 30 °C	RSSB (2013), Palin et al. (2013)	Mean number of days/year	Length of railway network
Railway adverse weather days	Max temperature above 25 °C, or min temperature below −3°C, or daily rainfall > 40 mm, or snow depth > 50 mm.	Network Rail (2020a)	Mean number of days/year	Length of railway network
Agriculture				
Growing degree days	Sum of degrees above 5.6 °C during the thermal growing season	Rivington et al. (2013)	Average annual value	Area of cropland and improved grassland
Wheat heat stress during anthesis	Days between 1 May and 15 June with max temperature>32 °C	Jones et al. (2020)	Annual likelihood of at least one day	Area of cropland
Agricultural drought risk	Time with the Standardised Precipitation Evaporation Index (SPEI) < -1.5. SPEI calculated over 6 months	Parsons et al. (2019)	Proportion of time	Area of cropland and improved grassland
Wildfire				
MOFSI ‘exceptional’ fire danger	Days with the Met Office Fire Severity Index greater than the ‘exceptional danger’ threshold		Mean number of days/year	Area of heathland, bog, marsh and grassland
FFMC > 99th percentile	Days with the FFMC component of MOFSI greater than the reference period 99th percentile	de Jong et al. (2016)	Mean number of days/year	Area of heathland, bog, marsh and grassland
Hydrological				
Severe hydrological drought	Time with the Standardised Streamflow Index (SSI) < -1.5, accumulated over 12 months	Barker et al. (2015), Svensson et al. (2017)	Proportion of time	Not weighted
Flood magnitude	Magnitude of the 10-year return period peak flow		Annual likelihood of experiencing the 1981–2010 10-year peak flow	Not weighted

The transport indicators are based on critical thresholds for road and railway infrastructure and performance (Chapman, 2015; Palin et al., 2013; RSSB, 2013). Asphalt road surfaces begin to melt and suffer from rutting and melting at surface temperatures above 50 °C. The relationship between road temperature and air temperature is complex, and depends on incoming radiation, windspeed and surface properties, but it is not uncommon for road surface temperatures to exceed 50 °C when air temperature exceeds 25 °C (Chapman, 2015). Empirical evidence over the period 2008 to 2011 (RSSB, 2013) shows that the number of daily incidents relating to rail track buckling and signalling increase ‘very significantly’ when daily maximum temperatures exceed 26 °C, and incidents relating to rail power supplies and warning systems increase ‘very significantly’ above 30 °C. When rail track temperatures exceed critical thresholds, specific operational measures – such as speed restrictions - are introduced. These critical (air) temperatures vary between 21 °C and 35 °C depending on track condition (Palin et al., 2013). Given this wide range in critical infrastructure threshold for the transport sector, the analysis here concentrates on two illustrative thresholds – daily maximum temperature above 26 °C and 30 °C – and presents the average number of days per year exceeding these thresholds. Bad weather not only affects transport infrastructure, but also affects operations. Rail operating companies are required to meet performance and punctuality standards, but these standards are slightly relaxed on days with ‘bad’ weather. Network Rail operating standards (Network Rail, 2020a) define thresholds for adverse or extreme wind, rain, temperature and snow (Supplementary Material), and ‘adverse weather days’ are here counted as the number of days per year when one or more of the adverse thresholds are exceeded.

The three agri-climate indicators (Arnell and Freeman, submitted) are proxies for crop and livestock productivity (Rivington et al., 2013; Harding et al., 2015; Parsons et al., 2019). Growing degree days are a proxy for the productivity of permanent grassland and the potential for annual crops. Growing degree days are calculated from daily average temperature with a threshold of 5.6 °C using the same algorithms as in Kendon, M et al. (2019), and the growing season starts once temperatures have exceeded 5.6 °C for at least five days. Days with high temperatures can limit growth (and at the extreme kill plants) and cause discomfort to livestock, but the critical thresholds vary between crops and animals and vary through the year. For example, the prevalence of one particular (costly) parasitic infection of sheep increases linearly with the number of days above 9 °C, and milk yields in dairy cattle fall if maximum temperatures exceed around 23 °C (Jones, et al., 2020) – assuming typical values for relative humidity). Temperatures of between 32 and 35 °C during the flowering and grain filling period lead to reductions in wheat yield (Jones, et al., 2020). The indicator used here is the annual likelihood of having at least one day between 1 May and 15 June with maximum temperatures>32 °C, representing heat stress during the critical flowering period (anthesis) for wheat (Jones, et al., 2020). Drought is characterised by the Standardised Precipitation-Evaporation Index (SPEI), calculated over a six-month accumulation period: Parsons et al. (2019) showed that this correlated well with drought impacts on agriculture in the UK. The drought indicator is the proportion of time that $SPEI_6$ is below −1.5. By definition, this happens around 6.7% of the time during the 1981–2010 reference period. Arnell and Freeman (submitted) also calculate other agri-climate indicators characterising change in the climate resource for agriculture (growing season length, potential soil moisture deficit), change in hazard during the growing season (low and high temperatures and drought), and change in operations (soil workability).

Wildfire hazard (Arnell et al., 2021) is characterised by two indicators of fire danger based on a version of the Met Office Fire Severity System (MOFSI), which is itself based on the Canadian Forest Fire Weather Index System, and which calculates fire danger from meteorological data. This model was developed for Canadian conditions but represents fire danger in the UK well (Glaves, et al., 2020), and is used in practice to set restrictions on public access to open access land and to issue public fire danger warnings via the Met Office web site. One indicator is the average number of days per year with an ‘exceptional’ fire danger warning. This is very similar to the exceptional warnings issued through the European Union Forest Fire Information System (EFFIS). The other is the average number of days with the Fine Fuel Moisture Code (FFMC) component of MOFSI greater than the 99th percentile calculated over the period 1981–2010. This threshold varies across the UK, and de Jong et al. (2016) argue that this provides a more appropriate representation of spatial variability in fire danger. Arnell et al. (2021) present another four wildfire indicators, showing results in terms of both days per year (‘frequency’) and chance of occurrence (‘likelihood’).

The final two indicators are proxies for the effect of climate change on river flood risk and on water resources drought (see Kay et al., 2020; Kay et al., submitted for more indicators). The flood risk at a place depends on the level of protection provided by flood defences. The indicator here is the likelihood of experiencing a flood greater than the reference period 10-year flood. Most communities and infrastructure are protected to a higher level, so this is a proxy for the occurrence of flood events rather than the occurrence of flood loss. However, the proportional *change* in likelihood of the 10-year event is a good approximation to the change in likelihood of damaging events. Water resource drought frequency is also strongly determined by water management measures in place and local operating procedures. The Standardised Streamflow Index (Barker, et al., 2015; Svensson et al., 2017) is therefore a proxy for water resources drought frequency. These indicators are calculated across Great Britain using the UKCEH Grid-to-Grid model (G2G: (Bell et al., 2009), a national-scale rainfall-runoff and routing model that runs on a 1 km grid across Great Britain, using high-resolution spatial data bases. G2G is computationally intensive, so was only run for a subset of the climate projections and was not run for Northern Ireland. A simpler hydrological model (Gosling and Arnell, 2010) was therefore run at a coarser spatial resolution with all projections: this reproduced well the G2G seasonal runoff changes, but not changes in high and low flow extremes.

Although the study calculates indicators relevant to a wide range of sectors, there are some important omissions. The indicators do not necessarily represent the most important dimensions of impact in a sector, and they are not equally important. There are no indicators directly relevant to the management of the natural environment, or to the management of the coastal zone (sea level rise is excluded). There are no indicators relating to extreme storms and gales, because there are no quantitative estimates for these in the UKCP18 projections. There are no indicators directly related to extreme short-duration precipitation (relevant for example for surface water flooding and the transport network) because the study applies monthly precipitation changes to daily data and does not therefore account for potential additional increases in the intensity of heavy rainfall (the transport ‘adverse weather days’ indicator includes extreme daily precipitation totals, but in practice is most influenced by temperature extremes). The hydrological and wildfire indicators used here are relatively insensitive to assumed differences in changes in rainfall intensity with different magnitudes, because they are effectively based on accumulated rainfall over time. Finally, the study does not calculate indicators of compound or linked events, such as the chance of wildfires occurring during heatwaves in a drought.

2.3. Climate scenarios

2.3.1. Observed climate data

All but the high-resolution hydrological indicators used the HadUK-Grid 12 km resolution observational data set (Met Office, 2018a, 2018b; Hollis et al., 2019), supplemented by ERA5 reanalysis data (Copernicus Climate Change Service, 2017). There are 1711 12x12km observed grid cells over the UK land area. The HadUK-Grid 12 km data set includes daily minimum and maximum temperatures and rainfall up to 2018, but sunshine hours, windspeed and relative humidity are only available as monthly averages. Daily windspeed and relative humidity was therefore estimated from the ERA5 reanalysis, rescaling the ERA5 reanalysis so that the monthly mean equalled the HadUK-Grid monthly mean. Sunshine hours were interpolated linearly from the monthly to the daily resolution, maintaining the correct monthly mean. The wildfire and SPEI indicators uses potential evaporation calculated using the Penman-Monteith formula, which was calculated from temperature, relative humidity, windspeed and net radiation: net radiation was calculated from temperature, relative humidity and sunshine hours (Supplementary Material). The 12x12km gridded observed data inevitably smooth out low and high values at a point, particularly where the variation in topography is large.

The G2G hydrological model used the HadUK-Grid 1 km resolution observational dataset (Met Office, 2018b) for daily precipitation and daily minimum and maximum temperature, plus 40 km grids of monthly potential evaporation for short grass from MORECS

(Hough and Jones, 1997).

2.3.2. Climate projections

There are four strands to the UKCP18 climate projections over land: probabilistic, global, regional, and local. This study used the first three strands. The probabilistic projections (Murphy et al., 2018) are provided at a spatial resolution of 25x25km, for four Representative Concentration Pathway (RCP) emissions scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5: RCP4.5 is not used here). These four scenarios can be interpreted as 'low', 'medium-low', 'medium-high' and 'high' emissions respectively. The probabilistic projections are based on 3000 individual, equally-plausible, climate projections, and each grid cell is independent. The global projections are at a resolution of 60x60km, and consist of two sets of projections based on 15 plausible variants of the Hadley Centre HadGEM3 climate model representing parameter uncertainty and 12 other climate models representing model structure uncertainty (CMIP5: one of the 13 models presented on the UKCP18 data portal was excluded due to data limitations). These projections use the RCP8.5 ('high emissions') pathway. The regional projections are at a spatial resolution of 12x12km, and are based on 12 of the 15 variants of the HadGEM3 climate model. These are driven at their boundaries by data from the HadGEM3 global model variants: in practice they produce very similar changes to the global HadGEM3 strand so are not discussed further here.

The different sets of projections span different ranges of climate outcomes and have different characteristics and potential uses (Lowe et al., 2018). The probabilistic projections provide the broadest range of future climate outcomes and are available for four different pathways of forcing, but the individual ensemble members are not necessarily spatially-coherent meaning that changes in one place may not be consistent with changes in another. The statistical approach used to produce the probabilistic projections attempts to take account of relationships between the different variables, but it is not clear whether the strength of this relationship in the sample data produced adequately reproduces the relationship between the same variables in particular climate models. The global and regional strand projections maintain the physical relationships between climate variables and places that are simulated in the climate models, but do not necessarily span the full range of uncertainty.

