



Improved Understanding and Characterisation of Climate Hazards in the UK

*Jennifer Catto, Simon Brown, Clair Barnes, Steven Chan,
Daniel Cotterill, Murray Dale, Laura Dawkins,
Hayley Fowler, Freya Garry, Will Keat, Elizabeth Kendon,
Jason Lowe, Colin Manning, David Pritchard, Peter Robins,
David Sexton, Rob Shooter and David Stephenson*

Abstract

- This chapter describes new methods and datasets, developed through UK Climate Resilience Programme (UKCR) projects, to better understand climate hazards.

Lead Authors: Jennifer Catto & Simon Brown

Contributing Authors: Clair Barnes, Steven Chan, Daniel Cotterill, Murray Dale, Laura Dawkins, Hayley Fowler, Freya Garry, Will Keat, Elizabeth Kendon, Jason Lowe, Colin Manning, David Pritchard, Peter Robins, David Sexton, Rob Shooter & David Stephenson

J. Catto (✉) · D. Stephenson
University of Exeter, Exeter, UK
e-mail: j.catto@exeter.ac.uk

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- We describe projections of hazards using new tools and provide examples of applications for decision-making.
- Going forward, this new physical and statistical understanding should be incorporated into climate risk assessments.

Keywords Climate hazards · Flood · Extreme weather · High-resolution modelling · Statistical methods for extremes

1 INTRODUCTION

To improve resilience in response to climate change, it is vital to have the best possible understanding of weather and climate hazards facing the UK both now and in future. The latest IPCC report [1] used the concept of ‘climate impact-drivers’ (CID), which are particular climate states that may or may not lead to hazards and subsequent impacts, depending on the global location [2]. This is only one part of the consideration of impacts, since the vulnerability and exposure also need to be considered. Here, we specifically consider a subset of CID that are expected to have

S. Brown (✉) · D. Cotterill · L. Dawkins · F. Garry · W. Keat · E. Kendon ·
J. Lowe · D. Sexton · R. Shooter
Met Office, Exeter, UK
e-mail: simon.brown@metoffice.gov.uk

C. Barnes
University College London, London, UK

S. Chan · H. Fowler · C. Manning · D. Pritchard
Newcastle University, Newcastle upon Tyne, UK

M. Dale
JBA Consulting, Exeter, UK

E. Kendon
University of Bristol, Bristol, UK

P. Robins
Bangor University, Bangor, Wales, UK

negative impacts on the UK namely key hazards of extreme precipitation, high winds and heat extremes. Through the work of the UKCR programme, the data and methods used to identify and characterise these hazards—such as physical and statistical models—have advanced significantly. Researchers now have a better physical understanding of relevant hazards (e.g. how extreme rainfall interacts with different weather systems), which will underpin projections of the three key hazards in the UK. These new insights also enable researchers to better distil and communicate climate information (and associated uncertainties) to decision-makers.

In this chapter, we will discuss each of these aspects and provide a list of datasets and tools described (see Table 1). For further detail on how hazard information has been translated into decision-relevant knowledge, please refer to Chaps. 10 and 11.

2 ADVANCES IN HAZARD DATA

Numerical climate models, which simulate future weather based on our knowledge of the physics of the climate system, are used to simulate future hazards in the UK. Two simulations of the UK Climate Projections (UKCP18), which allow a detailed investigation of the UK and Europe, were used in several UKCR projects: UKCP Regional projections (12 km resolution) and UKCP Local projections (2.2 km resolution). Studies found that the local simulations are superior to the regional simulations, when compared with observational datasets for certain variables [12]. For example, the effects of conurbations on extreme temperatures in the present climate are found to be more realistically simulated for UKCP Local compared with UKCP Regional [13], and the representation of seasonal mean as well as short duration heavy rainfall events is also better [12]. Further, estimates of future river flooding using the DECI-PHeR hydrological model for two benchmark catchments (Rivers Thet and Dyfi) differ considerably between UKCP Local and UKCP Regional [14], implying that high-resolution space–time varying precipitation fields are important in flood risk analysis.

