

ClimAtt: Tools for Climate Change Attribution of Extreme Weather Events

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ClimAtt: Tools for Climate Change Attribution of Extreme Weather Events

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EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Cork and Oxford University

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

The ClimAtt project aimed to assess a set of tools for investigating the attribution of extreme weather events in Ireland to climate change. Probabilistic event attribution (PEA) is a relatively new branch of climate science that has not been previously applied to Ireland. PEA allows for evidence-based communication of the impacts of climate change to the general public and decision-makers by investigating the link between specific types of events (e.g. regional droughts) and anthropogenic climate change. PEA has been made possible by the availability of large ensembles of climate model simulations brought about by advances in computing power. The use of large ensembles allows a probabilistic approach to be taken. Each run in an ensemble is obtained under similar specified climate forcings. One ensemble may include atmospheric forcing due to human activities, and a paired ensemble may exclude them. The likelihood of a particular type of extreme weather event occurring can be estimated by counting the number of times it occurs in a particular ensemble.

This report gives a background to the field of attribution, describing an inventory of past extreme weather events that may form the basis for further attribution studies. It also introduces the state of the art in PEA, provides a case study of the application of the technique to a past extreme weather event in Ireland, proposes a suitable hydrological modelling framework for flood attribution, and makes recommendations for future attribution work.

The primary focus of the work is on precipitation extremes. Although attribution of extreme rainfall events is more difficult than attribution of temperature extremes, rainfall extremes are the events that tend to have the greatest economic and societal impacts in Ireland. The meteorological event that led to the widespread floods of November 2009 is selected as a case study. This allows for a detailed appraisal of the observational record to be carried out and then for several of the available attribution datasets to be validated against the observations. A

subset of 20 observation stations was selected from the Met Éireann database of precipitation records. These were identified as having the best spatial representativeness, data quality, continuity and temporal coverage of the available records. These were used to generate regional cluster averages and multi-station averages against which to compare attribution model datasets.

Several climate change attribution model datasets from the Coupled Model Intercomparison Project and other sources and downscaled simulations from the EURO-CORDEX programme are validated against observed rainfall events in Ireland. Some of the models exhibited low bias when compared with observations, which provided confidence in the general representativeness of those models for Irish climatic conditions. Owing to the strong marine influence on the climate of Ireland, the accuracy of the sea surface temperature (SST) representation in the model datasets has a strong influence on the models' performance against observations. For the heavy rainfalls of 2009 that led to the widespread and hugely damaging floods of November 2009, no anthropogenic influence was detectable from any of the attribution model datasets. These findings demonstrate the difficulty of attributing changes in precipitation extremes in a relatively small and marine-influenced target area such as Ireland.

For future attribution studies on Irish extreme weather events, we recommend using a model dataset with prescribed values of SST, which will more accurately represent local mean conditions and natural variability. The recommendation for end-to-end attribution of fluvial flooding impacts in Ireland is to use a lumped hydrological model such as the Probability Distributed Model, developed by the Centre for Ecology and Hydrology in the UK. This class of model requires several orders of magnitude fewer input data than the other type of model considered, i.e. fully distributed models such as GEOtop.

1 Introduction

1.1 Background

Although Ireland has a maritime influence that moderates its climate, extreme weather events are of increasing concern. The slow-onset changes in the climatic system, such as the increase in sea surface temperature (SST) and the rise in sea level, that have been taking place since 1950 due to human influence (Pachauri and Meyer, 2014) also affect Ireland. However, extreme weather and climate events, rather than gradual changes, are of particular concern owing to their high societal and economic impacts (Field et al., 2012).

Anthropogenic emissions of greenhouse gases (GHGs) have led to increases in mean global temperatures and, as a consequence, an increase in the moisture-holding capacity of the atmosphere. This relationship between temperature and water vapour-carrying capacity is expected to bring more frequent and/or more intense extreme precipitation events. Several studies have confirmed the connection between changes in the risk of extreme precipitation events and anthropogenic climate change (Min et al., 2011; Trenberth, 2011; van der Wiel et al., 2017; Otto et al., 2018).

The development of a relatively new subfield of atmospheric science termed probabilistic event attribution (PEA) (Allen, 2003; Otto, 2016; Stott et al., 2016) allows for the estimation of the human influence on the odds of occurrence of a specific class of weather event. PEA offers a wide range of approaches and methods that are determined by how the attribution question is framed, and it has been applied to study the influence of anthropogenic climate change on extreme weather-related events such as heavy rainfalls, floods, droughts, heat waves and wind storms. The PEA methodology will be described in detail in section 2.2.

1.2 Study Area Definition

The area of study is Ireland, which lies between 51.5° and 55.5° N and 5.5° and 10.5° W. Many of the events and gridded datasets analysed in this report also apply to parts of Northern Ireland, but only observation

records from Ireland are used. Ireland has an average altitude of 150 m in the central region, with mountains of around 600 m, the highest of which reaches 1041 m above sea level (Rohan, 1986).

Ireland's climate is highly influenced by the Atlantic Ocean, where depressions may form and then travel across the country from west to east (Rohan, 1986). As a consequence, there are a large number of rain days throughout the year, with up to 250 rain days (days with 1 mm or greater of rain) experienced near the west coast, and the differences between the winter and summer seasons are buffered (Rohan. 1986). The location of Ireland leads to a gradient in precipitation, with higher annual values in the west of the country, while the precipitation may be higher in the north in autumn and winter (Perry, 1972) because of the trajectory of the storms. It is not surprising then that large-scale floods particularly affect the west and south-west of Ireland, especially during periods of southerly or cyclonic circulation types (Sweeney and O'Hare, 1992).

1.3 Precipitation Extremes in Ireland

Rainfall patterns in Ireland are heavily influenced by the depressions that sweep across the country from west to east, forcing warm and moist air to the north, with the cold and dry air behind the front moving southwards (Rohan, 1986). The spatial distribution of the precipitation across the country is also influenced by the trajectory of these depressions from the Atlantic. Heavy convective precipitation events are less severe and frequent than in continental Europe, but some notable events have occasionally occurred, e.g. the heavy rainstorm of 11 June 1963 in Dublin (Morgan, 1971).

There is a seasonal difference in rainfall patterns between the north and the south of Ireland. In the northern part of the country, most of the rainfall occurs in autumn and winter, in the majority of cases due to depressions from the Atlantic (Perry, 1972). In eastern parts of the country, average annual rainfall can reach values between 750 and 1000 mm, while in the west values may be 1000–1250 mm, or even 1500 mm in

coastal areas (Rohan, 1986). Values of 2000 mm and 3000 mm per annum can be found in the mountains of the south-west and west, respectively (Rohan, 1986). The average rainfall amount falling at lowland stations in an hour having rain is between 1 and 2 mm. The mean minimum and maximum duration of rainfall is found at noon and early morning, respectively (Rohan, 1986). A change point indicating an increase in annual average precipitation around the year 1975 has been identified by previous studies (Kiely et al., 2010; Leahy and Kiely, 2011), coincident with a change in phase of the North Atlantic Oscillation (NAO). An increase has also been detected in the late 1970s in the annual precipitation and frequency of extreme precipitation events, which was strongest on the west side of the country (Kiely, 1999). Furthermore, a positive trend has been detected in the average precipitation anomaly on the west coast, with change points occurring between 1975 and 1978 (Kiely et al., 2010). Walsh (2012) compared long-term climate averages for Ireland for the periods 1961-1990 and 1981-2010 and observed an overall 5% increase in rainfall totals in the second period compared with the first, with higher increases in the west and lower increases in the east. McElwain and Sweeney (2007) observed a significant increase in the number of days with rainfall greater than 10 mm at locations in the west of the country. Recent research has led to an improved availability of homogenised monthly rainfall data for Ireland (Noone et al., 2016).

A negative trend in July precipitation has been observed in the east and south-east areas of Ireland since 1975. However, annual flows in the Rivers Suir, Nore and Fergus, in the east part of the country, have increased as a result of the increase in precipitation during March and October after 1975 (Kiely *et al.*,

2010). In this eastern part of the country, a general increase was also observed in the spring and summer rainfall, along with increased storm severity and frequency (Leahy and Kiely, 2011).

Changes in precipitation and extreme rainfall events in Ireland have been studied based on projections for different future scenarios of GHG emissions (Nolan et al., 2017). Extreme rainfall events in autumn and winter are likely to increase but with uncertainties in the projections (Steele-Dunne et al., 2008). Under two different scenarios of future climate change, 2041–2070 and 2061–2090, a widespread reduction in run-off across all the country is predicted, especially affecting the east and south-east, whereas a slight increase is predicted in the north-west, particularly for the period 2061–2090 (Charlton et al., 2006).

To the best of our knowledge, no analysis has been carried out on the extent to which anthropogenic climate change has already influenced extreme precipitation in Ireland. This study aims to understand better the impact to date of GHG emissions and other anthropogenic factors on extreme precipitation in Ireland by means of PEA. The results will not only help to increase knowledge of the human influence on extreme precipitation in Ireland, but hopefully also provide a deeper insight into the climate system and the physical processes underlying those changes, as well as inform climate change adaptation strategies.

1.4 Project Objective

The overall objective of the project was to specify, implement and demonstrate a probabilistic extreme weather event climate change attribution methodology, appropriate for deployment and further development in Ireland.

2 Probabilistic Event Attribution

2.1 Background

The overall warming of the global climate system since the 1950s cannot be fully explained by natural climate forcings alone. Anthropogenic emissions of GHGs are the most probable cause of this warming (IPCC, 2014). The observed increase in the mean global temperature has a direct impact on the moisture-holding capacity of the atmosphere, with increments of 6-7% per degree Celsius according to the Clausius-Clapeyron relationship. This increase in atmospheric water vapour has led to enhanced mean precipitation and more frequent occurrences of heavy precipitation (Steele-Dunne et al., 2008), has intensified global precipitation extremes over land, and has modified the patterns of heavy precipitation (IPCC, 2014). In Europe, the intensity and frequency of heavy precipitation have increased (Pauling and Paeth, 2007). As a result, there is greater risk of flooding at regional scales (IPCC, 2014).