The HadGEM3-based projections generally produce changes in temperature that are higher than the CMIP5 projections and at the top end of the probabilistic range, and tend to produce greater reductions in precipitation in England and Wales. The HadGEM3 climate models used to construct the UKCP18 global and regional projections are increasingly being used to assess changes in other aspects of weather such as storm frequency and atmospheric circulation patterns. HadGEM3 has been demonstrated (Williams et al., 2017) to have a lower bias than earlier climate models, including those in the CMIP5 ensemble. Its relatively high response to an increase in emissions is a result of improvements in the representation of climate processes within the model and is consistent with projections made by other current generation climate models (Andrews et al., 2019).

It is increasingly argued (e.g. (Hausfather and Peters, 2020) that RCP8.5 represents an unrealistically large increase in emissions and therefore in global mean temperature; such emissions could only plausibly be reached in one out of the five Shared Socioeconomic Pathway socio-economic scenarios (Riahi et al., 2017). However, Schwalm et al. (2020) highlight that compared to cumulative emissions to date and policy options to mid-century RCP8.5 might still be a prudent choice to consider at least in the near-term. It is therefore here argued that whilst RCP8.5 should not be interpreted as a 'business as usual' scenario, it should still be included in an analysis and for the latter part of the 21st century can be considered a 'worst case' emission scenario that would arise if current international emission policy pledges were not implemented. This has implications for the interpretation of the projected climate indicators in policy discussions. Note that whilst there are some differences between the emissions scenarios early in the century, especially in aspects such as aerosol forcing, the difference in climate between the emissions scenarios increases considerably after 2040.

2.3.3. Application of climate projections to observed climate data

The climate projections were applied to the daily observed climate data using the delta approach in the following stages (Fig. 1):

1. Each variable (for a given grid cell) for each year, month and scenario member was expressed as an anomaly from that member's simulated monthly average over the reference period 1981–2010 (absolute anomaly for temperature and net radiation, and ratio anomalies for the other variables: Fig. 1a).
2. The anomaly time series include both year-to-year variability and the underlying signal of climate change, so to remove the effects of year to year variability and isolate the climate change signal a running 31-year mean anomaly was calculated to define an anomaly for each year. In order to calculate anomalies for the last 15 years of the projections, the anomaly time series were extrapolated using linear regression from the last 40 years of record. The time series for the global and probabilistic strands extend to December 2099, so were extrapolated to 2115 (Fig. 1a).
3. The UKCP18 projections define change in monthly climate, but the indicators are calculated from daily climate data. There can be large differences in anomaly from one month to another, which could introduce unrealistic steps at month boundaries: this is most apparent for temperature and therefore the temperature-based indicators (Fig. 1b). The monthly anomalies were therefore interpolated linearly to produce daily anomalies (Fig. 1b), scaling to preserve the correct monthly anomaly. This interpolation was not applied when constructing scenarios for the high-resolution hydrological modelling.

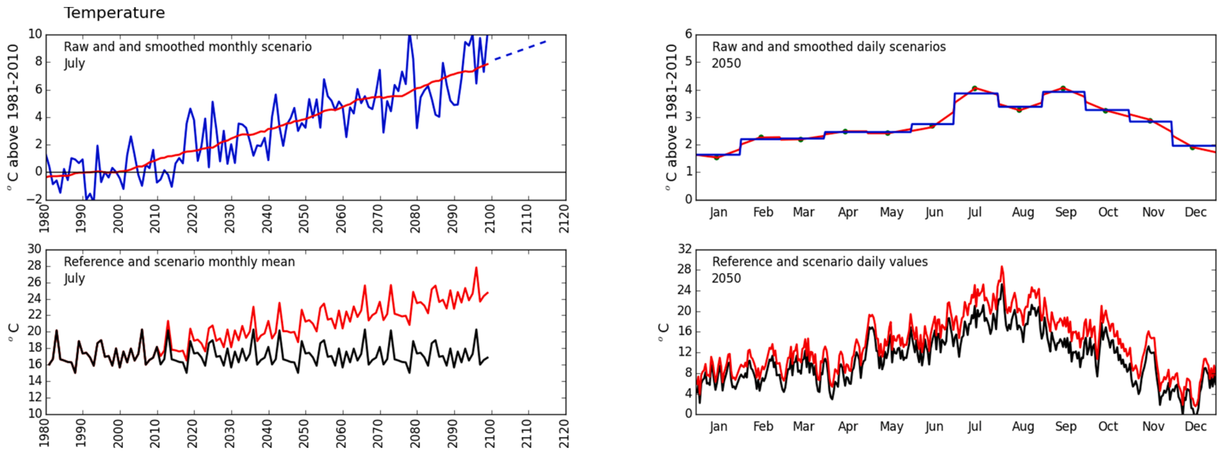

Fig. 1. Illustration of the method used to construct climate scenarios. (a) Original UKCP18 anomaly for change in climate variable in one month, interpolated change (dotted line) and 31-year running mean. (b) Monthly anomaly and interpolated daily anomaly, for a sample year. (c) Repeated reference time series (black) and series with running mean anomaly applied (red), for month. (d) Reference and daily climate variable, for a sample year. The example uses mean temperature for a location in southern England; plots (a) and (c) show July as an example month, and (b) and (d) show 2050 year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. A long reference time series was constructed by repeating the 1981 to 2010 observed time series[1] three more times to 2100, and the annual climate change anomalies applied (Fig. 1c; Fig. 1d). Repeating the observed time series preserves the temporal sequencing of the original data. For example, the warm summer of 2003 appears every 30 years. However, this does not substantially affect the projected effects of climate change, because indicators are presented as averages or frequencies over a 30-year period.

This application of the delta method implicitly assumes (i) that there is no change in relative variability in climate from year to year and (ii) that the proportional change in a variable does not vary with the magnitude of that variable. Omitting the effect of increased summer variability means that changes in indicators based on high temperature extremes may be underestimated. Both physical principles and the high resolution 2.2 km UKCP18 projections (Kendon, E et al., 2019) suggest that the second assumption may be invalid in detail too. There is evidence that daily rainfall would increase proportionately more on wetter days than on days with lower rainfall. This again will have little effect on the indicators used in this study because they are not sensitive to short duration rainfall (and indeed indicators based on short-duration rainfall were not calculated for this reason).

The study has used the delta method to apply monthly changes in climate variables to observed daily time series, rather than apply bias adjustment to the monthly UKCP18 climate projections, for three reasons. First, observed data is used to characterise the current climate because this observed experience is familiar to stakeholders. Second, different bias adjustment approaches exist (Gohar et al., 2018) and correct for different aspects of bias, but all assume that the adjustments continue into the future. Third, it would have been impractical to test and apply bias adjustment methods for all UKCP18 projection ensemble members, for all locations across the UK.

The climate projections do not explicitly incorporate potential increases in the urban heat island effect, but the current heat island effect is incorporated through the gridded reference data.

2.3.4. *Scenarios for 2, 3 and 4 °C pathways*

The UKCP18 projections are based on RCP forcings and emissions scenarios, but policymakers are also interested in pathways which reach specific temperature targets. Scenarios representing pathways reaching 2, 3 and 4 °C above pre-industrial levels by the end of the 21st century were extracted from the ensembles of RCP2.6, RCP6.0 and RCP8.5 probabilistic projections respectively (Fig. 2). In each case, the 100 members with the mean global average temperature over the period 2091–2099 closest to the target increase were selected from the full ensemble of 3000 members. Note that the uncertainty range in these projections is small by the end of the century because they are constrained to be close to a specific temperature increase. The 2 °C pathways appear to produce slightly greater increases in temperature to 2040 than the 4 °C pathways (Fig. 2), but this is not to be interpreted too literally: it reflects the relatively small sample sizes.

2.4. *Regional weighting*

The indicators are calculated at the 12x12km scale (1x1km for the hydrological indicators), and here averaged to the national scale (England, Wales, Scotland and Northern Ireland) and the governmental statistical region scale (9 regions in England, 3 in Scotland, and Wales and Northern Ireland: Fig. 3). The regional averages hide considerable variability within a region – depending on indicator – but

[1] December 1980 to November 2010 for the high-resolution hydrological indicators

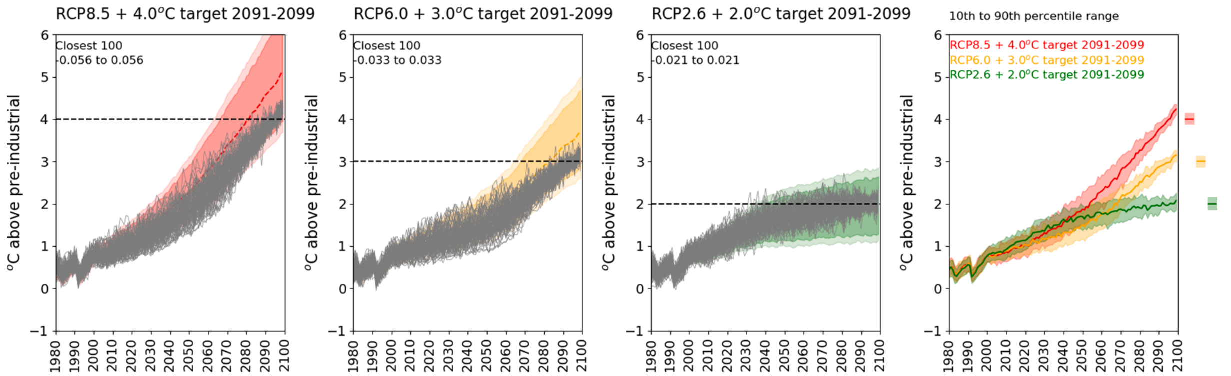

Fig. 2. Scenarios consistent with pathways to 2, 3 and 4 °C warming by the end of the 21st century. The three panels on the left show the 100 individual projections with an increase in temperature by 2091–2099 closest to 4, 3 and 2 °C above pre-industrial levels, selected from the RCP8.5, RCP6.0 and RCP2.6 ensembles respectively. The plots show the full RCP range (10th to 90th percentile range (dark shading) and 5th to 95th percentile range (light shading)), along with the range in differences from the target temperature. The right panel shows the 10th to 90th percentiles, plus the median, of the three pathway scenarios: the bars to the right show the 2091–2099 average.

are indicative of general trends.

Different weights were applied to the different indicators (Table 4), using the data sources listed in Table 5. The land classes used to weight the wildfire indicator are those which have the majority of UK wildfires both by number and area (de Jong et al., 2016). The weights are based on current exposure of assets and land cover (assumed here not to change over time), so the weighted indicators effectively characterise risk as a function of hazard and exposure. The regional heatwave and heat alert indicators represent the average likelihood of thresholds being exceeded within a region, rather than the likelihood of a heatwave or heat alert being triggered somewhere in the region. Note also that the Met Office heatwave thresholds vary within regions in south and east England, so the regional average likelihood of a heatwave in these regions reflects these variable thresholds.

2.5. *Current climate hazard and resource*

Fig. 4 shows the geographical distribution of hazard and resource as experienced over the period 1981–2010: it is a map of experience, not of risk. The proportion of time in drought, the chance of experiencing the 10-year flood and the number of days with wildfire danger greater than the 99th FFMC percentile are by definition constant across the UK (0.067, 2% and 3.65 days/year respectively).

The heatwave and heat-health alert thresholds vary across the UK. Even accounting for this, heatwave and amber alert events are much more likely across southern England and the Midlands than further north and west, as are the occurrences of hot days for roads, railways and agriculture. Heating and cooling degree days show strong variability, and cooling degree days are very low across Scotland. Railway adverse weather days are primarily determined by high temperatures (in the south) and low temperatures and snow in the north of England and Scotland. Growing degree days are greatest in south and east England. Over the period 1981 to 2010, wheat heat stress days occurred only in limited parts of eastern England.