To complement the UKCP18 data, the project ‘ExSamples’ [11] has provided a large and rich set of extreme winter scenarios for the late twenty-first century, using an atmosphere-only model at 60km resolution, run on distributed computing via <https://www.climateprediction.net> for climateprediction.net. The atmosphere is forced with prescribed sea

Table 1 The table provides UKCR outputs relating to hazards, as described in this chapter: tools and code (blue); websites for data exploration (yellow); and datasets (green)

Project	Product	Resources
STORMY-WEATHER	Front identification code	Ref: Sansom and Catto [3] Webpage: https://github.com/phil-sansom/front_id
FUTURE-DRAINAGE	RED-UP Rainfall Perturbation Tool	Ref: Dale [4] https://ukwir.org/How-do-we-achieve-zero-uncontrolled-discharges-from-sewers-by-2050#case-studies
Improving Climate Hazard Information	HOTdays tool	Ref: Brown [5] Contact: simon.brown@metoffice.gov.uk
Stochastic Simulation	Stochastic weather generator	Contact: hayley.fowler@newcastle.ac.uk
SEARCH	Risk of compound flooding map	Ref: Lyddon et al. [6] Webpage: https://www.researchgate.net/publication/363166162_Historic_Spatial_Patterns_of_Storm-Driven_Compound_Events_in_UK_Estuaries
EuroCORDEX-UK	Data explorer webpage	Webpage: https://github-pages.ucl.ac.uk/UKCORDEX-plot-explorer/
Multiple Hazards	Case studies of agricultural compound hazards	Ref: Garry et al. [7]
STORMY-WEATHER	Storm type dataset	Ref: Catto et al. (in prep) [8] Contact: j.catto@exeter.ac.uk
FUTURE-DRAINAGE	Design rainfall flood uplifts	Ref: Chan et al. (under review) [9] Webpage: https://artefacts.ceda.ac.uk/badc_datadocs/future-drainage/FUTURE_DRAINAGE_Guidance_for_applying_rainfall_uplifts.pdf
Improving Climate Hazard Information	Return levels at high resolution	Ref: Shooter and Brown (under review) [10]
ExSamples	Extreme winter scenarios	Ref: Leach et al. [11]

surface temperatures (SSTs) from unusually warm (Fig. 1) or wet future winters, allowing robust sampling of extreme atmospheric states. This information is potentially suited to informing adaptation planning and decision-making—including high risk scenarios that have impacts across multiple sectors and regions of the UK,—such as infrastructure damage. Aspirations for future work in this area include using higher resolution models and potentially converting these samples into a product for use in UKCP.

Hydrodynamic modelling is required to translate multiple meteorological hazards, such as extreme high sea levels and rainfall, into a compound flooding hazard. The ‘SEARCH’ project has developed 20–50m scale

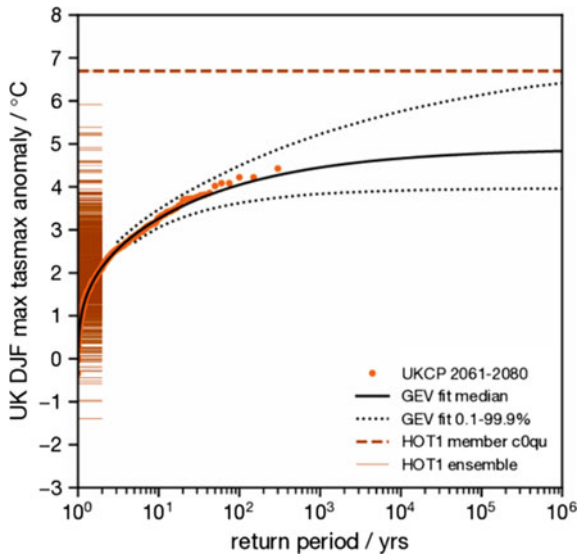


Fig. 1 Return period diagram (From Leach et al. [11]) showing the return period of UK DJF maximum surface temperature anomaly from the UKCP ensemble from 2061–2080. The black curve shows the median of the generalised extreme value (GEV) model fit and the dotted lines show the 0.1–99.9% confidence interval on the GEV fit. The thin orange lines on the left show the UK DJF maximum surface temperature anomalies from the ExSamples ensemble. This figure demonstrates that using the relatively low-resolution model in this study, forced with the SSTs from an extreme hot winter, produces even larger anomalies than the UKCP ensemble. Reproduced according to the CC-BY licence