Anthropogenic climate change can affect the mean values and extremes of precipitation in several ways. The resulting changes in precipitation can vary in magnitude and change from positive to negative between adjacent areas and over different time scales. Furthermore, the frequency and magnitude of responses of an extreme event to anthropogenic climate change may exhibit opposite behaviours, with certain types of extreme event becoming more severe but less frequent, and vice versa (Otto *et al.*, 2012; Archfield *et al.*, 2016; Burke *et al.*, 2016).

2.1.1 Previous studies

The new field of PEA allows the evaluation of the effects of anthropogenic forcing in weather extremes (Allen, 2003). In order to avoid apparent contradictions between results from different studies, the way the initial question is posed and the characterisation of the event have to be clear (Otto, 2016; Otto *et al.*, 2017) In the UK, a 10-day extreme winter rainfall such as the event that occurred during winter 2013/14 was

found to be eight times more probable under a humaninfluenced climate (Hermanson et al., 2016). Events such as Storm Desmond in December 2015 have been found to be 59% more likely to occur as a result of anthropogenic climate change, although there was a considerable margin of uncertainty associated with this figure (Otto et al., 2018). The choice of attribution method may influence the conclusions of an attribution study, so the use of multiple methods is recommended (Gudmundsson et al., 2017; Wilcox et al., 2017). The definition of the event is also important, particularly its spatial and temporal extent, and it has been proposed that selecting a temporal and spatial scale that maximises the rarity of the type of event of interest (e.g. extreme rainfall leading to a flood) is an objective approach that does not influence the outcome of the attribution (Cattiaux and Ribes, 2018).

Hilberts *et al.* (2011) found a significant increase in the risk of flooding under human influence in England and Wales. Similarly, an increase in flood risk during the months of October and December was attributed to anthropogenic climate change in several catchments in England by comparing ensembles of simulations from a hypothetical non-industrial climate without anthropogenic GHGs with ensembles from an industrial climate (Kay *et al.*, 2011). Simulations of 1.5°C and 2.0°C of future warming from the HAPPI¹ project have been used to predict an additional increase of up to 0.2 mm in the 95th percentiles of 3-h and 24-h precipitation in the British Isles under the 2.0°C scenario compared with the 1.5°C scenario (Barcikowska *et al.*, 2018).

The American Meteorological Society has published an annual collection of extreme weather attribution studies since 2011. These studies have included analyses of droughts (Szeto *et al.*, 2016), floods (Szeto *et al.*, 2015), record sunshine hours (Christidis *et al.*, 2016) and the European heat wave of 2018 (Yiou *et al.*, 2020). In general, it is more difficult to attribute rainfall events than temperature events to climate

¹ HAPPI project: Half a degree Additional warming, Prognosis and Projected Impacts. See https://www.happimip.org/

change. This is partly because of the greater natural variability of rainfall than of temperatures.

However, the influence of anthropogenic climate change on extreme events has not been detected in all such studies. The 1-day precipitation event during December 2015 that caused severe floods in India could not be attributed to human influence, according to one study (van Oldenborgh et al., 2016a). Some attribution studies have even reported a decrease in extreme weather events or changes in opposite directions for magnitude and frequency. For example, Schaller et al. (2014) did not find any anthropogenic influence on the occurrence of heavy precipitation in the Upper Danube and Elbe basin. In the Okavango basin in southern Africa, the flood risk was gauged to have decreased in the factual world, i.e. the world including anthropogenic influences (Wolski et al., 2014), compared with a fictitious world that is free from the influence of human-induced climate change.

The results of attribution studies therefore must be put into context, taking into consideration in particular the possible existence of other, confounding, influences on the climate system or of other compensating mechanisms, such as aerosols (van Oldenborgh *et al.*, 2016b) or imperfections in the climate models themselves. Land use and management can in particular play an important role in the results of extreme event attribution (Szeto *et al.*, 2016; Wilcox *et al.*, 2017).

2.2 Method

In general, the event attribution method may be summarised as follows.

Ensembles of atmospheric simulations are carried out with and without anthropogenic forcings present. The ensemble with the actual climate, including anthropogenic forcings, is often referred to as "ALL forcings", or "ALL" for short. This set of forcings may also be described as "HIST", i.e. all historical forcings, both natural and anthropogenic, are present. The ensemble without the anthropogenic forcings is usually referred to as the "natural climate", or "NAT" for short, and represents a "counterfactual" world (Figure 2.1). Usually, "atmosphere-only" models are used, which means that SST must be externally prescribed for both the ALL and NAT model runs.

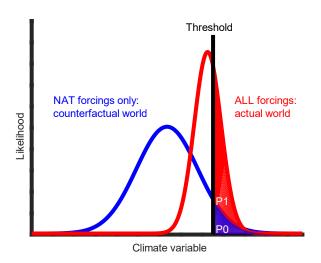


Figure 2.1. Illustration of the PEA methodology showing the difference in distributions of a climate variable in the ALL and NAT worlds. An event threshold is illustrated by the dotted line. The probability of occurrence of this event is P0 in the NAT world and P1 in the ALL world.

A typical method for ascribing suitable SST values in the natural case is described in Christidis *et al.* (2012).

- 2. The ALL simulations are validated against observational data, or data derived from observations, such as reanalysis data.
- 3. An exceedance threshold for a particular meteorological value of interest is identified. The process of identifying a suitable variable and threshold to represent a particular type of event observed in the past may be difficult, and this often constitutes much of the work required in attribution studies. A typical value may be the 24-h rainfall in respect of a flood event, or the number of consecutive days without rainfall in respect of a drought. The second most extreme event, rather than the most extreme event, is often used to define the threshold to eliminate selection bias.
- 4. The probabilities of exceedance of the threshold are calculated for the ALL ensemble and for the NAT ensemble, $P_{\rm ALL}$ and $P_{\rm NAT}$, respectively.
- 5. The exceedance probabilities from each ensemble may be used to calculate the fraction of attributable risk (FAR), defined as $1-P_{\rm ALL}/P_{\rm NAT}$.
- Return periods may be calculated for each ensemble using the inverses of the probabilities, 1/P_{ALL} and 1/P_{NAT}.

The uncertainty associated with the FAR estimate may be estimated using a bootstrap resampling procedure.

2.3 Models and Datasets Used in Attribution Studies

Many different datasets of meteorological observations, reanalysis data, general circulation models and Earth system models have been used in attribution studies. Model datasets used in attribution studies may be broadly categorised as follows.

- Global atmosphere—ocean models constrained with prescribed values of SSTs and sea ice extent. Prescribed values are based on observational data or, in the case of the NAT simulation, model estimates. In general, model runs with prescribed SSTs capture internal variability well and tend to correlate more closely in time with observed events, and are therefore suited to attribution studies, particularly for events such as rainfall extremes, in which there is a large influence of natural variability.
- Coupled global atmosphere—ocean models, in which SSTs and sea ice are unconstrained. This type of configuration cannot capture particular events but is useful in attribution studies for examining broad trends, for example in precipitation.

Some of the most widely used datasets are briefly discussed in the following sections.

2.3.1 Coupled Model Intercomparison Project phase 5

Phase 5 of the Coupled Model Intercomparison Project (CMIP5) was a set of experiments that examined variations in different global circulation model outputs under similar forcings. It also aimed to address the broader questions of model performance in the recent past and the general ability of such models to predict climate over decadal timescales (Taylor *et al.*, 2012).

The models examined are coupled atmosphere—ocean general circulation models (AOGCMs), although some sets of experiments were carried out in "atmosphere-only" (Atmospheric Model Intercomparison Project, AMIP) mode to reduce the computational effort required. The CMIP5 project is described in detail by Taylor *et al.* (2012) and on the CMIP5 project website.² The usefulness of the CMIP5 datasets stems from the availability of pre-industrial control runs from which anthropogenic forcings are excluded. The other so-called "core" model simulations in the CMIP5 framework are:

- a present-day climate run;
- a historical run from c.1850 to present that is forced by observed changes in atmospheric composition, incorporating both natural and anthropogenic influences, as well as historical changes in land cover.

Some CMIP products also include a "historical NAT" simulation – a historical run but including only natural forcings. The successor project to CMIP5, phase 6, is now producing datasets.³

2.3.2 Hadley Centre Event Attribution System

This model framework is based on the HadGEM3-A (Hadley Centre Global Environmental Model. version 3). The models are run with prescribed SSTs and sea ice. The HADGEM-3 framework has been recently upgraded via the European Climate and Weather Events: Interpretation and Attribution (EUCLEIA) project.4 This dataset has an excellent resolution (85 vertical levels and c.60 km horizontal resolution). The study of extreme winter sunshine in the United Kingdom by Christidis et al. (2016) used ensembles of 15 members each for the NAT and ALL cases, over a period of 54 years from 1960 to 2013 inclusive. The system was upgraded on 1 December 2013 to create an effective 105-member ensemble, and again on 1 January 2016 to create an effective 525-member ensemble (Ciavarella et al., 2018). The system has been used extensively for near-real-time attribution studies.

² See http://cmip-pcmdi.llnl.gov/

³ See https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6

⁴ See https://www.climateprediction.net/projects/completed-project/completed-weatherhome-projects/eucleia/

2.3.3 The weather@home project and its derivatives

The weather@home project is part of the climateprediction.net distributed computing project operated by the University of Oxford. Weather@home allows a worldwide network of volunteers to donate spare computer central processing unit (CPU) cycles to help run very large ensembles of regional climate model simulations. Schaller et al. (2016) used data from the weather@home project for the first documented end-to-end event attribution study that investigated anthropogenic influence on the severe floods of winter 2014 in southern England. This involved a super-ensemble of 134,354 simulations of ALL and NAT climatic conditions. The weather@home simulations were based on the HadRM3P regional climate model (RCM) nested inside the HadAM3P general circulation model. SSTs and sea ice cover were prescribed. The weather@home Australia and New Zealand (w@h ANZ) simulations were used by Karoly et al. (2016) in a study of record low rainfall in Tasmania during October 2015. w@h ANZ is based on the global atmosphere-only model HadAM3P, which drives the nested RCM HadRM3P, run at 0.44° horizontal resolution.