2.6. *Change in climate across the UK*

The regional average change in seasonal temperature and rainfall with the global strand RCP8.5 projections is shown in Fig. 5 (a corresponding plot with the probabilistic projections is given in Supplementary Material). The temperature increase is greatest in summer, reaching an increase of up to 6 °C above the 1981–2010 level by the 2080s in southern England with the HadGEM3 ensemble. Rainfall is projected to increase in winter and decrease in summer (particularly in the south of England), with less change in spring and autumn. There is a clear difference between the HadGEM3 and CMIP5 ensemble.

3. Climate risk indicators with high emissions

Figs. 6 and 7 show the indicators listed in Table 4 through to 2071–2100 with RCP8.5 'high' emissions, by region and nation respectively. National results are summarised in Table 6, and regional tables are provided in Supplementary Material. The figures show the HadGEM3 and CMIP5 global ensembles separately, plotting the median across each ensemble together with the range excluding the lowest and highest members. The plots show the mean or likelihood over 30 years plotted at the middle year of the 30-year period (so the 2071–2100 value is plotted at 2085, for example). There is considerable variability within a region or nation, and the plots should be regarded as indicative of the direction of change rather than the magnitude of the indicator at a point. Fig. 8 shows the median estimate of the HadGEM3 projections for 2071–2100 at the 12x12km resolution (similar plots for 2041–2070, and with the CMIP5 ensemble, are presented in Supplementary Material).

There are four main points to draw from these figures: there is a consistent pattern towards very large increases in climate risk for

Fig. 3. UK regions.

all indicators (except for the heating degree day indicator which decreases), but there can be large differences in the rate of change between regions, the range across the projections shows large uncertainty in the magnitude of change, and there is a clear difference between the two sets of projections. With the notable exception of river flood risk, the HadGEM3 projections generate larger increases in risk than the CMIP5 projections.

The annual chance of experiencing a heatwave (using the Met Office definition) more than doubles across England and Wales by 2050 and it becomes an annual event. In Scotland and Northern Ireland the chance increases by a factor of four or five. The increases

Table 5
Sources of spatial data for calculation of weighted regional averages.

Data set	Source
Population	2011 Census Data
Land cover	CEH LCM2015 CEH (2017)
Road network	OS Meridian™ 2 via EDINAOSNI Open Data 50 k Transport Lines via Open data NI
Rail network	OS Meridian™ 2 via EDINAOSNI Open Data 50 k Transport Lines via Open data NI

are smaller with the CMIP5 projections. By the 2050s, the annual chance of having an amber heat-health alert is between 60 and 80% across southern and eastern England (compared to between 5 and 15% now): increases in the north are smaller. The rate of increase in likelihood is greatest in eastern England, which is consistent with the conclusions of Sanderson & Ford (2016) using earlier UKCP09 projections.

Heating degree days decrease consistently across the UK (in percentage terms), and by the 2050s could be 30–40% lower than at present. The increase in cooling degree days is much more variable across the UK, reflecting the strong variability in reference period cooling degree days. In southern and eastern England cooling degree days may increase by a factor of four or five by the 2050s: the proportional increase further north is greater but from a much lower base.

The number of hot days that cause problems for the transport network increases very substantially across the UK, although from a much lower base in the north. For example, the average number of days with maximum temperatures >26 °C increases in south east England from around 10 to between 45 and 60 by the 2050s, and 80 to 100 by the 2080s. Days with maximum temperatures >30 °C increase by a greater proportion and by the 2050s occur even in northern England and parts of Scotland. The pattern of change in the chance of railway ‘adverse weather days’ is more complicated. In the south and east of England the likelihood increases very substantially because most of the adverse days are due to high temperature extremes. Further north, particularly in Scotland, most of the current adverse days are due to low temperatures and/or snow. The number of these days decreases as temperatures rise, but after the 2050s this reduction is more than offset – except in Northern Scotland - by the increasing number of adverse days caused by high temperature.

Growing degree days increase consistently (in proportional terms) across the UK, and may be 50–60% higher by the 2050s. This will benefit permanent crops – such as pasture – but will have less beneficial effect on the productivity of annual crops where yields are influenced by the time taken to achieve maturity rather than total growing degree days over a growing season. Days with high temperatures during the critical wheat flowering stage remain very low across the UK until the 2050s, when the likelihood increases very substantially across most of England: in eastern England, however, the likelihood could be 5% even by the 2030s. The proportion of time in agricultural drought also increases consistently across the UK. Under the HadGEM3 projections, the proportion of time in drought may increase by four or five times by the 2050s, although increases are smaller with the CMIP5 projections.

Similarly, wildfire danger increases rapidly across the UK, although there is a difference between the two indicators. The number of days with MOFSI exceptional warnings increases across most of England, Wales and parts of Scotland after the 2050s, with an earlier increase in eastern England. Using the FFMC percentile indicator, danger increases from the present day, with the rate of increase accelerating through the 21st century.

Both the HadGEM3 and the CMIP5 projections produce an increase in the likelihood of experiencing the current 10-year flood in western England, Wales and Scotland. However, in southern and eastern England (including the north east) the HadGEM3 projections suggest little change in flood frequencies whilst the CMIP5 projections show a consistent increase.

There is also a qualitative difference between the two sets of projections in the direction of projected change in hydrological drought occurrence. The HadGEM3 projections produce consistent and large increases in drought occurrence across the UK (except in western Scotland), whilst the CMIP5 projections produce little consistent change except in south east England. One of the HadGEM3 models produces a very large increase in drought occurrence to the 2060s (not shown).

The variation across the UK in the changes in the risk indicators can generally be explained in terms of the characteristics of the indicators. Four of the 14 indicators (drought, flood and FFMC) are based on critical thresholds defined at the local scale. The variation in the changes in these indicators across the UK are therefore determined by variation in the change in climate. For the FFMC fire danger indicator the pattern reflects differences in the amount of temperature increase and change in humidity (Arnell et al., 2021). For the flood and drought indicators variation in change in rainfall is most important, and this is superimposed onto the effects of variation in catchment properties (Kay et al., 2014, 2020). Seven of the indicators (heat waves, heat-health alerts, the three transport indicators, wheat heat stress and MOFSI fire danger) are based on absolute critical thresholds – dominated by temperature – that are constant over large areas (by region or across the whole of the UK). For these indicators, the variation in change across space and through time is dependent on how often these thresholds are currently exceeded rather than the variation in climate change (although it is important to note that this would not necessarily apply with critical thresholds based on rainfall). The other three indicators (heating, cooling and growing degree days) are based on constant thresholds so their absolute values vary across the UK, but the changes are much more consistent because variability in change in temperature across the UK is small.

Eight of the indicators just use temperature, and the uncertainty ranges shown in Figs. 6 and 7 and Table 6 therefore represent uncertainty in projected changes in temperature. The uncertainty ranges for the other six (the two drought indicators, rail adverse weather days, river flooding, and the two wildfire indicators) also include uncertainty in projected changes in other variables, to varying degrees. Most of the uncertainty in the flood and drought indicators is due to uncertainty in change in precipitation. Uncertainty in the wildfire indicators is primarily caused by uncertainty in change in temperature and relative humidity (Arnell et al.,

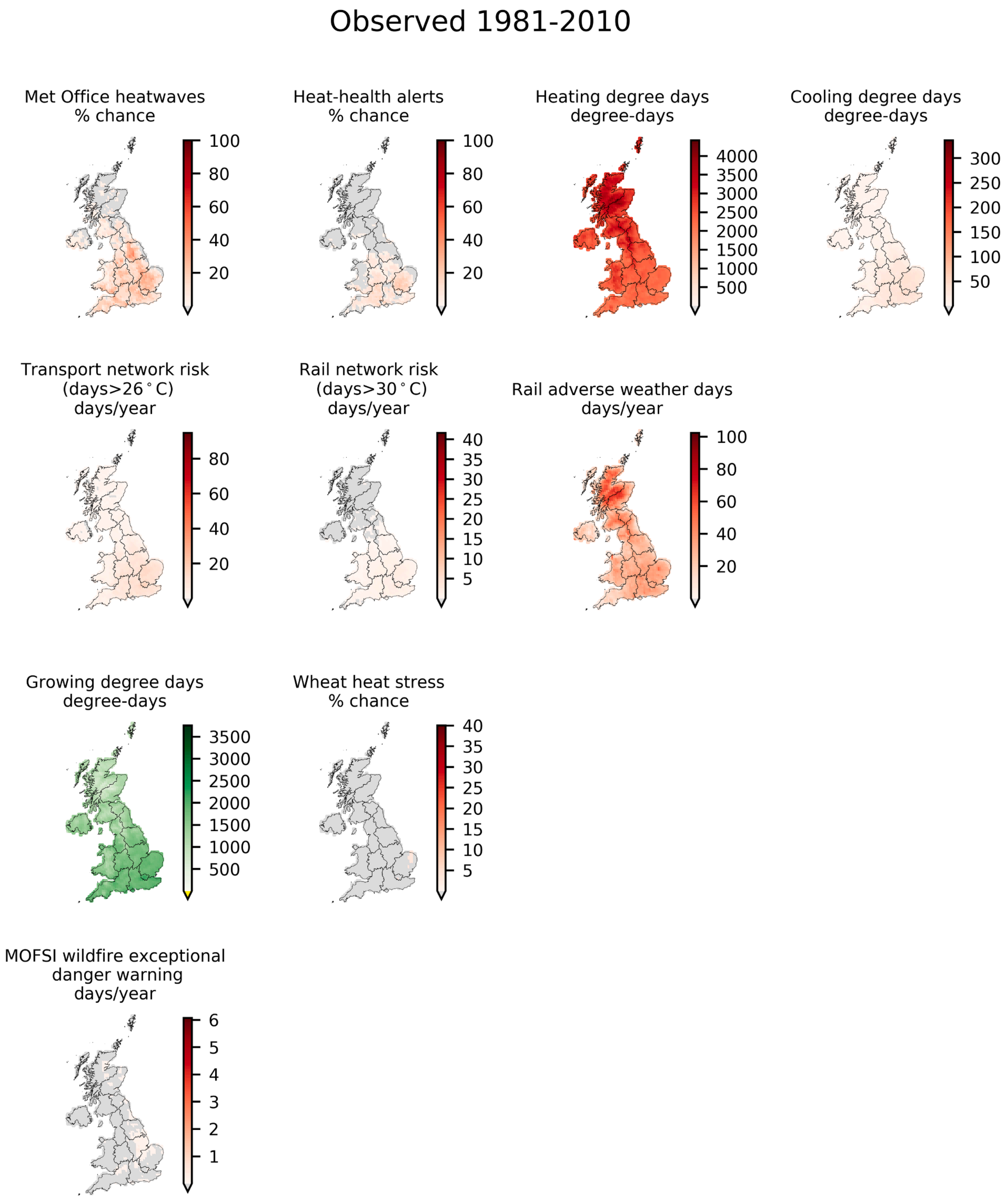

Fig. 4. Observed climate hazards and resources: 1981–2010. See Table 3 for definitions of indicators. The plots show the regional boundaries used to construct regional averages.

2021: rainfall uncertainty has some effect on the MOFSI indicator). Although the rail adverse weather indicator includes snowfall and rainfall, these are less important than temperature extremes – except in Scotland - so uncertainty is largely driven by uncertainty in temperature change.