digital elevation models (that include flood defence heights) for 12 UK estuaries, which are used to parameterise flood inundation models in the landscape evolution model CAESAR-Lisflood. These models have demonstrated that sub-daily river discharge and sea level data are required to understand flood risk in UK estuaries [6, 15, 16] and have established local-scale thresholds for the drivers of flooding. Historical compound flooding across 126 estuaries of Britain was investigated [6] at sub-daily scale to isolate catchments that are currently most vulnerable to storm-driven compound events, such as many of the steep catchments on the west coast of Britain. These tools, together with future projections of extreme rainfall and sea level variability, have been used to determine the future compound flooding hazard for UK catchments and will be available as a risk map.

Physical modelling of climate hazards requires significant computing resource, whereas statistical modelling offers a potentially less expensive alternative, as explored through the UKCR embedded researcher ‘Stochastic Simulation’ project and the (non-UKCR) ‘FUTURE-STORMS’ project. This has improved accessibility, openness and usability of a well-established spatio-temporal stochastic weather generator, including extreme value modelling of rainfall improvements. Functionality has also been improved, making it easier for users to run the weather generator with climate perturbations from UKCP18—and helping to overcome barriers to use, thereby allowing a wider range of users to conduct their own simulations for bespoke future hazard characterisation.

A new approach (and dataset) has been developed that allows user-specified heatwave definitions, including day of year and degree of global warming [5]. This allows for the precise characterisation of the severity, duration and frequency of heatwaves for any date and time of year and estimates the probability of heatwaves that are more extreme than any observed or simulated in climate models.

3 ADVANCES IN METHODS FOR CHARACTERISING HAZARDS

The accurate characterisation of a hazard is necessary for rigorous risk estimates and appropriate adaptation, but by construction is very difficult due to the rarity of very extreme events. Therefore, robust statistical methods, that make the best use of all available data, are required. A new approach to estimating extreme properties involved pooling data from multiple sites to aid extremal inference at a given location, without losing spatial

detail and differences between sites [17, 18]. Using a ‘generalised additive model’ framework, extreme value distributions are fitted to observations from the UK station network—together with smooth covariates that are functions of elevation, latitude and longitude—to produce extreme value distributions for the whole of the UK at a resolution of 1km. Values for daily precipitation [10] and annual wind gusts were produced at 10, 50 and 100-year return levels. These are available online.

The UKCR project ‘Multiple Hazards’ has also used generalised additive models to build robust event sets from UKCP18 data, to help quantify probabilities of both uni-variate and multi-variate extreme events occurring by creating larger datasets with the same spatial and temporal statistical properties [19]. The project has also identified how multi-variate climate hazards may impact UK agriculture [7], helping the farming sector understand its adaptation needs. Further research by the project considers UKCP18 model biases in multi-variate relationships [20]. For example, at a given location, when the model tends to be warmer than observed, does it also tend to be too dry or too wet? [20] These interrogations are crucial to understanding uncertainties in current model projections of multi-variate climate hazard and risk, as well the development of future model simulations.

The UKCR project ‘STORMY-WEATHER’ has developed an objective front identification method that is scalable so that it can be applied to the ERA5 dataset, as well as other high-resolution datasets [3]. A dataset of storm types (combinations of cyclones, fronts and thunderstorms) [8, 21, 22] has been produced for ERA5, which allows hazards (e.g. extreme precipitation and winds) and their co-occurring events to be characterised as associated with particular weather systems. Future changes in the hazards can then be determined based on changes in the frequency or characteristics of the storm types, enabling an analysis of plausible worst-case storms for the future.