2.3.4 CLIVAR C20C+ detection and attribution project

The World Climate Research Programme established a subprogramme, "CLIVAR", to study climate variability, which in turn created the Climate of the 20th Century Plus (C20C+) project. The project created sets of atmospheric global climate model (GCM) simulations specifically for attribution studies. The outputs of the model runs are freely available via the project website⁵ and the Earth System Grid Federation website.⁶

Some of the attribution model datasets used in previous attribution studies of extreme weather events are summarised, with metadata, in Table 2.1.

2.4 The EURO-CORDEX Downscaled Model Runs

The EURO-CORDEX (Coordinated Regional Downscaling Experiment) regional climate model

ensemble runs (Jacob et al., 2014) produced outputs for European regions with a resolution of 0.11° × 0.11° (12km, approximately). The runs are forced by GCM simulations from the CMIP5 initiative, and are therefore influenced by "free" SSTs. There are three general simulation periods: (1) control, 1951–2005; (2) hindcast, 1989–2008; and (3) scenarios, 2006–2100. Not every model dataset is available for the full extent of the three periods. The model domain encompasses the European landmass, portions of North Africa and the Atlantic offshore from 27° N to 72° N and from 22° W to 45° E. The time periods simulated include the hindcast period of 1989–2008, the control period of 1951-2005 and "future" scenarios from 2006 to 2100 based on envisaged projections of atmospheric GHG concentrations in the 21st century, the Representative Concentration Pathways (RCPs) 4.5 and 8.5. The EURO-CORDEX outputs are not strictly PEA model datasets, as they are based upon coupled atmosphere-ocean models, but they have been successfully used to examine long-term trends in parameters such as precipitation. Their application will be discussed in section 4.8.

2.5 Attribution of Weather Extremes in Ireland

2.5.1 Observational data sources for attribution studies

Observations of the parameters of interest in attribution studies (e.g. precipitation or temperature) are used to validate the values simulated by the models run in ALL mode (i.e. including "all" forcings – natural and anthropogenic). The observations may be archives of surface meteorological observations or gridded observational data. In addition, observed SST values are often prescribed as boundary conditions to allow "atmosphere-only" runs of ALL simulations. In the corresponding NAT simulations (i.e. "natural" forcings only, without anthropogenic influences), the SST values are modified to remove the known spatial and temporal response of SST to anthropogenic forcings (Bichet *et al.*, 2015).

⁵ See http://portal.nersc.gov/c20c/

⁶ See https://esgf.llnl.gov/

Table 2.1. Model datasets used in previous attribution studies

Dataset name	Horizontal resolution	Model domain	Ensemble members	Temporal coverage	Model bases	Reference
CMIP5 family	Model dependent	Global	Model dependent	Near term (–2035); long term (–2100)	Many	Taylor <i>et al</i> . (2012)
Hadley Centre Attribution System	c. 60 km (0.56° × 0.83°); up	Global	15 (105 post 2013; 525 post 2016)	1960-present	HadGEM3-A (EUCLEIA update)	Christidis <i>et al</i> . (2012)
	to 85 vertical levels					Ciavarella et al. (2018)
C20C+ attribution subproject	GCM library	Global	To be finalised	1980–2010; possibly more	Several	Folland <i>et al</i> . (2014)

Some observation datasets used in attribution studies:

- GHCN, the Global Historical Climatology Network: a very large archive of quality-controlled hourly, daily and longer period observations.
- HadGHCND, the Hadley Centre extreme temperature dataset: daily maximum temperatures from 1951–2010 (Caesar et al., 2006). This is derived from the GHCN dataset.
- NCIC, the United Kingdom's National Climate Information Centre: gridded climate information and statistics from surface observations in the UK.⁷

2.5.2 Reanalysis data for attribution studies

Reanalysis data may also be useful in lieu of observational data for attribution studies. However, caution is advised when using reanalysis data for trend analysis, as changes in the data assimilated into a reanalysis dataset over time may result in spurious trends. Although no reanalysis data were used in this project, some potentially suitable reanalysis datasets include:

 ERA-Interim Reanalysis: the European Centre for Medium-Range Weather Forecasting's gridded set of global atmospheric data derived from a consistent set of weather forecast model outputs. The dataset covers the period from 1979 to the present. A large number of gridded data products are available at various time resolutions down to 3h (Dee et al., 2011). The horizontal resolution is approximately 79 km and there are 60 vertical model layers.

- NCEP-NCAR reanalysis: a reanalysis dataset developed by the National Centers for Environmental Prediction and the National Center for Atmospheric Research, both in the USA. The time resolution is 6 h, and the temporal coverage is from 1948 to the present.8
- The MÉRA reanalysis dataset for Ireland, provided by Met Éireann, the Irish meteorological service: this dataset has a high horizontal spatial resolution over Ireland (2.5km) and has been validated with observational data from Ireland, but the temporal coverage starts in 1981, which may limit its use in attribution work (Gleeson et al., 2017).

Table 2.2 lists some recent attribution studies and the model, observation and reanalysis datasets used.

2.6 Observational Data in Ireland

In Ireland, the datasets most likely to be used for validation purposes are Met Éireann's archive of surface observations recorded at the weather observation station network, the climatological station network and the wider network of daily rain gauges. A more recent study created a homogeneous, long-term record of rainfall for 25 stations on the island of Ireland on a monthly time step between 1850 and 2010 – the Island of Ireland Precipitation (IIP) network (Noone et al., 2016). The authors state that this dataset is suitable for the analysis of long-term variability in precipitation. A gridded dataset of monthly and daily

⁷ See http://www.metoffice.gov.uk/research/climate/climate-monitoring/uk-monitoring

⁸ See https://rda.ucar.edu/datasets/ds090.0/

Table 2.2. List of recent attribution studies and associated model and validation datasets

Study reference	Model data	Observation/validation data	Quantity of interest	Region
King et al. (2015)	CMIP5 (12 experiments)	Central England temperature dataset	Temperature	Central England
Christidis et al. (2016)	Hadley Centre system (HadGEM3)	NCIC; NCEP-NCAR reanalysis	Sunshine	United Kingdom
Hauser et al. (2016)	CESM 1.2 (CAM-5.3 and CLM 4.0)	ERA-Interim; HadGHCND	Extreme temperature	Western Russia
van Oldenborgh <i>et al.</i> (2016a)	weather@home, EC- Earth, CMIP5	GHCN-D; local observation network	Extreme precipitation	Chennai, India
Burke <i>et al.</i> (2016)	HadGEM3-A; JULES land surface	Local observation network	Extreme rainfall	South-east China
Lawal et al. (2016)	CAM5.1 and MIROC5	Local observation network	Rainfall (delayed wet season)	Nigeria
Trenary et al. (2016)	CMIP5 (12 experiments)	GHCN	Daily surface temperature	Eastern USA
Schaller et al. (2016)	weather@home (GCMs from CMIP5)	ERA-Interim	Flooding (precipitation; temperature)	Southern England
Karoly et al. (2016)	w@h ANZ	Local observation network	Extreme low rainfall	Tasmania, Australia
Wehner <i>et al.</i> (2016)	C20C+ project: CAM5.1; SSTs from CMIP5	HadISD v.1.0.4.2015p	Extreme heat; humidity	India and Pakistan

CAM, Community Atmosphere Model; CLM, Community Land Model; CESM, Community Earth System Model; GHCN, Global Historical Climatology Network; JULES, Joint UK Land Environment Simulator; MIROC5, Model for Interdisciplinary Research on Climate; NCIC, National Climate Information Centre (UK).

rainfall from 1941–2019 at a 1 km resolution is also available from Met Éireann.9

2.6.1 Precipitation observation network

Observational data on precipitation are provided by Met Éireann. There are three types of stations in the network:

- A network of 25 weather observing stations, operated by Met Éireann. These were previously referred to as synoptic stations and observe a wide range of hourly weather parameters including rainfall.¹⁰
- Approximately 60 climatological stations run by volunteers and public bodies that report daily observations of rainfall measured at 09:00 UTC (coordinated universal time). All climatological stations also report air temperature, and some report other parameters such as soil temperatures and wind speeds and directions.
- Over 500 daily rainfall stations run by volunteers that are read at 09:00 UTC.

The temporal coverage of the records varies, with data available for Valentia Observatory, for example, from 1850. However, many station records commence in the early or mid-20th century. In this report, a series of observational datasets of precipitation from Met Éireann is selected from the three types of station records, examined in detail and a subset of the stations identified for use in attribution studies.

2.6.2 Record selection and quality control

The goal of this exercise was to select a set of observational records with the longest possible durations up to, or nearly up to, the present day, with uninterrupted observations. The records from the weather observing stations and the climatological stations are of very high quality and are continuous, long-term records. These are of several decades' duration in most cases. Some of the records from daily rainfall stations may be of shorter duration or may have gaps in the records, because they are operated by volunteers. However, there are many continuous, long-term datasets in this category, too.

⁹ See https://www.met.ie/monthly-rainfall-and-temperature-grids/

¹⁰ See https://www.met.ie/climate/available-data/daily-data

One of the main difficulties when choosing appropriate stations from Met Éireann's database is that there may exist different station codes for a single location, for example where a station has changed from manual to automatic operation. There may be pairs of stations with similar or slightly different latitude and longitude coordinates or reported altitude. Station records were also inspected for multiple entries with the same timestamp and for missing records. Special attention was also paid to the format of the dates, as it may vary even within a single data file.

The station list was reviewed to identify stations with different identification numbers that were, or can potentially be treated as, the same location. This was carried out to obtain records for the longest period possible. For example, stations that were given new identification codes after moving from manual to automatic recording, without a change in station location, were deemed to be the same. After reviewing the stations, there was an initial list of 185 observation locations, chosen from the three categories.