The HadGEM3 projections have consistently larger increases in temperature than the CMIP5 projections, and this is the primary reason why the two ensembles produce different changes. The HadGEM3 projections also show greater increases in rainfall the north

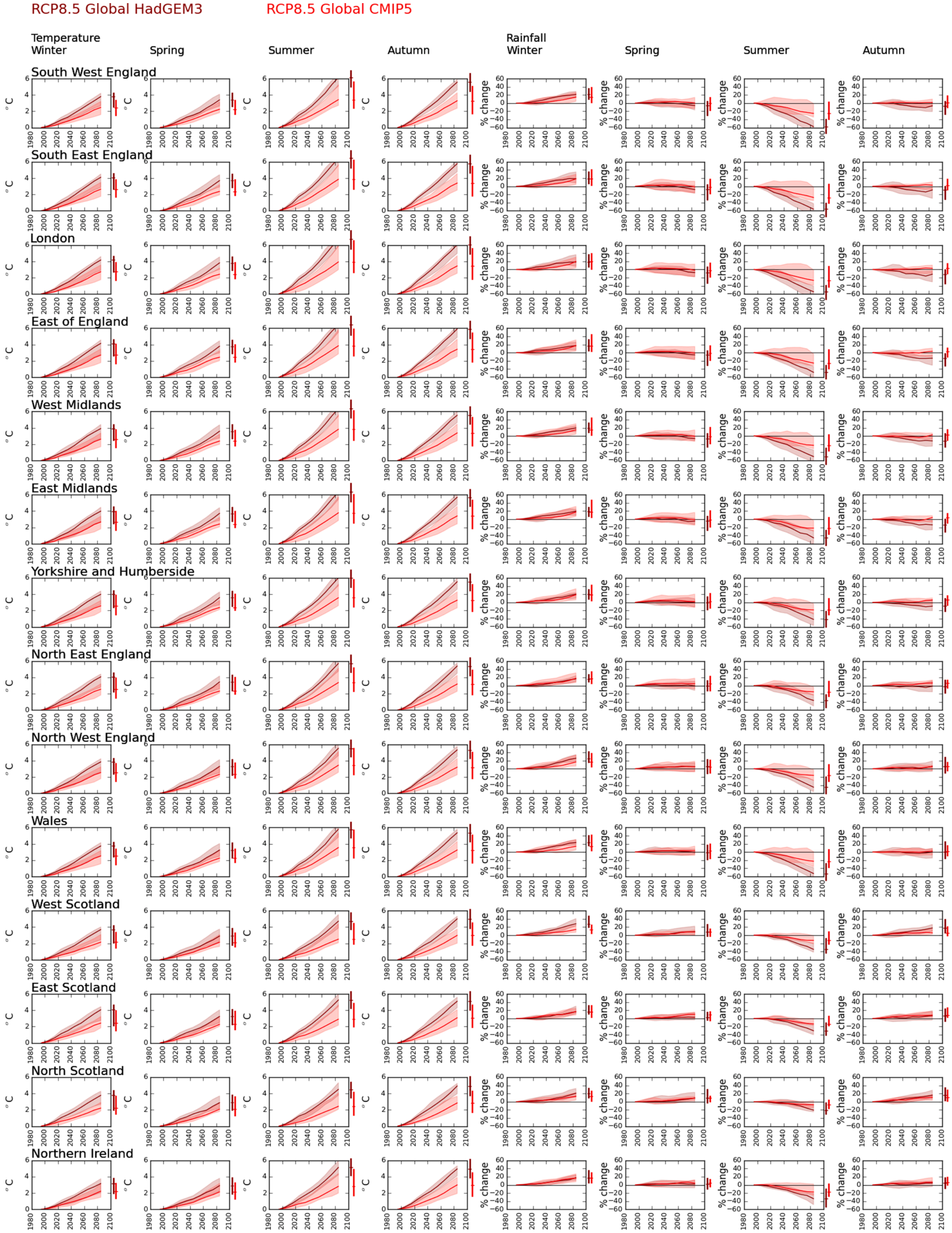

Fig. 5. Change in seasonal mean temperature and rainfall relative to 1981–2010, with the HadGEM3 and CMIP5 RCP8.5 ensembles. The plots show the 30-year mean change, plotted at the mid-point of the 30-year period. The shading shows the range across the ensemble members, (excluding the highest and lowest), and the solid line the median. The bars show the full range for each ensemble.

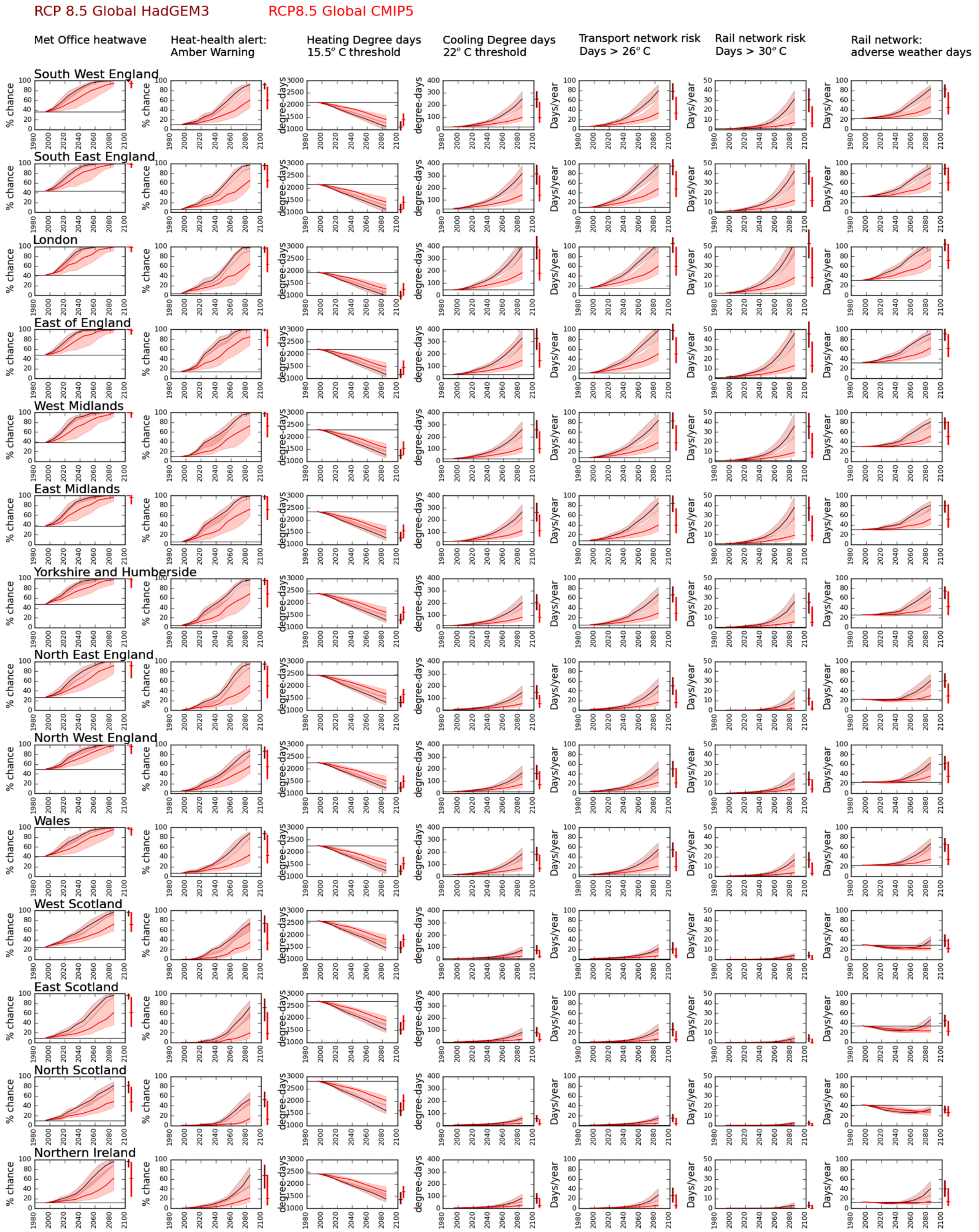

Fig. 6a. Climate Risk Indicators by administrative region with RCP8.5 emissions and the HadGEM3 and CMIP5 global ensembles: heat, energy and transport indicators. The plots show the 30-year mean change, plotted at the mid-point of the 30-year period. The shading shows the range across the ensemble members, (excluding the highest and lowest), and the solid line the median. The bars show the full range for each ensemble. See Table 4 for indicator definitions.

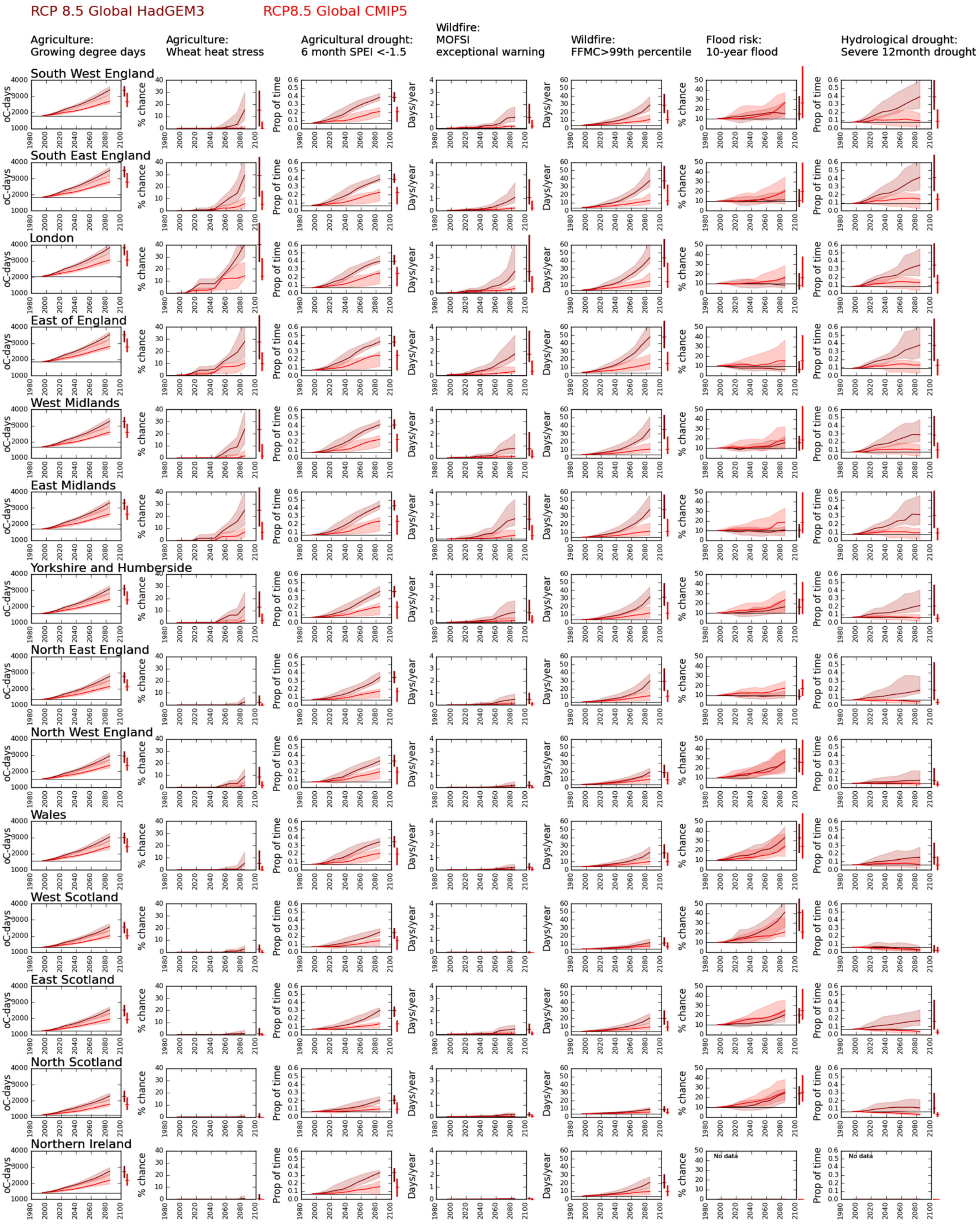

Fig. 6b. Climate Risk Indicators by administrative region with RCP8.5 emissions and the HadGEM3 and CMIP5 global ensembles: agriculture, fire and water indicators. The plots show the 30-year mean change, plotted at the mid-point of the 30-year period. The shading shows the range across the ensemble members, (excluding the highest and lowest), and the solid line the median. The bars show the full range for each ensemble. See Table 4 for indicator definitions.