4 IMPROVED PHYSICAL UNDERSTANDING OF HAZARDS

By making use of new datasets and characterisation of hazards, the physical understanding of these hazards in the present climate can be refined, thereby improving confidence in future projections. UKCR projects explored the urban influence on changes in local weather extremes through UKCP Local and Regional simulations. The local model reproduced the night-time heat island effect more accurately than the regional model due to improved land-surface and urban representation. The two

models give different future projections of the urban heat island effect, with very little change projected by the local model [13] associated with differences in the land-surface model and the influence of soil moisture. These results have implications for urban planning and public health.

For flood hazard estimation, hydrological models have typically used input from regional scale models. The UKCP Local simulation data used in catchment scale models indicate larger increases (or smaller decreases) in future peak river flow than previously found in some catchments. Further, a pilot study for Bristol looking at pluvial flooding using the LISFLOOD hydrodynamic model [14] shows that future changes in flood hazard are very different when the model is driven by UKCP Local data compared with precipitation ‘uplifts’. This shows the importance of fully capturing changes in space/time rainfall variability and how it interacts with the landscape and demonstrates the need for a national scale follow-on study.

5 FUTURE HAZARDS

The UKCP Local projections, providing 12 high-resolution convection-permitting simulations of the future, were used as part of the UKCR project ‘FUTURE-DRAINAGE’ to develop UK-wide rainfall intensity uplifts [9]. These uplifts were applied to ‘design rainfall’ at particular return periods (e.g. a one in 50 year event), which is used as the industry standard for all UK flood risk studies and assessments. Through the project, quantitative uncertainty estimates of these uplifts have been provided for the first time; they have already been used by the Environment Agency and the Scottish Environment Protection Agency to develop peak rainfall climate change allowances, used for designing and evaluating flood risk management options. The uplifts are also being used by UK water and sewerage companies to help manage and avoid current and future sewer flooding [4]. The UKCP Local projections were also used to develop new time series rainfall projections at very high temporal resolutions (sub-five-minute) for the UK water industry, to better understand and manage impacts on pollution spills from sewer networks [4].

The UKCR project ‘Improving Climate Hazard Information’ found that, over the past 100 years, extreme precipitation events during autumn increased in frequency by 60% [23] and are expected to increase even more in future [24]. Mean autumn rainfall is expected to decrease in future, due to an increase in dry summer-type weather patterns and

fewer wet winter-type patterns, based on the latest Coupled Model Inter-comparison Project (CMIP6) models and UKCP climate projections [25]. Complementing this research, the ‘FUTURE-STORMS’ project also found that summer and autumn precipitation is heavily influenced by organised convective systems on scales of up to 50km, and the contribution of these systems to heavy precipitation is projected to at least double in future [26]. This results in an unequal distribution of heavy precipitation events in time and space. Projections show a 14-fold increase in slow-moving convective storms, with the potential for high precipitation accumulations over land across Europe by 2100 [27]. These results indicate a simultaneous increase in risk from both flood and drought.

Using the UKCP18 ensemble, the UKCR project ‘STORMY-WEATHER’ predicted significant future increases in the frequency of extreme windstorms over the UK; one in 20-year storms in the 1990s could occur once every 10 years by the 2070s under a high emissions scenario [28]. This is consistent with the projected increase in intensity of the strongest storms found using CMIP6 models [29], and the projected increase in the occurrence of sting jets found using convection-permitting climate models (CPM) [30]. In terms of climate hazards, these windstorms pose the greatest risk to electricity distribution networks in the UK and are a significant cause of insured losses in the sector. Communication with relevant stakeholders on the characterisation of hazards is ongoing, via the following projects: ‘Climate services for a Net Zero resilient world’ (CS-N0W) funded by the Department for Business, Energy and Industrial Strategy (BEIS) (<https://www.gov.uk/government/organisations/department-for-business-energy-and-industrial-strategy>); and ‘Assessment of climate change event likelihood embedded in risk assessment targeting electricity distribution’ (ACCELERATED) funded by Western Power Distribution (now National Grid). Knowledge of the precursors of sting jets has also been used to provide a new forecasting tool at the Met Office, which has already been useful for producing timely weather warnings [31].