A period of interest was established that would allow working with a suitable number of stations with records for the longest period possible. Although some high-quality digitised records extended back to the 1920s or earlier, the period 1961–2016 was chosen because several high-quality records commenced in 1961. This resulted in a total of 56 years of daily precipitation records for all the selected stations. A threshold for missing days of 1% of the time series was established at each station. In other words, 99% of the days should be present in order to proceed with further analysis.

A total of 976 volunteer daily rainfall stations were open in or before 1961, but most of them had closed by 2016. Specifically, 183 stations had zero years of operation between 1960 and 2016, and 469 stations had fewer than 30 years of operation. Therefore, a total of 324 stations had been left with 30 years or more of near-continuous operation. From these stations, 90 continue to record up to the present day or finished recording in 2017 (in the case of station 2604). After applying filters, a total of 51 daily stations

remained that had more than 99% of days present in the time series. Of the 51 daily stations, there were six that had a complete record for the 56-year period, and so these were chosen for the final check of homogeneity directly. For the remainder, and given that these stations are run by volunteers, they were checked one by one. Some stations were ruled out owing to the presence of long gaps, despite having more than 99% of the overall records present.

Homogeneity tests

The importance of long and homogeneous records of daily time series of precipitation is informed by the fact that extreme weather events are rare by definition, and so the longer the record, the more reliable the results. Records were checked using four different tests for homogeneity: the standard normal homogeneity test, the Buishand range test, the Pettit test and the Von Neumann ratio test. In order to carry out the homogeneity tests, the iki.dataclim package of the R statistical computing environment was applied to monthly data¹¹ (Orlowsky, 2014).

2.6.3 Precipitation observation database for attribution studies

For the period 1961–2016, 20 stations were finally identified that could be potentially used for the calculation of the extreme indices of precipitation. These stations were a combination of six volunteer stations and 14 climatological stations or Met Éireann weather observing stations and their locations are shown in Figure 2.2.12 The 10 indices of precipitation recommended by the expert team, composed of representatives of the Commission for Climatology, CLIVAR and the Joint Technical Commission on Oceanography and Marine Meteorology, were downloaded (annual and monthly), corresponding to those previously obtained for the Met Éireann stations. The 10 indices of extreme precipitation are presented for annual and monthly periods except for consecutive wet days (CWD) and consecutive dry days (CDD), which are only presented on an annual basis.

¹¹ See https://cran.r-project.org/web/packages/iki.dataclim/index.html

¹² Phoenix Park and Merrion Square stations in Dublin city are included in some analyses; however, they are not counted in the final list of 20 stations.

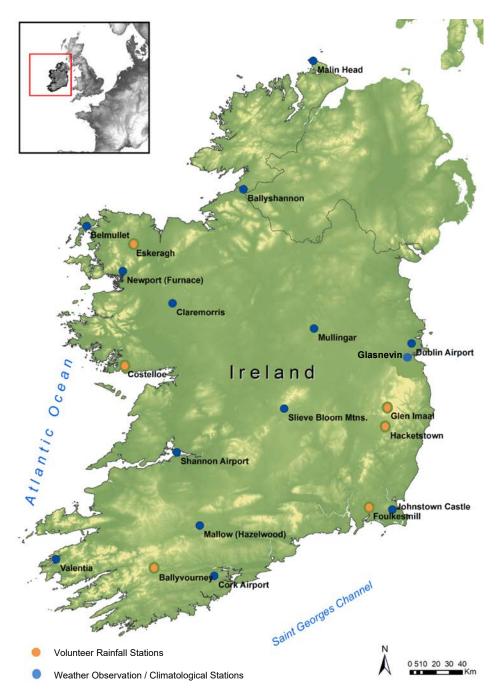


Figure 2.2. The 20 selected precipitation stations with quality-controlled records from 1961 to 2016. Stations run by volunteers are indicated in orange; climatological and/or synoptic stations are in blue.

2.7 Indices of Extreme Precipitation

A total of 27 indices suitable for representing extreme precipitation were considered. These follow the definitions and recommendation of the CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI). Regarding extreme precipitation indices, a total of 10 indices are calculated according to the ETCCDI definitions. In the case of Ireland, where snow and hail represent a very small proportion of total precipitation, rainfall

and precipitation are considered equivalents. Indices of extreme precipitation (and temperatures) were previously calculated by McElwain and Sweeney (2007), and a gridded dataset of rainfall depths for multiple durations (15 minutes to 25 days) and return periods for the island of Ireland, based on observations from 577 surface stations, has also been prepared by Met Éireann (Fitzgerald, 2007).

The nine indices (italic) recommended by the ETCCDI and downloaded from the Home European

Climate Assessment & Dataset (ECA&D) website are explained hereafter:

Rx1day (mm): maximum precipitation amount in 1 day during a period (generally a year).

Maximum 1-day precipitation: Rx1dayj=max (RRij).

Rx5day (mm): maximum precipitation amount (sums) in 5 consecutive days (ending in day 5) during a period (generally a year).

Maximum consecutive 5-day precipitation: Rx5dayj=max (RRkj).

SDII (simple daily intensity index) (mm): sum of the precipitation amount for wet days (≥1 mm) during a period, divided by the total number of wet days.

R10mm: (heavy precipitation days) number of days with precipitation (PRCP)≥10 mm during the period j (year). Annual count of days when PRCP≥10 mm: RRij≥10 mm.

R20mm: (very heavy precipitation days) number of days with precipitation (PRCP)≥20 mm during the period j (year). Annual count of days when PRCP≥20 mm: RRij≥20mm.

The last two indices can be customised as **Rnnmm**, replacing nn for a user-defined quantity. Annual count of days when PRCP≥nnmm: RRij≥nnmm.

CDD (consecutive dry days): largest number of consecutive days with daily precipitation amount < 1 mm (dry spell). Maximum length of dry spell, maximum number of consecutive days with RR<1mm: RRij<1 mm.

CWD (consecutive wet days): largest number of consecutive days with daily precipitation amount ≥1 mm (wet spell). Maximum length of wet spell, maximum number of consecutive days with RR≥1 mm: RRij≥1 mm.

R95pTOT: annual sum of the amount of precipitation for days with ≥1 mm (wet days), provided that this amount of daily precipitation is greater than the 95th percentile of precipitation of wet days for the period of reference, i.e. 1961–1990.

Precipitation fraction due to very wet days (>95th percentile) (%) (mm): R95pTOT is the fraction from very wet days, calculated as R95p (mm) [annual contribution from very wet days (mm), i.e. the annual sum of daily precipitation >95th percentile], as

R95px100 divided by the annual total precipitation in wet days (PRCPTOT).

R99pTOT: annual sum of the amount of precipitation for days with ≥1 mm (wet days), provided that this amount of daily precipitation is greater than the 99th percentile of precipitation of wet days for the period of reference, i.e. 1961–1990.

The ECA indices are calculated from the observations of the selected stations. Apart from the nine indices listed above, six more can be included:

RR (mm): daily precipitation amount for a specific period.

RR1 (mm): number of days with daily precipitation amount ≥1 mm for a specific period.

R75p: annual sum of the amount of precipitation for days with ≥1 mm (wet days), provided that this amount of daily precipitation is greater than the 75th percentile of precipitation of wet days for the period of reference, i.e. 1961–1990.

R75pTOT: annual sum of the amount of precipitation for days with ≥1 mm (wet days), provided that this amount of daily precipitation is greater than the 75th percentile of precipitation of wet days for the period of reference, i.e. 1961–1990.

R95p: annual sum of the amount of precipitation for days with ≥1 mm (wet days), provided that this amount of daily precipitation is greater than the 95th percentile of precipitation of wet days for the period of reference, i.e. 1961–1990.

R99p: annual sum of the amount of precipitation for days with ≥1 mm (wet days), provided that this amount of daily precipitation is greater than the 99th percentile of precipitation of wet days for the period of reference, i.e. 1961–1990.

These indices describe the magnitude, the probability and even the depth (mm) of extreme precipitation. These extreme indices can be used for detection and attribution analysis. They can be calculated using the R statistical package iki.dataclim. Extreme indices of precipitation can be calculated for different baseline periods such as 1961–1990 or 1981–2010. With respect to the periods analysed, authors usually employ the historical period/baseline period from 1961 until 1990 for climate change studies. The World Meteorological Organization is now using 1981–2010

rather than 1960–1990 as the baseline as it is more representative of current conditions, but has retained the 1961–1990 period as a reference for long-term climate change assessment studies.

It is emphasised by Wilcox *et al.* (2017) that applying more than one attribution method in the case of a

particular event can increase the overall confidence in any attribution statement that arises from the work, if the results obtained from multiple methods are in agreement with each other. However, the results of different attribution methods may not necessarily be in agreement with each other (Gudmundsson *et al.*, 2017).

3 Extreme Weather Event Inventory

3.1 Introduction

This research attempts to build an inventory of weather extremes that took place in Ireland between 1980 and 2018 and hence provide material on which to carry out attribution studies. It also proposes a single method that can be applied to extend this dataset in time and to include future, as well as past, events.

The weather disaster events from 1980 onwards presented here have had a significant impact on Ireland, accounting for 17 fatalities, hundreds of injuries and €2.971 billion in damages, according to the NatCatSERVICE reinsurance database provided by Munich RE¹³ (Table 3.1). This damages figure should be considered a crude estimate at best; the true figure is likely to be considerably greater than €3 billion.

The term "storm" was used to describe any event of heavy precipitation and/or strong winds associated with a deep area of low pressure. "Flood" was used to describe events of inundation caused by rivers breaking banks or wind-driven sea surges. Fodder crises are classed as events resulting in significant shortages of fodder for cattle, with resulting economic impacts. Such crises may arise as a result of prolonged drought or prolonged wet conditions, which impede grass growth (Hennessy et al., 2013). The most commonly reported events were floods, almost all of which were fluvial. Cold spells were the next most common, followed by storms and, finally, fodder crises. It must be noted that some of the entries on storms relate to exceptionally stormy seasons, including multiple individual storms, as occurred in winter 2013-14, which, according to Matthews et al. (2014), was the stormiest winter on record for Ireland stretching back to 1877, based on an analysis of synoptic charts.