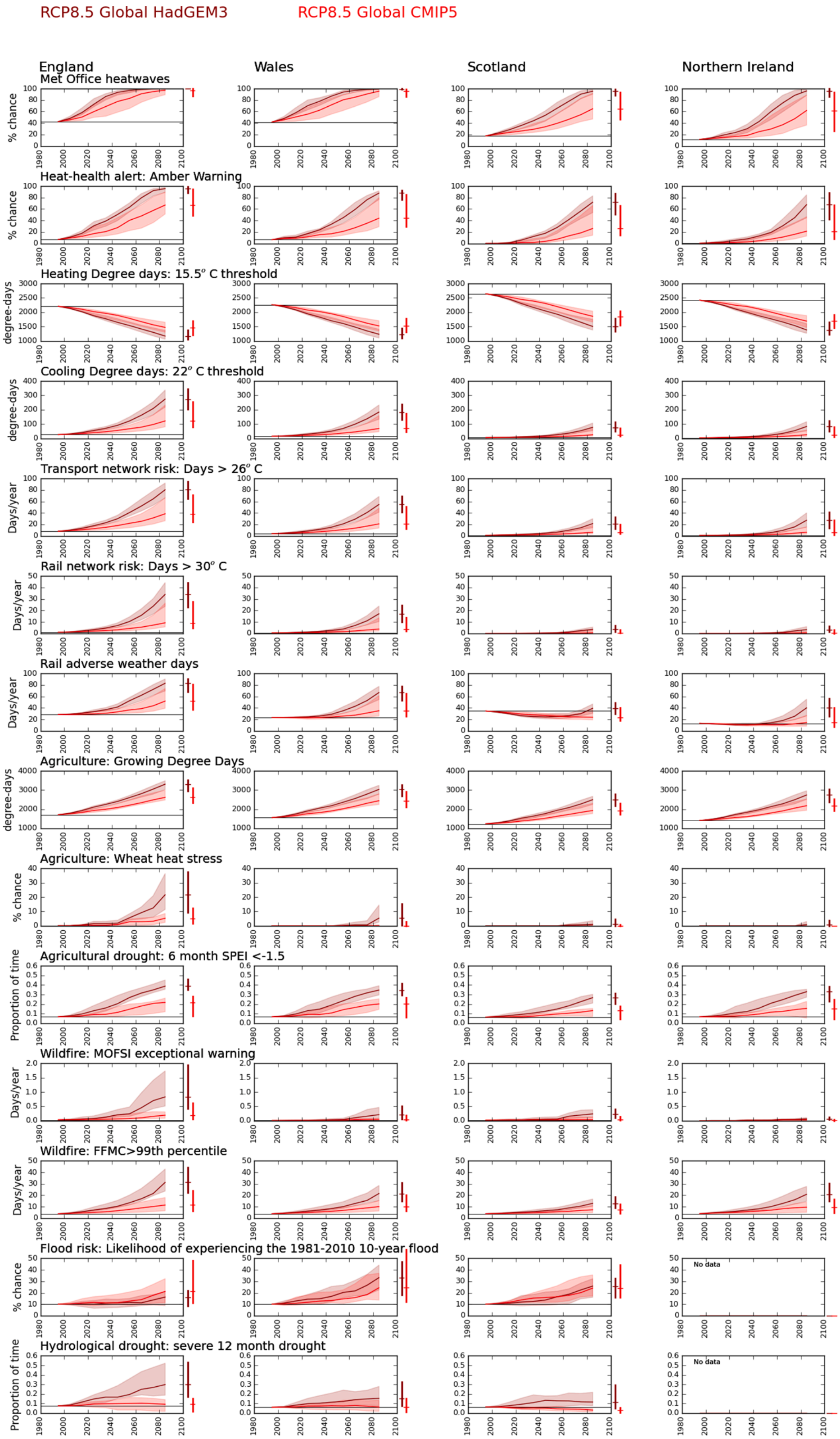

Fig. 7. Climate Risk Indicators by nation with RCP8.5 emissions and the HadGEM3 and CMIP5 global ensembles. The plots show the 30-year mean change, plotted at the mid-point of the 30-year period. The shading shows the range across the ensemble members, (excluding the highest and lowest), and the solid line the median. The bars show the full range for each ensemble. See Table 4 for indicator definitions.

Table 6
National-level indicators with RCP8.5 emissions.

England			HadGEM						CMIP5					
		1981–2010	2041–2070			2071–2100			2041–2070			2071–2100		
			med	range		med	range		med	range		med	range	
Met Office heatwave	% chance of at least one	42	96	93	99	100	100	100	83	65	95	97	89	100
Heat-health alerts	% chance of at least one	7	63	55	71	95	89	97	40	22	56	67	51	89
Heating Degree Days	°C-days	2207	1526	1660	1443	1168	1365	1062	1786	1858	1619	1471	1649	1303
Cooling Degree Days	°C-days	26	121	103	149	270	218	337	67	45	93	122	81	232
Transport: days > 26 °C	Days/year	8	40	35	50	78	66	92	22	14	31	38	26	66
Rail network: days > 30 °C	Days/year	1	10	8	14	33	24	44	4	2	7	9	6	26
Rail network: adverse weather days	Days/year	28	52	46	58	81	70	90	36	31	44	52	39	74
Growing degree days	°C-days	1710	2577	2462	2715	3296	3027	3485	2210	2142	2496	2617	2482	2988
Wheat heat stress	% chance at least one day	0	5	4	8	21	11	36	3	0	5	5	2	9
Agricultural drought: 6 m SPEI < -1.5	Proportion of time	0.07	0.25	0.23	0.33	0.38	0.36	0.45	0.15	0.08	0.2	0.22	0.12	0.26
FFMC 99th percentile	Days/year	4	13	12	20	28	24	43	8	5	12	11	6	18
MOFSI exceptional danger	Days/year	0	0	0	0	1	0	1	0	0	0	0	0	0
10-year flood	% chance of exceedance	10	11	8	15	12	9	21	13	9	21	21	12	32
Hydrological drought: 12 m SSI < -1.5	Proportion of time	0.06	0.21	0.17	0.44	0.33	0.2	0.63	0.09	0.02	0.17	0.08	0.01	0.14

Wales			HadGEM						CMIP5					
		1981–2010	2041–2070			2071–2100			2041–2070			2071–2100		
			med	range		med	range		med	range		med	range	
Met Office heatwave	% chance of at least one	42	94	89	97	99	99	100	81	62	90	96	86	99
Heat-health alerts	% chance of at least one	7	43	35	55	85	77	92	21	14	34	44	29	80
Heating Degree Days	°C-days	2263	1580	1708	1510	1227	1406	1103	1850	1909	1666	1523	1701	1349
Cooling Degree Days	°C-days	14	69	59	92	182	133	233	37	26	53	69	47	159
Transport: days > 26°C	Days/year	4	21	18	29	54	41	69	11	7	16	21	14	48
Rail network: days >30°C	Days/year	0	4	3	6	15	10	24	1	1	3	4	2	14
Rail network: adverse weather days	Days/year	23	34	31	42	64	54	77	26	22	30	35	26	61
Growing degree days	°C-days	1555	2338	2251	2512	2994	2783	3244	2024	1966	2279	2443	2244	2807
Wheat heat stress	% chance at least one day	0	0	0	1	5	3	14	0	0	0	0	0	1
Agricultural drought: 6m SPEI<-1.5	Proportion of time	0.07	0.23	0.2	0.31	0.34	0.3	0.39	0.14	0.08	0.2	0.2	0.14	0.25
FFMC 99th percentile	Days/year	4	10	9	14	19	15	28	7	5	9	10	6	15
MOFSI exceptional danger	Days/year	0	0	0	0	0	0	0	0	0	0	0	0	0
10-year flood	% chance of exceedance	10	19	16	27	26	22	44	15	11	23	24	14	37
Hydrological drought: 12m SSI<-1.5	Proportion of time	0.05	0.12	0.06	0.34	0.14	0.06	0.39	0.07	0.03	0.16	0.05	0.02	0.15

Scotland			HadGEM						CMIP5					
		1981–2010	2041–2070			2071–2100			2041–2070			2071–2100		
			med	range		med	range		med	range		med	range	
Met Office heatwave	% chance of at least one	17	66	56	76	95	90	98	39	30	57	65	47	92
Heat-health alerts	% chance of at least one	0	27	18	34	68	54	83	7	3	22	26	14	66
Heating Degree Days	°C-days	2642	1910	2032	1811	1490	1752	1381	2196	2273	2004	1857	2034	1660
Cooling Degree Days	°C-days	5	26	20	36	75	54	106	13	9	22	25	16	68
Transport: days > 26°C	Days/year	1	7	5	9	21	14	30	3	2	5	6	4	18
Rail network: days >30°C	Days/year	0	1	0	1	3	2	5	0	0	0	1	0	3

(*continued on next page*)

Table 6 (*continued*)

Scotland			HadGEM						CMIP5					
		1981–2010	2041–2070			2071–2100			2041–2070			2071–2100		
			med	range		med	range		med	range		med	range	
Rail network: adverse weather days	Days/year	34	24	21	30	37	31	47	26	21	28	24	19	36
Growing degree days	^{o}C-days	1232	1905	1810	2024	2493	2249	2669	1627	1542	1855	1931	1776	2304
Wheat heat stress	% chance at least one day	0	0	0	0	1	0	4	0	0	0	0	0	1
Agricultural drought: 6m SPEI<-1.5	Proportion of time	0.06	0.15	0.14	0.21	0.26	0.21	0.3	0.1	0.07	0.11	0.13	0.07	0.15
FFMC 99th percentile	Days/year	4	7	6	9	12	10	17	6	4	7	7	5	11
MOFSI exceptional danger	Days/year	0	0	0	0	0	0	0	0	0	0	0	0	0
10-year flood	% chance of exceedance	10	16	10	21	26	16	32	16	12	26	24	17	35
Hydrological drought: 12m SSI<-1.5	Proportion of time	0.07	0.1	0.08	0.28	0.16	0.1	0.31	0.04	0.01	0.08	0.02	0	0.05
Northern Ireland			**HadGEM**						**CMIP5**					
		1981–2010	2041–2070			2071–2100			2041–2070			2071–2100		
			med	range		med	range		med	range		med	range	
Met Office heatwave	% chance of at least one	11	60	46	73	93	88	99	30	18	53	62	36	89
Heat-health alerts	% chance of at least one	0	19	15	25	67	45	85	7	3	18	21	13	46
Heating Degree Days	^{o}C-days	2419	1746	1882	1687	1376	1600	1267	2005	2082	1822	1691	1884	1467
Cooling Degree Days	^{o}C-days	4	23	18	35	78	52	116	11	6	21	25	13	58
Transport: days > 26°C	Days/year	1	6	4	9	26	15	40	2	1	5	6	3	15
Rail network: days >30°C	Days/year	0	0	0	1	3	1	6	0	0	0	0	0	1
Rail network: adverse weather days	Days/year	13	14	12	19	38	26	55	11	8	12	14	8	27
Growing degree days	^{o}C-days	1405	2115	2028	2264	2738	2511	2960	1801	1731	2065	2182	1941	2534
Wheat heat stress	% chance at least one day	0	0	0	0	0	0	3	0	0	0	0	0	0
Agricultural drought: 6m SPEI<-1.5	Proportion of time	0.07	0.19	0.17	0.28	0.31	0.27	0.35	0.12	0.08	0.15	0.16	0.05	0.23
FFMC 99th percentile	Days/year	4	10	8	15	19	15	28	7	4	8	10	5	14
MOFSI exceptional danger	Days/year	0	0	0	0	0	0	0	0	0	0	0	0	0
10-year flood	% chance of exceedance	–	–	–	–	–	–	–	–	–	–	–	–	–
Hydrological drought: 12m SSI<-1.5	Proportion of time	–	–	–	–	–	–	–	–	–	–	–	–	–