The UKCP simulations were further used in the UKCR project ‘Multiple Hazards’, which looked at how compound hazards may affect the UK agricultural sector, such as the increase in hot dry summers like that of 2018 [7]. When high temperatures couple with high humidity, the risk of heat stress in livestock and blight in potato crops increases; for example, there may be a tenfold increase in the number of days of dairy cattle heat stress in the next 50 years in the South West of England [7]. These results were communicated to industry partners and fed into the

United Kingdom Food Security Report, published by the Department for Environment, Food and Rural Affairs (Defra) in December 2021.

6 DISTILLING CLIMATE INFORMATION

The advancements in our understanding and projection of climate hazards achieved by the UKCR programme are of significant value to the production of user information on climate risk. To understand the impact of climate hazards on UK communities, we must consider how to quantify uncertainties around the fidelity of models, the use of different models, bias adjustment and projections with different warming levels. For example, in the UKCR ‘Risk Assessment Frameworks’ project, heat-stress risk was estimated using an open-source risk assessment framework (CLIMADA) and temperature and humidity data from multiple data sources. Part of the uncertainty associated with risk can be attributed to hazard information, highlighting the need to further understand the hazards and how best to bias-correct in the data sources, as well as having improved observations against which to evaluate the data sources [32]. Understanding these biases is also key for the multi-variate relationships between heat and humidity used to estimate risk to agriculture and other sectors [7]. Developing an uncertainty budget for risk (a function of hazard, exposure and vulnerability) that includes such nuances would be valuable for decision-making.

According to findings from the ‘EuroCORDEX-UK’ project, the uncertainty described above is associated with the different levels of warming seen in different model projections. While the UKCP18 and EuroCORDEX ensembles display similar biases in surface air temperature over the UK in the present day, they project very different levels of warming after this, resulting in corresponding differences in hazards such as heat, drought and extreme precipitation. Further understanding of the rates of warming in the simulations—or associating impacts to global warming levels rather than timescales—would help to constrain these projections.

7 CONCLUSIONS

The UKCR projects described above highlight the importance of considering the nuances between models when examining how climate-related hazards may change in future in the UK. Uncertainties between the UKCP Regional and Local simulations suggest that it is essential to have a physical understanding of the hazards when interpreting model output.

Incorporating more detailed information into the smaller-scale ensemble would further add confidence in the projections—capturing future urban changes, for example, is important because of the influence of the built environment on convective storms, and because the effect of urbanisation on climate impacts is unclear. Some projects have used data from model simulations at regional (or lower) resolution; this could be extended to the higher resolution convection-permitting model data, which provides a much more reliable representation of hourly rainfall, local extremes and future change. However, improvements to the uncertainty estimates associated with the CPMs could be made by using a multi-model GCM ensemble to drive the CPM [33] or ensembles of CPMs themselves.

New physical (e.g. flooding) and statistical (e.g. heatwave) models have contributed to projections of worst-case scenarios for the hazards in question. In addition, there has been a focus on the physical causes of hazards; for example, precipitation extremes have been considered in terms of slow-moving storms, weather system types and seasonal weather patterns. This information helps with the interpretation of future hazards, which is a function of both the changing frequency and the hazard characteristics of the driver. Evaluation is now needed to assess how the new information (e.g. precipitation uplifts) is actually being used.

A key challenge going forward is how to convert new information on hazard to estimates of risk, by considering the risk budget of hazard, vulnerability and exposure. Data from CPM (and other) models needs to be fed into hydrological (and other) models on a national scale, requiring a much better understanding of vulnerability and exposure and improved collaboration between different disciplines.

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