3.2 Previous Inventories and Research

Despite some examples of databases of weather extremes that focus on or include Ireland, this research could not identify a single resource that adopted a systematic approach that would allow for consistent comparison and trend analysis of extreme weather events in Ireland over time. At the same time, these incomplete inventories proved a great resource for finding weather extremes and compiling a preliminary list to work with. Five such datasets and inventories were especially helpful and merit acknowledgement.

- 1. Met Éireann's Major Weather Events web page¹⁴ lists extreme meteorological events that affected Ireland and extends back as far as 1798. Each included extreme event is issued with a report that gives an overview of the event and in many cases provides analysis of the causal factors and weather data. These reports, however, vary from brief notes to comprehensive analysis, have no standardised structure, and usually include no information on the socio-economic impact of the event in question. There is also no information on which events were selected for the inventory and on what bases, and upon scrutiny it quickly becomes apparent that some important and disastrous events are missing. Given the improvements in recording since the first entries, it is expected that the list is biased towards more recent events.
- 2. The Office of Public Works (OPW) flood hazard mapping website¹⁵ houses a large database of floods in Ireland, where maps, photographs and official reports can be found for flooding events of all magnitudes. The obvious downside of this resource is its sole focus on one type of weather extreme, as well as non-standardised entries.

¹³ Munich RE NatCatSERVICE https://www.munichre.com/en/solutions/for-industry-clients/natcatservice.html

¹⁴ See https://www.met.ie/climate/major-weather-events

¹⁵ See https://www.floodinfo.ie/

Table 3.1. Overview of event types and impacts from 1980 to 2016

Year	Month/season	Туре	Fatalities	Damages (adjusted to Jan 2018 euro values)
1980	November	Flood	0	12,000,000
1988	February	Storm	5	31,000,000
1998	December	Flood	0	Unknown
2000	November	Flood	1	153,000,000
2001	December	Cold spell	0	56,000,000
2002	February	Cold spell	0	147,000,000
2002	November	Flood	0	82,000,000
2004	October	Storm, flood	0	58,000,000
2008	August	Flood	1	94,000,000
2009	January	Cold spell	0	48,000,000
2009	November	Flood	0	378,000,000
2009/10	Winter	Cold spell	0	392,000,000
2010	November-December	Cold spell	5	278,000,000
2011	October	Flood	2	188,000,000
2012	June	Flood	0	72,000,000
2012/13	Winter-summer	Wet period, fodder crises	0	500,000,000
2013/14	Winter	Storms	2	270,000,000
2014	February	Storm	Included above	Included above
2015/16	Winter-spring	Storms, floods	1	214,000,000
	Total (1980-2016)		17	2,971,000,000

Note: impacts are taken from the NatCatSERVICE database of Munich Re and are rounded to the nearest €1m.

- 3. Munich RE's NatCatSERVICE¹⁶ is an archive of worldwide natural disasters and their socio-economic impacts. It is also the only dataset of weather extremes in Ireland with a defined event inclusion criterion and methodology. Nonetheless, upon closer scrutiny, many discrepancies and inconsistencies in the data for Ireland were found that the company struggled to clarify upon request. Further inconsistencies were encountered upon comparison with other sources and, while overall NatCatSERVICE is perhaps the best inventory of weather extremes in Ireland to date, it is still somewhat inconsistent and lacks precision and transparency.
- 4. The European Severe Weather Database¹⁷ is a database of weather extremes for all of Europe, and its archives can be searched by locality, type of event and date of its occurrence. Rather than compiling a single comprehensive
- report, the database contains many entries for the same event. For example, for Storm Darwin the database returns seven entries, none of which identifies it as a major storm wreaking havoc across much of Ireland, but rather as six separate instances of locally damaging severe wind and one instance of an unconfirmed tornado. In addition, the entries are extremely brief and sometimes concern trivial affairs in the face of the overall scale of an event.
- 5. Another potentially valuable resource in this research was data obtained from Insurance Ireland¹⁸ on the cost of extreme weather events in Ireland in 2000–2018. These data provide a consistent and trustworthy estimate of total insurance claims stemming from a particular event. Unfortunately, there is no disclosed methodology and the data are available only on post-2000 events.

¹⁶ See https://natcatservice.munichre.com/

¹⁷ See https://www.eswd.eu/

¹⁸ See https://www.insuranceireland.eu/

3.3 Challenges

Classifying weather events as extreme can be arbitrary owing to the lack of a single definition and a variety of adopted thresholds and conditions, or lack thereof (Meehl et al., 2000). In the Irish context, attempts to understand past weather events can be hindered because some weather data records are of insufficient duration or some older records have not yet been digitised, despite the availability of some very long-duration records and a relatively high density of recording stations. Lack of data is the main obstacle in setting out statistical thresholds for recognising weather events as extreme. Historical sources such as press articles and government bodies' reports are often the only source of information on the socioeconomic impacts of past weather extremes and, unfortunately, data such as estimates of financial losses are rarely accompanied by an explanation of what exactly they encompass. In the case of both weather statistics and economic losses, data are harder to obtain the further back we go in time. With older events, additional challenges lie in the change of recording instruments, weather station relocation

and data calibration, as well as simple scarcity of data and comprehensive reports. These challenges can be overcome with careful quality control and homogenisation. In the case of economic data, it is recognised that economic impacts are influenced by land use decisions (e.g. large-scale basin drainage, urbanisation or changes in settlement patterns in the case of floods). It is very difficult to control for such influences.

NatCatSERVICE data were used to perform trend analysis by other researchers (Höppe and Grimm, 2009; Schmidt *et al.*, 2009). It qualifies events as extreme based on the losses and fatalities caused, and the thresholds vary between countries based on their annual GDP. For Ireland, as a country in the high-income group, this threshold is set at minimum of one fatality and/or US\$3 million (approx. €2.65 million) (Munich RE, personal communication, May 2018). As discussed previously, this dataset for Ireland proved to be inconsistent and problematic. Other research cited in Bruce (1999) set the threshold for natural disasters at 1% of a country's annual GDP (gross domestic product) in damages, affecting more than 1% of its

Box 3.1. Sample event summary

EVENT NAME: Storm Darwin

DATE: 12 February 2014

TYPE OF EVENT: Windstorm

RETURN PERIOD: N/A

EXTENT: Countrywide; strongest in the west and south-west, weakest in the Midlands

IMPACTS: Two international airports temporarily shut down and aircraft damaged. 260,000

Electricity Supply Board customers with interrupted power supply, 8000 ha of woodland damaged. Traffic disruptions due to blown down power lines and trees

DAMAGES: €286 million (in insured property Europe-wide)

FATALITIES: 0

EVENT NARRATIVE: Storm originated from an area of low pressure (approx. 1005 hPa) south of Nova

Scotia on 10 February. Rate of deepening while crossing the Atlantic almost double the "weather bomb" threshold for the relevant latitude. North-east track. Landfall in Ireland on the morning of 12 February, hurricane force westerly and south-westerly winds. Weather warnings in effect until the following morning

SOURCES: Met Éireann, Mallow Field Club Journal, University College Cork Flood Study

Group, Cork County Council and OPW reports, press articles

KEYWORDS: Windstorm, storm, rainfall

population, or resulting in 100 or more deaths. These thresholds are set much too high for the scale of extremes affecting Ireland.

3.4 Adopted Weather Extreme Definition

This study adopts a financial loss threshold of €30 million (January 2018 value), which is equivalent to an annual GDP contribution (2017) of approximately 500 Irish people. Despite this definitive criterion, inclusion and categorising of some events comes down to a judgement call, for example in the case of events that were minor in meteorological terms and/or highly localised in their extent, and met the financial threshold only because their impacts were exacerbated by human factors. Events of the same type occurring in short intervals are considered one cumulative event (i.e. cyclone clustering or recurring floods) if they share a common cause and each component event does not meet the threshold. However, where one of the events in the series is of an extraordinary magnitude and meets the damage threshold independently, it is treated as a separate event.

3.5 Weather Data

Virtually all weather data (unless stated otherwise) utilised in this part of the research were sourced from Met Éireann's website or publications. Owing to the majority of weather extremes in Ireland being hydrological in nature (floods and storms), the daily and monthly observational rainfall records of Met Éireann were used to characterise such events (refer to section 2.6.1). Variables such as wind speed and direction, temperature and snow depth are recorded at fewer stations than precipitation.

3.6 Data on Financial Losses

As acknowledged by other researchers, data on losses from extreme weather events are generally not easily found (Changnon *et al.*, 2000). In this study an attempt is made to provide financial estimates for damages caused by each included event, including the overall loss amount and its insured component. In most

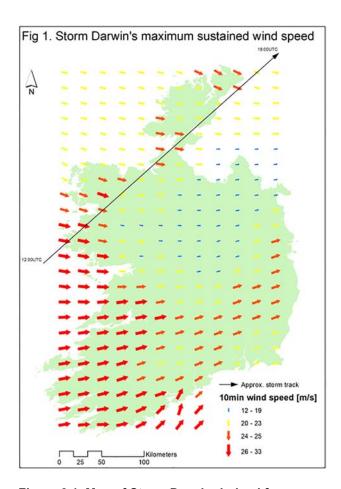


Figure 3.1. Map of Storm Darwin derived from event database information.

cases these data were provided either by Insurance Ireland (personal communications, May 2018) or by Munich Re (personal communications, June 2018) but some were sourced from press articles and various reports. For ease of comparison, loss figures are also adjusted for inflation by converting them to January 2018 values using the Irish Central Statistics Office's Consumer Price Index Inflation Calculator. Where an event spans more than 1 month, the mean value for all relevant months is converted to the January 2018 value.

3.7 Return Periods

Return periods are given for events when they are available from secondary sources; most times the estimation method and the dataset used are not provided, and hence these values should be treated as indicative rather than definite.