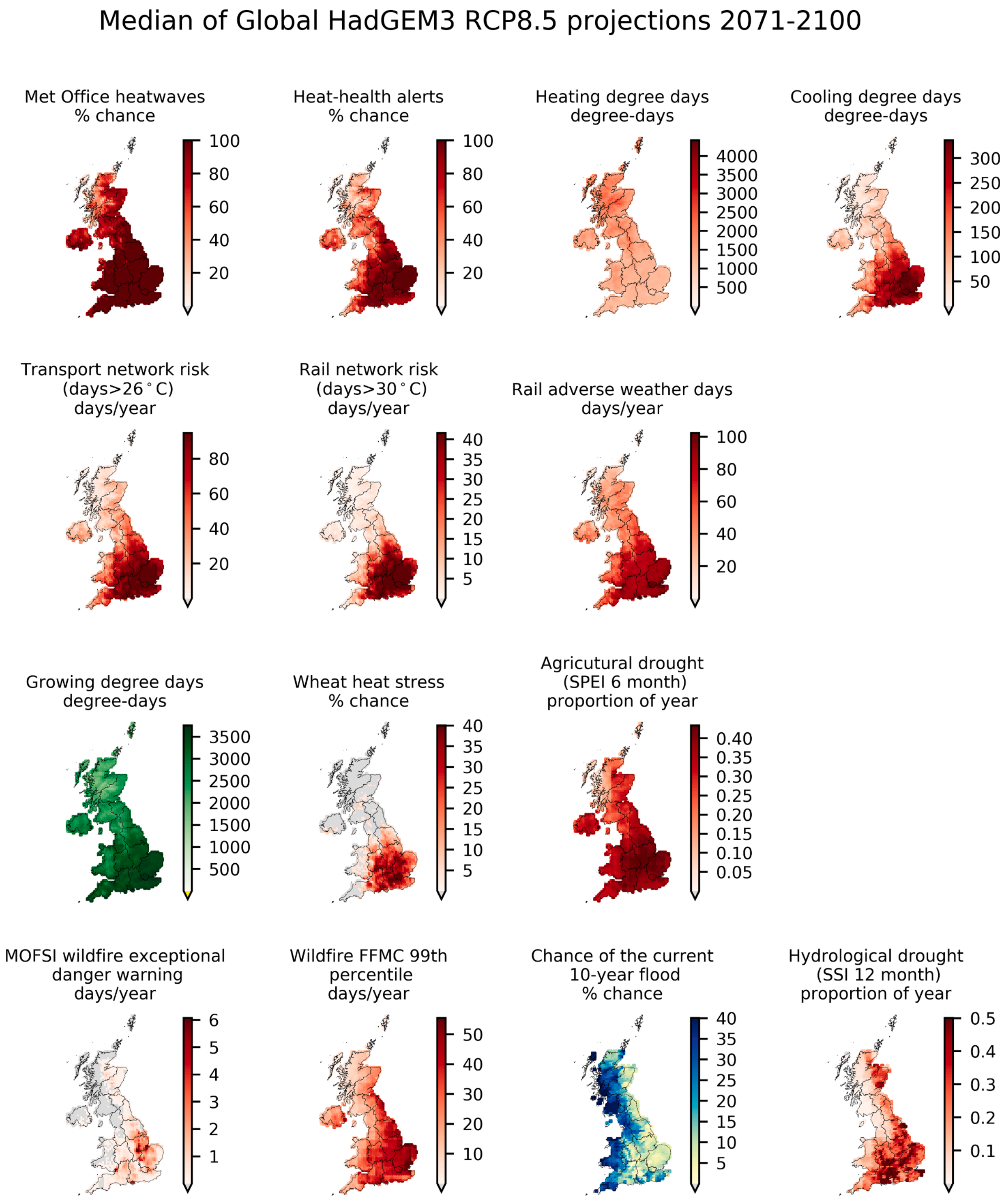

Fig. 8. The climate risk indicators over the period 2071–2100. Median estimate from the HadGEM3 ensemble. The flood and hydrological drought indicators were not calculated for Northern Ireland.

and west in winter, and greater decreases in the south in summer and autumn than the CMIP5 ensemble (Murphy et al., 2018), and this explains the difference between the flood and drought projections. The HadGEM3 ensemble also has larger reductions in relative humidity than the CMIP5 ensemble, and this further exaggerates the difference in wildfire indicators between the two ensembles (Arnell et al., 2021).

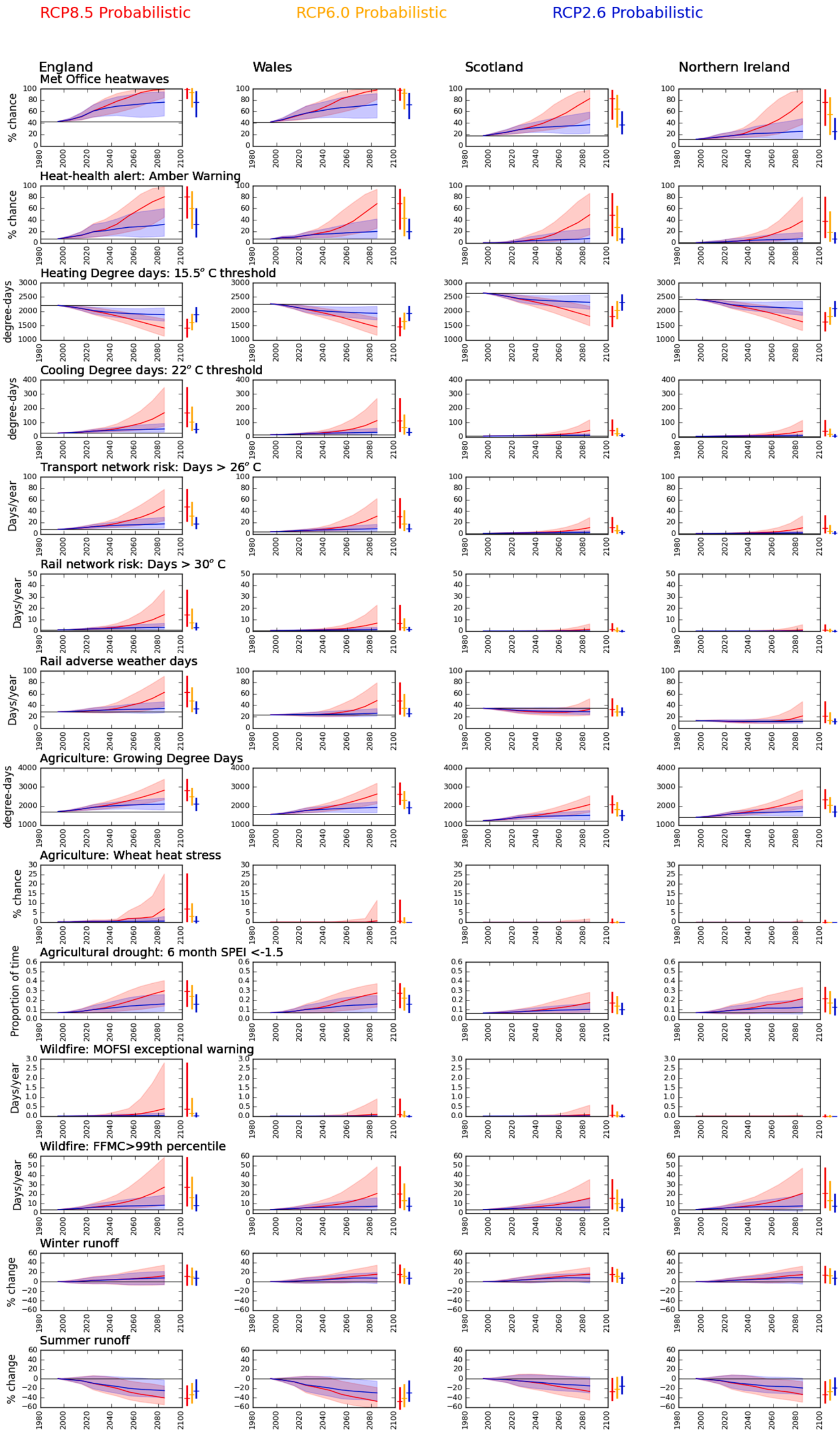

Fig. 9. Climate Risk Indicators by nation with RCP2.6, RCP6.0 and RCP8.5 emissions. Each figure shows the median plus the 10th to 90th percentile ranges, and plots the value calculated over 30 years at the middle year of the 30-year period. See Table 4 for indicator definitions.

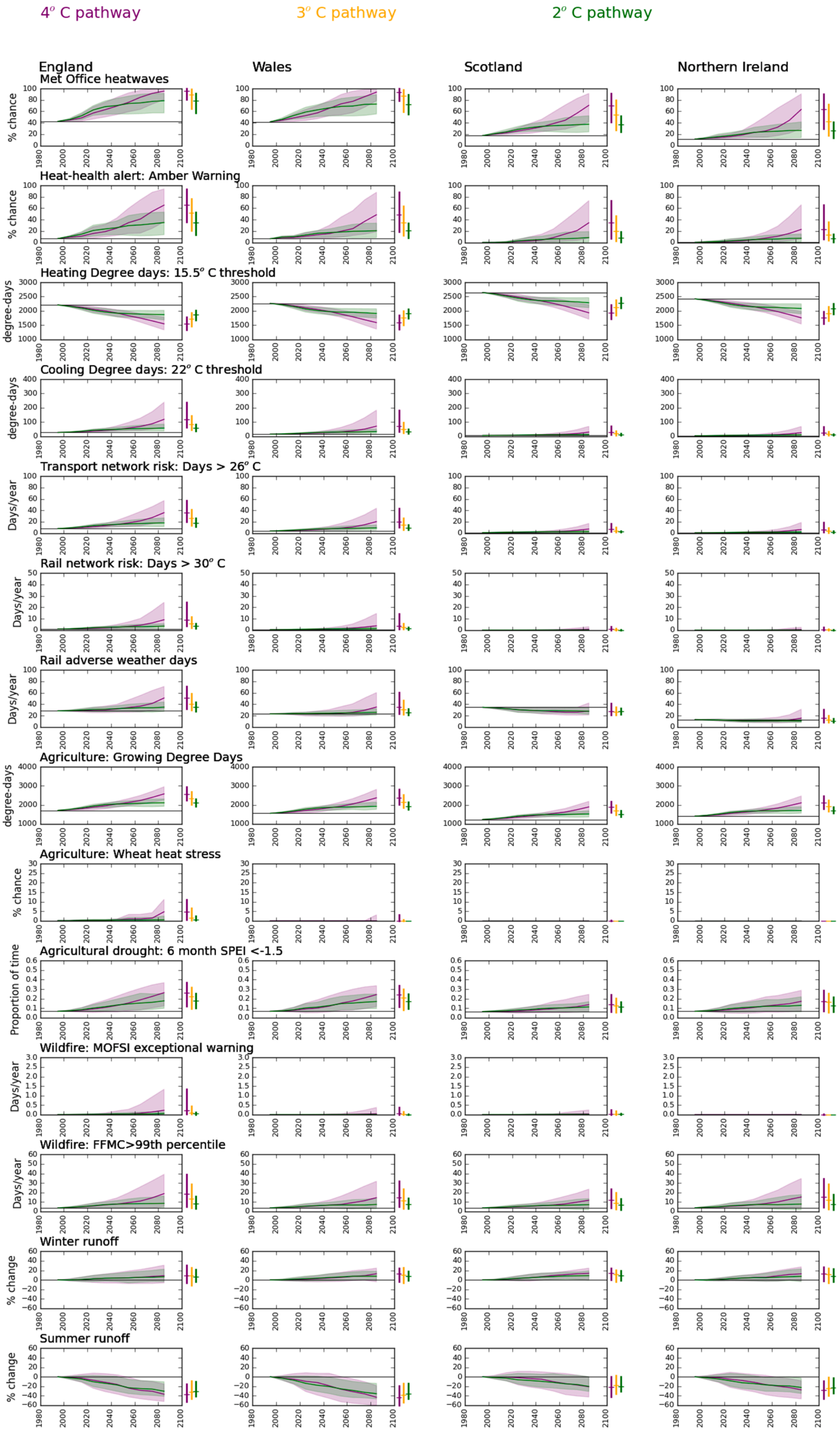

Fig. 10. Climate Risk Indicators by nation with 2, 3 and 4 °C pathways. Each figure shows the median plus the 10th to 90th percentile ranges, and plots the value calculated over 30 years at the middle year of the 30-year period. See Table 4 for indicator definitions.

4. The effect of reductions in emissions on indicators of climate risk

The previous section has described risk indicators across the UK with high emissions. National and international climate policy is aimed at reducing future emissions, which would therefore reduce impacts and risks in the UK. This section assesses the effect of reductions in emissions (i) to provide high level information on the effects of policy for risks in the UK and (ii) to evaluate the effect of mitigation policy on resilience strategies. It uses the UKCP18 probabilistic projections representing low, medium and high emissions scenarios (RCP2.6, RCP6.0 and RCP8.5 respectively), together with the subset of probabilistic projections reaching specific temperature increases by 2100. RCP2.6 is broadly consistent with an emissions policy aiming for a 2 °C increase in temperature, but RCP8.5 leads to an increase of between 4 and 6 °C by the end of the 21st century. RCP6.0 produces a median estimate of just under 4 °C, and a range of 3 to 4.5 °C.

The section uses most of the same indicators as the previous section, but substitutes winter and summer runoff changes estimated using the simpler hydrological model for the changes in flood and drought frequency calculated using G2G. This is because G2G was not used with the probabilistic projections.

Fig. 9 shows the indicators by nation (corresponding plots by region are given in Supplementary Material). The characteristics of changes with the RCP8.5 high emissions are similar to those shown in Fig. 7 using just the global strand projections. Note that the uncertainty range for the wildfire indicators is probably too high, due to the lack of physical consistency between the different climate variables in the probabilistic projections (Arnell et al., 2021). There are three main conclusions to draw from these plots.

First, the effect of reducing emissions lowers, but does not eliminate, the widespread increases in the risk indicators. Second, the effect of reducing emissions varies between indicators and – for some indicators - across the UK. The greatest effects are where a critical threshold is high and events are rare (for example for NHS amber heat alerts, wheat heat stress, the MOFSI wildfire indicator and the Met Office heatwave indicator in the north of the UK) or where the indicator is an accumulation over a period of time (heating, cooling and growing degree days). Third, until at least the 2040s the difference between the low and high emissions projections is small relative to the uncertainty range, but this varies between indicators.

In the second half of the 21st century high emission risks can be considerably greater not only than low emission but also medium emission (RCP6.0) risks. This has implications for the selection of an upper bound for resilience planning: using a lower upper bound – for example a 4 °C pathway – could result in substantially lower estimates of the 'worst case' risk. Fig. 10 shows the risk indicators with pathways leading to 2, 3 and 4 °C increases by 2100. Some of the risks – such as the chance of an NHS amber heat health alert and change in cooling degree days – are considerably smaller with the 4 °C pathway than RCP8.5.

5. Discussion and implications for climate resilience

Both the absolute magnitude of the risk indicators and the change in risk through the 21st century varies across the UK. For the temperature-based indicators, which are typically defined on the basis of absolute critical temperature thresholds, this largely reflects variation in the current climate. The absolute risk is generally larger in southern and eastern England than further north, but the rate of increase over time may be higher from the lower base levels in the north. For the hydrological indicators – flood and drought – the variation largely reflects variation in the change in rainfall and the compounding effects of variations in catchment properties. The biggest increases in river flood risk are therefore in the north and west, and the largest increases in drought risk in the south and east. This variation in change in risk across the UK means that adaptation and resilience priorities will vary within and between regions, and that national standards and policies need to account for this diversity.

There is relatively little difference between different emissions pathways for the next two or three decades, but after then the increase in risks can be considerably higher with high emissions. This has three main policy implications.

First, the effects of measures taken now to reduce emissions will not reduce risks in the next couple of decades: their effects will be seen later and there will be some increase in risk even with very large reductions in emissions. It is therefore necessary to both increase resilience to changing risks *and* reduce emissions. Climate policy should be broader than 'achieving net zero by 2050′.

Second, adaptation and resilience strategies for the near term do not need to be tied to specific assumptions about emissions, but a longer-term perspective does need to consider the effects of emissions policy.

Third – and most critically - adaptation and resilience strategies based around 'worst case' scenarios (e.g. 'hope for the best and prepare for the worst') need to consider very carefully the 'high' emissions scenarios and the more sensitive climate models. At present, both the Environment Agency (Reynard et al., 2017) and Highways England (2016), for example, use the 90th percentile of a high emissions projection (currently from UKCP09) to define a 'high' or 'upper' scenario, and Network Rail use the 90th percentile from the UKCP18 RCP8.5 probabilistic ensemble (Network Rail, 2020b). The increase in risks with the RCP8.5 emissions pathway central to the UKCP18 climate projections can be considerably larger than the increase with a 4 °C pathway. Using a 4 °C pathway as the basis for a resilience strategy may underestimate future risks – but at the same time using RCP8.5 may overestimate risks if it turns out that the assumed emissions are too high. Adaptation and resilience policymakers therefore need to make an explicit judgment on the plausibility of these (or other) 'worst cases', which has to be based on assessments of the global-scale effects of plausible future emissions pathways.

The UKCP18 global strand provides a powerful ensemble of climate projections that are both spatially-coherent and which maintain plausible physical relationships between different climate variables. However, there are some significant differences between the HadGEM3 and CMIP5 members of the ensemble. The HadGEM3 ensemble tends to produce larger increases in risk – particularly for the temperature-based indicators – than the CMIP5 projections, and are typically at the top end of the probabilistic range. Reliance on the HadGEM3 projections alone therefore potentially gives a partial indication of the range of uncertainty, and for a full appreciation it is necessary to use both the HadGEM3 and CMIP5 ensembles. This can to some extent be addressed by focusing the results on warming level scenarios rather than time evolution for a given emission scenario but the addition of other regional climate ensemble members which correspond to large-scale driving data from the CMIP5 models would be a desirable addition to UKCP.

For almost all of the risk indicators – with the exception of water resources drought in northern parts of the UK – the direction of change in risk is clear across the UKCP18 climate projections, but the magnitude of change by a specific year is uncertain. This makes it difficult to plan specific adaptation measures for specific time horizons. However, it is possible to look at adaptation and resilience planning from the other direction: focus not on what needs to be done when, but *when* something needs to be done to address a specific change in risk. Such an 'adaptation pathways' approach (e.g. Kingsborough et al., 2017), is based on developing plans that can be actioned as more information becomes available. For example, at some point over the next few years and decades the chance of experiencing an amber heat-health warning at a place will exceed 50%, and there will be >50 adverse weather days on the railway.

The paper has explicitly *not* attempted to classify the changes in hazard and resource into risk categories (for example red, amber and green) and therefore make an assessment. This requires the definition of class boundaries, which vary with context and need to be defined by stakeholders.

6. Conclusions

This paper has calculated a series of policy-relevant indicators of changing climate risks for the UK, spanning the health, transport, energy, agriculture, flood and water sectors. It has used a consistent approach across all sectors, using the new UKCP18 climate projections and focusing on changes in the hazard component of risk. It presents a categorization of climate risk indicators to help in the identification and selection of policy-relevant indicators. The results can inform an assessment of changing climate risks by stakeholders, for example through categorisation of the changes into levels of concern. The paper does not present predictions of future risks, but rather presents plausible projections of change in risk under different assumptions about how emissions of greenhouse gases change. It also does not consider the effects of changes in exposure and vulnerability – for example through changes to critical thresholds which define adverse impacts, or the numbers of elderly people vulnerable to heat extremes – which could reduce or exaggerate absolute change in risk expressed in economic or social terms. In practice, adaptation will reduce the risks as characterised here – and indeed the main point of the analysis is to evaluate what would happen if there were no conscious adaptation. The indicators also do not necessarily characterise the most important dimensions of climate change for the UK, and whilst they are all relevant to specific sectors are not equally significant at the aggregate national scale.

The results show that climate hazards will increase across the whole of the UK – in the absence of adaptation which changes critical thresholds - but at different rates and from different starting values in different regions. The number and likelihood of heat extremes affecting health, the operations of the National Health Service, the road and rail network and crop productivity will increase very markedly. Agricultural and hydrological drought risks increase across the UK, as does wildfire danger. Fluvial flood hazard increases particularly in the north and west. Demand for cooling energy will increase, but demand for heating energy will decline. Crop growing degree days will increase, benefiting the production of perennial crops. In general, the risks associated with high temperature extremes will increase the most in warmer southern and eastern England, but the rate of increase from a lower base may be greater further north and west.

Reducing future emissions of greenhouse gases reduces, but does not eliminate, climate risks. It will have little noticeable effect on risks in the next couple of decades, although action now will reduce the changes of very large impacts later in the century.

Apart from demonstrating the effects of climate change on UK risks, the paper has highlighted several implications for adaptation and resilience policy. This policy must recognise variability in change in risk across the UK. It is necessary to enhance adaptation and resilience alongside reducing emissions. In the near term, resilience policy does not need to be based on emissions assumptions, but over the longer term it is necessary to make explicit choices about 'worst case' emissions scenarios as they can influence strongly estimated changes in risk. Although the magnitude of change in risk is uncertain, the direction of change is clear. Finally, the HadGEM3-based projections in the UKCP18 suite do not span the full uncertainty range and need to be interpreted in the context of the full set of UKCP18 projections.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was funded through the UKRI Climate Resilience programme (Grant NE/S016481/1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2020.100265.

References

Andrews, T., et al., 2019. Forcings, feedbacks and climate sensitivity in HadGEM3-CC3.1 and UKESM1. J. Adv. Modell. Earth Syst. 11, 4377–4394.

Arnell, N.W., Freeman, A., submitted. The effect of climate change on agri-climate indicators in the UK.

Arnell, N.W., et al., 2013. A global assessment of the effects of climate policy on the impacts of climate change. Nat. Clim. Change 3 (5), 512–519. https://doi.org/10.1038/nclimate1793.