¹⁹ See https://www.cso.ie/en/interactivezone/visualisationtools/cpiinflationcalculator/

Table 3.2. Event summary from inventory (period 1947–1980; Pasik, 2019)

Year	Date(s)	Туре	Notes
1947	January–March	Cold spell	Heavy snowfalls
1954	December	Rainfall, floods	Widespread flooding
1961	16 September	Storm	Hurricane Debbie
1963	January/February	Cold spell	-
1963	11 June	Thunderstorms	Floods
1973	27–30 November	Rainfall, floods	Floods in south and south-west
1974	11–12 January	Storm	Winds up to 64 knots, widespread damage
1974	October 1974 to August 1976	Drought	April–August 1975, driest period in 150 years
1976	2 January	Storm	-
1979	13–16 August	Storm	Beaufort force 11/12. Fastnet disaster. 13-m waves

3.8 Fatalities

Historically, with some exceptions, weather extremes in Ireland produce few fatalities, especially in modern history. While loss of human life is acknowledged in summarising the events, it is not applied as an inclusion criterion.

3.9 Sample Event Profile

For each event in the inventory, a detailed profile has been developed, with relevant information on impacts and references to the source(s) of the information. A sample summary is given in Box 3.1. In addition to this summary information, a detailed text description of the evolution and impact of events is given. The spatial extent of events has also been recorded and used with ArcGIS mapping software to produce sample event maps (Figure 3.1).

3.10 Detailed Event Profile Descriptions

As part of the public outreach effort of the project, a project blog was established and several extreme weather events were described in detail for a general audience. Descriptions of Storm Ophelia,²⁰ Storm Emma and the "Beast from the East"²¹ and the Donegal floods of August 2017,²² as well as a discussion of meteorological factors involved in the genesis of the 2012/13 fodder crisis,²³ are available on the blog site.

In addition, the events from 1947 to 2017 included in Tables 3.1 and 3.2 are profiled in detail in Adam Pasik's Master of Research thesis (Pasik, 2019), which was supported by the project.

²⁰ See http://climatt.ucc.ie/2017/10/27/ex-hurricaneophelia/

²¹ See http://climatt.ucc.ie/2018/03/06/emma-and-the-beast/

²² See http://climatt.ucc.ie/2017/08/25/donegal-extreme-rainfall-floods-august-2017/

²³ See https://climatt.ucc.ie/2018/10/07/meteorological-factors-involved-in-the-genesis-of-the-2012-2013-fodder-crisis/

4 Attribution Case Study: Floods of November 2009

4.1 Introduction to the Case Study

This case study is used to demonstrate an application of the typical methodology employed in attribution studies and the challenges in extracting statistically meaningful results from available datasets, and in climate change attribution of complex multifactorial events such as floods.

Values for precipitation over Ireland from model datasets are compared with observational data. Eleven model datasets from the CMIP5, C20C and the EUCLEIA projects are considered, as well as 12 datasets from the EURO-CORDEX downscaling initiative. Twenty surface precipitation rain gauge locations with high-quality, continuous coverage were selected to act as validation data. This study represents the first ever comprehensive evaluation of model datasets suitable for carrying out probabilistic event attribution of extreme rainfall events in Ireland. The aim of the case study is twofold: firstly, to validate the attribution datasets for general extreme precipitation studies in Ireland, and, secondly, to apply the PEA method (see section 2.1.1) to the event of November 2009.

The chapter is structured as follows. Firstly, the climatological context of extreme precipitation events in Ireland is described. Observational records and simulation datasets that may be used in attribution studies for the region are described and analysed. Validation of the simulation datasets is carried out. Next, the variables and/or indices that best describe spatial and temporal characteristics of the widespread floods of November 2009 are investigated. Then, the datasets are used to carry out a climate change attribution study of the severe floods of November 2009. The performance of several CMIP5 models in reproduction of the precipitation that triggered the flood event is investigated. The results obtained are also compared with a counterfactual scenario. Lastly, the results are discussed and recommendations are made for future works in event attribution of extreme precipitation in Ireland.

4.2 Datasets and Methodology

4.2.1 Observations

For the characterisation of extreme precipitation events and the assessment of the attribution model datasets, observational data provided by Met Éireann were used. A total of 20 stations with long-duration, good-quality records were selected (Table 4.1 and Figure 4.1). The period analysed runs from 1980 to 2012, and long-term averages (LTAs) were calculated with respect to the period 1981–2010.

4.3 Models for Attribution Studies

Model simulations were obtained from different datasets with historical (HIST) and natural-only

Table 4.1. Location of the stations used in the analysis

Station name	Latitude (degrees)	Longitude (degrees)	Elevation (m asl)
Ballyshannon	54.492	-8.172	38
Ballyvourney	51.887	-9.142	152
Belmullet	54.223	-10.004	9
Casement	53.303	-6.437	91
Claremorris	53.707	-8.988	69
Cork Airport	51.842	-8.485	155
Costelloe Fishery	53.276	-9.536	12
Dublin Airport	53.423	-6.238	71
Eskeragh	54.107	-9.467	85
Foulkesmill	52.306	-6.76	71
Glen (of) Imaal	52.991	-6.539	213
Hacketstown	52.857	-6.552	189
Johnstown Castle	52.292	-6.491	49
Malin Head	55.372	-7.339	22
Mallow (Hazelwood)	52.187	-8.65	94
Mullingar	53.536	-7.357	101
Newport (Furnace)	53.921	-9.569	14
Shannon Airport	52.687	-8.917	15
Slieve Bloom Mountains	52.989	-7.703	219
Valentia Observatory	51.936	-10.238	24

Note: data provided by Met Éireann. asl, above sea level.

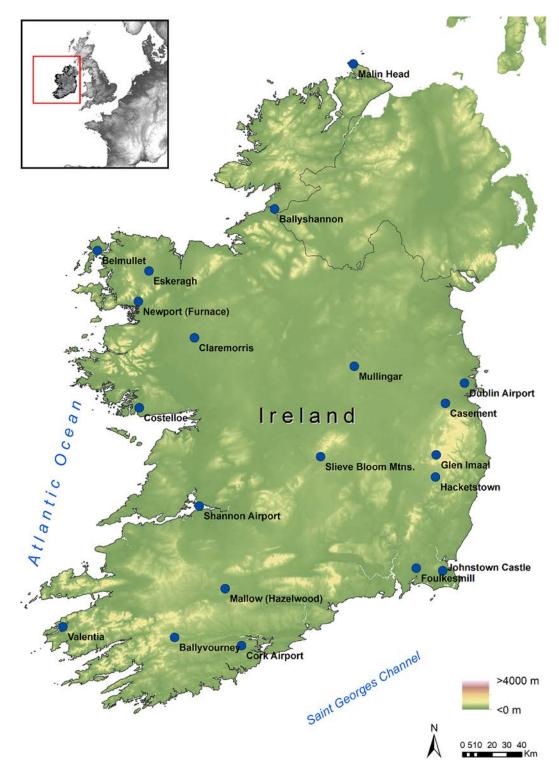


Figure 4.1. Map of Ireland showing locations of precipitation observation stations used in the case study.

(NAT) experiments. The models are run with different conditions: all forcings, i.e. natural and anthropogenic, or only natural forcings, for both experiments.

Monthly and daily variables were also available for simulations from CMIP5 (Taylor *et al.*, 2012), the C20C Detection and Attribution Project and the EUCLEIA project. For all the models, the first realisation was chosen (r1i1p1). A total of 11 models were available at

daily time resolution (Table 4.2). When historical runs end in 2005, RCP8.5 was used to extend the record up to 2012. The RCP8.5 experiment has a radiative forcing that increases throughout the 21st century, reaching a value of 8.5 W m⁻² at the end of the century, with a projected global surface temperature increase exceeding 2°C (Taylor *et al.*, 2012). Although RCP8.5 is a scenario of high anthropogenic GHG emissions, the differences between the RCP scenarios only become prominent in the late 21st century.

The EURO-CORDEX climate models' (Jacob et al., 2014) outputs for the European regions with a resolution of 0.11° × 0.11° (12 km, approximately) are also examined here. All the RCMs, as well as the driving GCMs, the periods analysed and the ensembles used, are specified in Table 4.3. In order to perform an extreme event attribution with the RCMs from the EURO-CORDEX project, a New World/Old World approach is used. In contrast to the datasets previously presented in this report, in the EURO-CORDEX data there is no separate representation of the factual and counterfactual worlds. Instead, two different periods are compared: a pre-industrial or less human-influenced period and a more recent period with greater impact from the emissions of anthropogenic GHGs. For this period of relatively low human influence, the interval 1971-2000 has been previously used (e.g. Luu et al., 2018).

Table 4.2. Models used in the study provided by CMIP5, C20C and the EUCLEIA project, and corresponding horizontal surface resolution

GCM	Resolution (degrees latitude or distance)	Resolution (degrees longitude or distance)
ACCESS 1.3	1.25°	1.875°
CNRM-CM5	1.4008°	1.40625°
CSIRO-Mk3.6.0	1.8653°	1.875°
CanESM2	2.7906°	2.8125°
HadGEM2-ES	1.25°	1.875°
IPSL-CM5A-LR	1.8947°	3.75°
IPSL-CM5A-MR	1.2676°	2.5°
NorESM1-M	1.8947°	2.5°
CAM5.1-1	1.0°	1.0°
HadGEM3-A-N216	60 km	60 km
HadAM3P-N96	130 km	130 km

CAM, Community Atmosphere Model.