Arnell, N.W., et al., 2021. The effect of climate change on indicators of fire danger in the UK. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abd9f2 (in press).

Azevedo, J.A., et al., 2015 Critique and suggested modifications to the degree days methodology to enable long-term electricity consumption assessments: a case study in Birmingham, UK. Meteorological Applications 22, 789-796.

Barker, L.J., et al., 2015. From meteorological to hydrological drought using standardised indicators. Hydrol. Earth Syst. Sci. 12,12827-12875.

Bell, V.A., et al., 2009. Use of soil data in a grid-based hydrological model to estimate spatial variation in changing flood risk across the UK. J. Hydrol. 377 (3-4), 335–350. https://doi.org/10.1016/j.jhydrol.2009.08.031.

Bell, V.A., et al., 2016. An assessment of the possible impacts of climate change on snow and peak river flows across Britain. Clim. Change 136 (3-4), 539–553. https://doi.org/10.1007/s10584-016-1637-x.

Brown, I., et al., 2011. Climate change, drought risk and land capability for agriculture: implications for land use in Scotland. Reg Environ Change 11 (3), 503–518. https://doi.org/10.1007/s10113-010-0163-z.

Burnett, D., et al., 2014. The UK solar energy resource and the impact of climate change. Renewable Energy 71, 333–343. https://doi.org/10.1016/j.renene.2014.05.034.

Carbon Trust, 2012. Degree Days for Energy Management. Carbon Trust: London.

CEH, 2017. Land Cover Map 2015 UK Centre for Ecology and Hydrology.

Chapman, L., 2015. Weather and climate risks to road transport. Infrastructure Asset Management 2, 58-68.

Cho, K., et al., 2012. Winter wheat yields in the UK: uncertainties in climate and management impacts. Clim. Res. 54 (1), 49–68. https://doi.org/10.3354/cr01085.

Committee on Climate Change, 2015. Reducing emissions and preparing for climate change: 2015 Progress Report to Parliament. Committee on Climate Change, London.

Committee on Climate Change, 2019. Progress in preparing for climate change: 2019 Progress Report to Parliament. Committee on Climate Change, London.

Copernicus Climate Change Service (C3S), 2017. ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), 30/07/2019. https://cds.climate.copernicus.eu/cdsapp#!/home.

Daccache, A., et al., 2012. Climate change and land suitability for potato production in England and Wales: impacts and adaptation. J. Agric. Sci. 150 (2), 161–177. https://doi.org/10.1017/S0021859611000839.

de Jong, M.C., et al., 2016. Calibration and evaluation of the Canadian Forest Fire Weather Index (FWI) System for improved wildland fire danger rating in the United Kingdom. Nat. Hazards Earth Syst. Sci. 16, 1217–1237.

Dunn, R.J.H., et al., 2014. Analysis of heat stress in UK dairy cattle and impact on milk yields. Environ. Res. Lett. 9, 064006.

European Environment Agency, 2017. Climate change, impacts and vulnerability in Europe 2016: an indicator based report. EEA Report 1/2017.

Fodor, N., et al., 2018. Spatially explicit estimation of heat stress-related impacts of climate change on the milk production of dairy cows in the United Kingdom. PLoS ONE 13(5), e0197076.

Glaves, D.J., et al., 2020. The causes and prevention of wildfire on heathlands and peatlands in England. Natural England Evidence Review NEER014. Peterborough: Natural England.

Gohar, G., et al., 2018. UKCP18 Derived Projections of Future Climate over the UK. Met Office.

Gosling, S.N., Arnell, N.W., 2010. Simulating current global river runoff with a global hydrological model: model revisions, validation and sensitivity analysis. Hydrol. Process. 25 (7), 1129–1145.

Hajat, S., et al., 2014. Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. J. Epidemiol. Community Health 68 (7), 641–648. https://doi.org/10.1136/jech-2013-202449.

Harding, A.E., et al., 2015. "Agro-meteorological indices and climate model uncertainty over the UK". Clim. Change 128 (1-2), 113–126. https://doi.org/10.1007/s10584-014-1296-8.

Harkness, C., et al., 2020. Adverse weather conditions for UK wheat production under climate change. Agric. For. Meteorol. 282-283, 107862. https://doi.org/10.1016/j.agrformet.2019.107862.

Hausfather, Z., Peters, G.P., 2020. Emissions – the 'business as usual' story is misleading. Nature 577 (7792), 618–620. https://doi.org/10.1038/d41586-020-00177-3.

Highways England, 2016. Climate Adaptation Risk Assessment Progress Update -2016. Highways England.

HM Government, 2012. *UK Climate Change Risk Assessment*: Government Report. Defra.

HM Government, 2017. *UK Climate Change Risk Assessment 2017*. HM Government.

Hollis, D., et al., 2019. HadUK-Grid—A new UK dataset of gridded climate observations. Geosci Data J 6 (2), 151–159. https://doi.org/10.1002/gdj3.78.

Hough, M., Jones, R.J.A., 1997. The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0– an overview. Hydrol. Earth Syst. Sci., 1(2), 227–239.

HR Wallingford, 2015. CCRA2: Updated projections for water availability for the UK. HR Wallingford MAR5343-RT002-R05-00.

IPCC, 2010. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). Field, C.B. et al. (eds). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jones, L., et al., 2020. Climate driven threshold effects in the natural environment. Report to the UK Climate Change Committee, May 2020.

Kay, A.L., et al., 2014. Probabilistic impacts of climate change on flood frequency using response surfaces. 1: England and Wales. Reg. Environ. Change 14, 1215–1227.

Kay, A.L., et al., 2020. Climate change impacts on peak river flows: combining national-scale hydrological modelling and probabilistic projections. Clim. Risk Manage. https://doi.org/10.1016/j.crm.2020.100263.

Kay, A.L., et al., submitted. Climate change effects on indicators of high and low river flow across Great Britain. submitted.

Kendon, E., et al., 2019. UKCP Convection-permitting model projections: Science Report. Met Office Hadley Centre.

Kendon, M., et al., 2019. State of the UK climate 2018. Int. J. Climatol. 39 (S1), 1–55. https://doi.org/10.1002/joc.6213.

Kingsborough, A., et al., 2017. Development and appraisal of long-term adaptation pathways for managing heat-risk in London. Clim. Risk Manage. 16, 73–92. https://doi.org/10.1016/j.crm.2017.01.001.

Lowe, J.A., et al., 2018. UKCP18 Science Overview Report. Met Office Hadley Centre, version 2.0.

Mäkinen, K., et al., 2018. Indicators for adaptation to climate change at national level - Lessons from emerging practice in Europe. European Topic Centre on Climate Change impacts, Vulnerability and Adaptation (ETC/CCA) Technical paper 2018/3.

McCarthy, M., et al., 2019. A new heatwave definition for the UK. Weather 74 (11), 382–387. https://doi.org/10.1002/wea.3629.

Met Office, 2018a. HadUK-Grid Gridded Climate Observations on a 12km grid over the UK for 1862-2017. Centre for Environmental Data Analysis, 15/07/2019. http://catalogue.ceda.ac.uk/uuid/dc2ef1e4f10144f29591c21051d99d39.

Met Office, 2018b. HadUK-Grid Gridded Climate Observations on a 1km grid over the UK for 1862-2017. Centre for Environmental Data Analysis, 15/07/2019.

Murphy, J.M., et al., 2019. UKCP18 Land Projections: Science Report. Met Office Hadley Centre, version 2.0.

Network Rail, 2020a. National Operating Procedures: Weather Arrangements. Network Rail, NR/L3/OPS/045/3.17 issue 3.

Network Rail, 2020b. Route CP6 Weather Resilience and Climate Change Adaptation Plans: Western, 2019-2024. Network Rail.

O'Neill, B.C., et al., 2018. The Benefits of Reduced Anthropogenic Climate changE (BRACE): a synthesis. Clim. Change 146 (3-4), 287–301. https://doi.org/10.1007/s10584-017-2009-x.

Palin, E.J., et al., 2013. Future projections of temperature-related climate change impacts on the railway network of Great Britain. Clim. Change 120 (1-2), 71–93. https://doi.org/10.1007/s10584-013-0810-8.

Parsons, D.J., et al., 2019. Regional variations in the link between drought indices and reported agricultural impacts of drought. Agric. Syst. 173, 119–129.

Pritchard, O.G., et al., 2015. Probabilistic soil moisture projections to assess Great Britain's future clay-related subsidence hazard. Clim. Change 133 (4), 635–650. https://doi.org/10.1007/s10584-015-1486-z.

Prudhomme, C., et al., 2012. The drying up of Britain? A national estimate of changes in seasonal river flows from 11 Regional Climate Model simulations: SCIENTIFIC BRIEFING. Hydrol. Process. 26 (7), 1115–1118. https://doi.org/10.1002/hyp.8434.

Public Health England, 2019. Heatwave plan for England. NHS England and Public Health England.

Qi, A., et al., 2018. Grassland futures in Great Britain – Productivity assessment and scenarios for land use change opportunities. Sci. Total Environ. 634, 1108–1118. https://doi.org/10.1016/j.scitotenv.2018.03.395.

Reynard, N.S., et al., 2017. The evolution of climate change guidance for fluvial flood risk management in England. Progr. Phys. Geograp. Earth Environ. 41 (2), 222–237. https://doi.org/10.1177/0309133317702566.

Riahi, K., et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environ. Change 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rivington, M., et al., 2013. Climate change impacts and adaptation scope for agriculture indicated by agro-meteorological metrics. Agric. Syst. 114, 15–31.

RSSB, 2013. TRaCCA Report WP1B: Operational weather thresholds analysis. Report prepared by Met Office for TRaCCA.

Rudd, A.C., et al., 2019. National-scale analysis of future river flow and soil moisture droughts: potential changes in drought characteristics. Clim. Change 156 (3), 323–340. https://doi.org/10.1007/s10584-019-02528-0.

Sanderson, M.G., Ford, G.P., 2016. Projections of severe heat waves in the United Kingdom. Clim. Res. 71 (1), 63–73. https://doi.org/10.3354/cr01428.

Sayers, P.M., et al., 2015. Climate Change Risk Assessment. In: Projections of future flood risk in the UK. Project A: Report prepared for the Committee on Climate Change. Sayers and Partners, UK.

Schwalm, C.R., Glendon, S., Duffy, P.B., 2020. RCP8.5 tracks cumulative CO_2 emissions. Proc Nat Acad. Sci 117, 19656–19657.

Svensson, C., et al., 2017. Statistical distributions for monthly *aggregations* of precipitation and streamflow in drought indicator applications. Water Resour. Res. 53, 999–1018.

Vallejo, L., 2017. Insights from national adaptation monitoring and evaluation systems. Climate Change Expert Group Paper no 2017 (3) OECD COM/ENV/EPOC/IEA/SLT(2017)3.

Vardoulakis, S., et al., 2014. Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia. Environ. Health Perspect. 122, 1285–1292.

Williams, K.D., et al., 2017. The Met Office Global Coupled Model 3.0 ad 3.1 (GC3.0 and GC3.1) Configurations. J. Adv. Modell. Earth Syst. 10, 357–380.

Wood, F.R., et al., 2015. The impact of climate change on UK energy demand. Infrastruct. Asset Manage. 2, 107–119.

Yawson, D.O., et al., 2016. Simulated regional yields of spring barley in the United Kingdom under projected climate change. Climate 4, cli4040054.

Yawson, D.O., et al., 2019. Regional variations in potential groundwater recharge from spring barley crop fields in the UK under projected climate change. Groundwater Sustainable Dev. 8, 332–345.