Table 4.3. EURO-CORDEX model datasets used in the study

Daily GCM*	EURO- CORDEX Model RCM	Ensemble member
CNRM-CERFACS-CNRM-CM5	CCLM4-8-17	r1i1p1
CNRM-CERFACS-CNRM-CM5	RMIB-UGent- ALARO	r1i1p1
ICHEC-EC-EARTH	CCLM4-8-17	r12i1p1
MOHC-HadGEM2-ES	CCLM4-8-17	r1i1p1
MPI-M-MPI-ESM-LR	CCLM4-8-17	r1i1p1
ICHEC-EC-EARTH	HIRHAM5	r3i1p1
MOHC-HadGEM2-ES	HIRHAM5	r1i1p1
NCC-NorESM1-M	HIRHAM5	r1i1p1
ICHEC-EC-EARTH	RACMO22E	r1i1p1
MOHC-HadGEM2-ES	RACMO22E	r1i1p1
MPI-M-MPI-ESM-LR	REMO2009	r1i1p1
IPSL-IPSL-CM5A-MR	WRF331F	r1i1p1

4.4 Method Overview

The annual, November, summer (June, July, August; JJA) and winter (December, January, February; DJF) anomalies were calculated for modelled and observational values of precipitation. The spatiotemporal variability of rainfall was investigated by means of *k*-means clustering, which divided the country into three regional clusters that exhibited similar inter-annual and intra-annual patterns of rainfall variability. The rainfall variables were analysed for the spatial average of Ireland, the spatial average of each regional cluster, and for each one of the stations. The anomalies of mean daily precipitation were calculated with respect to the period 1981–2010.

4.5 Spatio-temporal Variability: Regional Clusters

Previous studies have observed that changes in climate in Britain and Ireland display regional gradients (Mayes, 2000). With this in mind, and considering the fact that individual station records may be subjected to highly heterogeneous local effects, a station clustering exercise was carried out using the technique of *k*-means. The annual precipitation anomaly was calculated for each of the 20 stations, and the anomaly time series for all stations were analysed. From this analysis, three consistent regional clusters emerged: one in the north-west (NW), one

in the centre/south (CS/S) and one in the east (E). Similar clusters were obtained when the anomalies of November rainfall were used to perform the cluster analysis (Figure 4.2).

4.6 Event Description: November 2009 Heavy Rainfall and Floods

4.6.1 Hydro-meteorological background to the floods

The year 2009 was wetter than normal in Ireland, with values between 112% and 155% of annual precipitation with respect to the LTA (1961–1990) (Met Éireann, 2010). There were also up to 20% more rain days than the average, with Valentia Observatory recording the highest number of 272 rain days (Met Éireann, 2010).

June-November 2009

The summer of 2009 (JJA) was unusually wet in south-western Ireland. Rainfall totals during the season were up to twice the average (1961–1990) in some places. The number of wet days was higher than normal, double the average in some parts of the south and west, and up to 234% with respect to the 1961–1990 LTA at Valentia Observatory (Met Éireann, 2009).

The summer season was followed by an autumn wetter than the 1961–1990 LTA in the vast majority of the country. Although September was dry and October close to normal, November experienced very high rainfall, with the number of wet days and heavy precipitation days 1.5–2.5 times and 3–5 times higher than normal (1961–1990 LTA), respectively (Walsh, 2010). Total precipitation was the highest ever recorded in most stations for the month of November

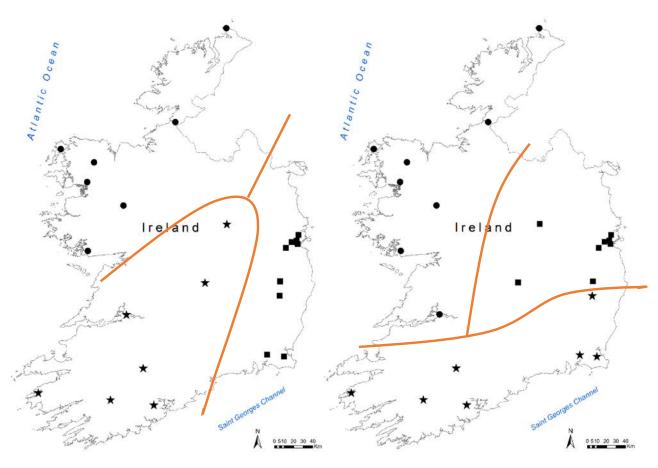


Figure 4.2. *k*-means cluster classification for the annual (left) and November (right) time series of the anomalies with respect to the long-term average from 1981 to 2010. Symbols represent the three different clusters: circles (NW), stars (CS/S) and square (E). The lines illustrate the indicative boundaries of the clusters.

(Walsh, 2010). It was also windy for almost all the month. This was the result of a succession of deep Atlantic depressions that were steered over Ireland, bringing mild, humid air to the country.

Flooding in the River Lee catchment

The response of a catchment to precipitation is influenced by different aspects such as land use, slopes, type of soils or bedrock, and occupation of floodplains. The combination of all those natural characteristics of a catchment and the human impacts present a challenge to the attribution analysis of a flood event.

The November 2009 heavy rainfall event

The rainfall of November 2009 was extreme, although the precipitation during the week of the floods – from the 16th to the 20th – was not unprecedented. The 24-h and 48-h rainfalls before the flooding of the 19th and 20th were also not unusually severe in magnitude.

Between the 18th and 20th, most areas in the southwest of Ireland recorded precipitation values of over 100 mm in 48h (especially on 19 and 20 November, with exceptional rainfall during 48h) (Hickey, 2010). Over 18 and 19 November, over 100 mm of rainfall occurred, which led to floods in the Lee catchment, particularly affecting Cork city on the 19th. The peak flow on the Lee occurred in the early hours of Friday 20 November. In some parts of the west and

south-west of the country, totals exceeded 100 mm over the 2 days of the 18th and 19th (Walsh, 2010). The Cork Airport meteorological station recorded 214% of the LTA November rainfall, with 51.2 mm over 24 h on the 19th (over 51.2 mm). In general, the maximum cumulative daily rainfall for 1 and 2 days' duration, as on 18 and 19 November, was found to have a return period of less than 50 years (Walsh, 2010). After the 27th, low pressure affected the east of the country (Walsh, 2010). The synoptic situation did not change until 10 December, when the long period of high rainfall finally came to an end (Hickey, 2010).

Local impacts on Cork city

A chain of factors triggered one of the most historically significant floods in Cork city. The flooding event was likely to have been at least partially influenced by the release of a large volume of water upstream of the River Lee, where there are two dams: Inniscarra and Carrigadrohid. A total of 800 m³ s⁻¹ of water was entering the system and only 535 m³ s⁻¹ was being discharged, and this was four times the normal rate of discharge (Hickey, 2010). The peak discharge from the dam in the hours prior to the flood event was the highest since its construction in the 1950s (Barrett, 2015).

As a consequence of the flooding, Cork city centre and western suburbs (from Washington Street to the Lee Fields) suffered disruption to different critical infrastructures such as the road network, water treatment plant, transformer stations, the Mercy

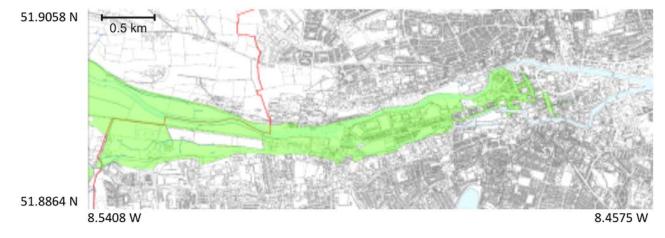


Figure 4.3. Spatial extent of inundation in Cork city during the November 2009 flood, based on OPW observations. Image reproduced from Comer *et al.* (2017) by permission of Dr Indiana Olbert, NUI Galway. Reproduction licensed under Creative Commons Attribution CC BY 3.0 licence (https://creativecommons.org/licenses/by/3.0/).

University Hospital and the university buildings (Figure 4.3). Around 87,000 people did not have access to drinking water at home, most of them in the northern part of the city (de Bruijn *et al.*, 2016), a total of 18,000 households, and 100 people had to be evacuated. The situation forced the declaration of a state of emergency (de Bruijn *et al.*, 2016). The flood event also demonstrated the weaknesses of the flood hazard policy, which was characterised as being overly reliant on a physical, rather than socio-economic, conceptualisation of flooding, and on reactive responses based on past experiences (Jeffers, 2011).

4.7 Analysis of the Precipitation Record

4.7.1 Annual observed precipitation anomalies

Figure 4.4 shows the annual mean daily precipitation anomalies for Ireland with respect to the LTA. The anomaly registered in 2009 is the highest for the time series (1980–2012). The observational records also depict a high positive anomaly in 2002, only slightly smaller than that of 2009.

Figure 4.5 presents the ranges of the anomalies in the observed annual mean daily precipitation (mm) for each of the observation stations. Anomalies are based on the

LTA 1981–2010. Whiskers of the boxplots indicate the 5th and 95th percentiles. The boxes indicate the median and the interquartile ranges. The values corresponding to the anomaly of 2009 are in red.

Multi-station averages are taken in order to represent the all-Ireland average precipitation anomaly. These are presented in Figure 4.6, along with the corresponding values derived from coupled models such as the EURO-CORDEX and CMIP5 datasets, and the ALL and NAT runs of constrained models with prescribed SSTs and sea ice such as HadGEM3-A. Of the coupled models, NorESM appears to match the observed distribution most closely. Only non-coupled models are capable of reproducing inter-annual variability year on year, and therefore matching a particular value of annual anomaly.

The year 2009 represents the highest value for a precipitation anomaly in the period of study in the stations situated in the southern part of the country: Valentia, Mallow (Hazelwood), Ballyvourney, Cork Airport and Johnstown Castle. The station of Glen of Imaal, in the east of the country, also registered the maximum value of its time series in the year 2009. In Claremorris, the value of the precipitation anomaly in 2009 corresponds to the highest anomaly of the upper quartile (4th percentile). For the stations of Belmullet, Eskeragh and Malin Head, the 2009 anomaly is found between the median and the third quartile. For the

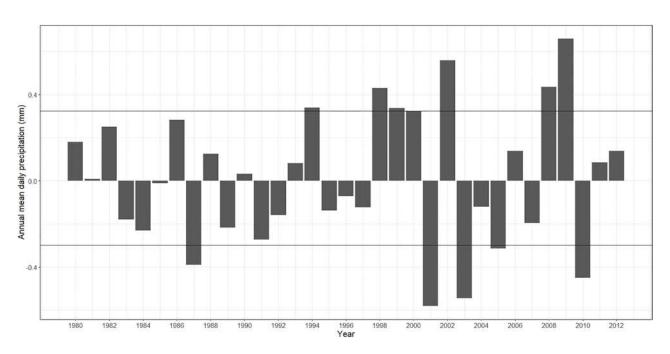


Figure 4.4. Anomalies in the observed annual mean daily precipitation for all Ireland, based on the observation stations selected for this project. Anomalies are calculated for the baseline 1981–2010.

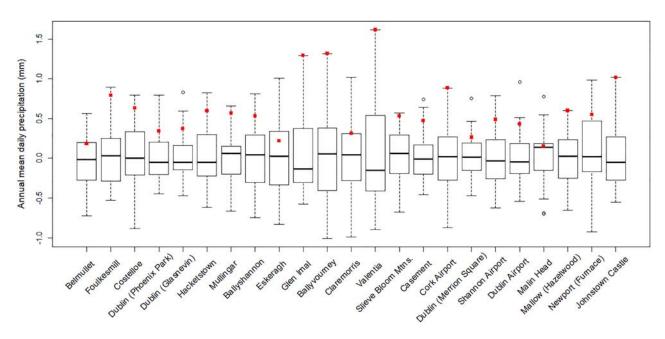


Figure 4.5. Anomaly of the observed annual mean daily precipitation (mm) for each of the observation stations considered in the study. Anomalies are based on the LTA 1981–2010. Red dots indicate the 2009 anomalies.

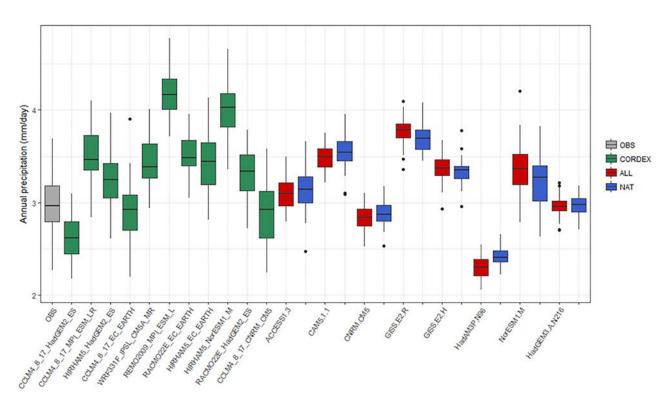


Figure 4.6. Distributions of annual anomalies in all-Ireland total annual precipitation, averaged over all stations, derived from observations, prescribed SST/sea ice, EURO-CORDEX and CMIP5 datasets.

rest of the stations, the value of 2009 lies between the 4th and 5th percentiles.

The 2009 positive precipitation anomaly is partly a consequence of the November precipitation

(4.2 mm d⁻¹) (Figure 4.7). The November monthly anomaly is also the highest of any November and even any month during the period 1980–2012. During the year 2009, July saw the second highest positive July anomaly recorded, which was also the second highest

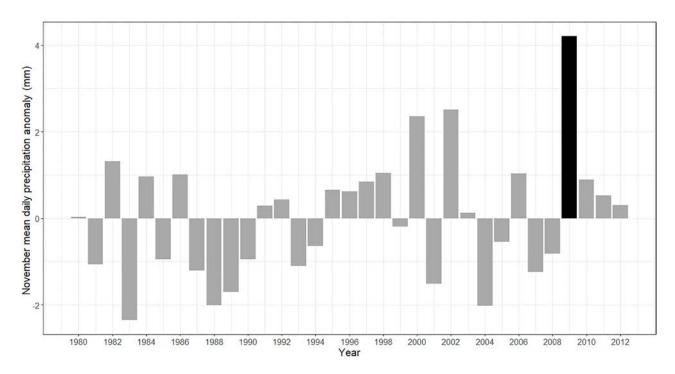


Figure 4.7. November precipitation anomaly (average over all stations), 1980–2012.

value registered during this month for the entire period. Furthermore, this month was followed by the fourth wettest August in the time series.

Sen's slope and the Mann-Kendall test were used to estimate the trend and the statistical significance of the annual anomalies in daily precipitation. The trend in the annual anomalies in daily precipitation for the longer period 1961–2012 is significantly positive (at the 95% confidence level) for the multi-station average. When considering the trends for each station individually, two of them show a negative but not significant trend: Hacketstown and Cork Airport. The rest of the trends were positive. For the stations of Eskeragh, Valentia, Costelloe, Casement, Belmullet, Ballyshannon, Ballyvourney, Claremorris, Slieve Bloom, Malin Head and Mallow Hazelwood, these positive trends were significant at the 95% confidence level. If the longer period, 1961-2012, is considered with respect to the same LTA, i.e. 1981-2010, the overall trend in the anomalies' time series is positive and significant at the 95% confidence level.

4.7.2 November precipitation

In November 2009, all stations registered precipitation between 156% (Belmullet) and 260% (Shannon Airport) of the average November precipitation for the period 1981–2010. In general, the highest percentage

increases were observed in southern Ireland. High values were also observed in the Midlands, and severe floods were also experienced in low-lying areas of the Shannon catchment. The lowest values were observed in the extreme north-west, although even these were still around 200% of the LTA.

Given the high precipitation that occurred during November 2009 and the high values of precipitation during the preceding summer, particularly in July and August, the precipitation anomalies in November 2009 were studied in further detail. Figure 4.7 shows the precipitation anomalies for November averaged over all stations in Ireland, and Figure 4.8 graphically illustrates individual station anomalies. The second and third highest November precipitation occurred in 2002 and 2000, respectively. The three years 2009, 2002 and 2000 were the only years with positive anomalies that exceeded the LTA by more than 1.5 standard deviations. Only one station, Valentia Observatory, exhibited a positive and significant trend in the anomaly.

4.8 Attribution Model Datasets Results

Anomalies in annual precipitation with respect to the LTA 1981–2010 were calculated for the four types of datasets (prescribed SST/sea ice models, CMIP5,

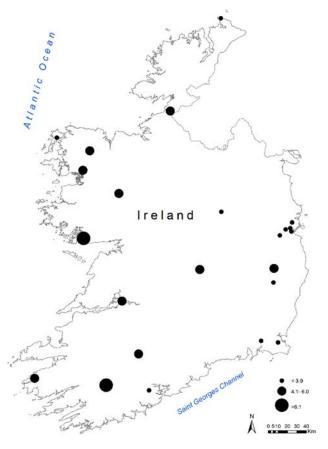


Figure 4.8. Map illustrating November 2009 precipitation anomalies (mm d⁻¹).

EURO-CORDEX and observations). The time series were scaled using the mean and deviation of each series for the period 1980–2012 (Figure 4.9). A similar calculation was carried out for the November anomaly time series (Figure 4.10). In general, models from the CMIP5 family exhibited positive trends in annual precipitation. Only the CAM-5.1.1, CanESM2 and HadGEM2-ES datasets showed a negative trend. Of these, only the CAM-5.1.1 had a significant trend at the 95% confidence level. EURO-CORDEX model trends were not significant and mostly negative. The only increasing trends were for the models IPSL-CM5A-LR/CCLM4.8.17, NorESM1-M/HIRHAM5 and CNRM-CM5/CCLM4.8.17.

In general, as discussed in section 2.3, models constrained with prescribed values of SST and sea ice are expected to better represent individual events than datasets derived from coupled models (e.g. CMIP5 and EURO-CORDEX).

4.9 Model Validation

4.9.1 Model bias, annual precipitation

Most of the historical experiments show a consistent sign of the bias for the annual anomalies of precipitation with respect to the LTA 1981–2010 at

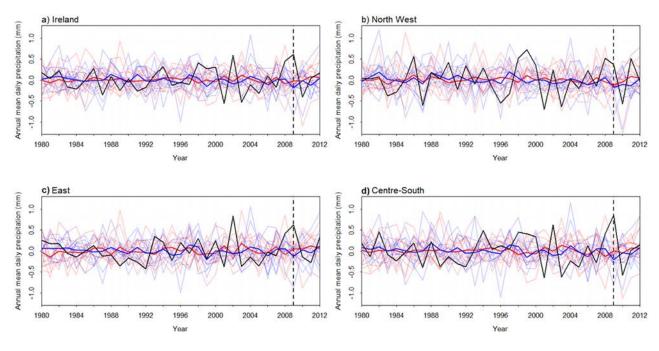


Figure 4.9. Observed (black) and modelled (HIST, red; NAT, blue) annual precipitation anomalies with respect to the 1981–2010 LTA, and multi-model means for (a) all-Ireland and (b–d) regional clusters. The year 2009 is indicated by the vertical dashed line. Individual model time series from HIST and NAT are in light red and blue, respectively, and multi-model means are indicated by heavier red and blue lines.

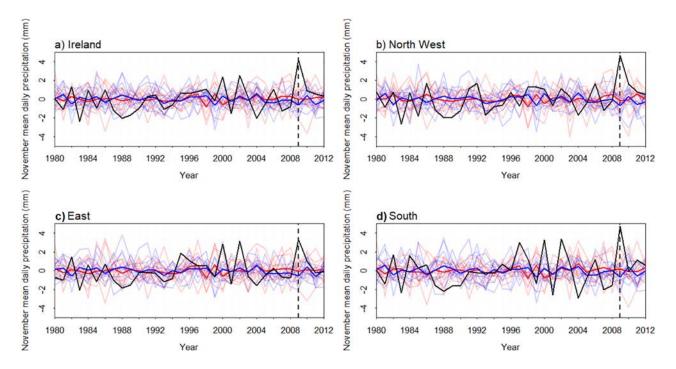


Figure 4.10. Observed (black) and modelled (HIST, red; NAT, blue) November precipitation anomalies with respect to the 1981–2010 LTA, and multi-model means for (a) all-Ireland and (b–d) regional clusters. Individual model time series from HIST and NAT are in light red and blue, respectively, and multi-model means are indicated by heavier red and blue lines.

the two different spatial scales: all-Ireland and each one of the three regional clusters (Figure 4.11). The only exception is the model HadGEM3-A-N216, which has a slightly negative bias in the east and centresouth areas, while it is positive in the north-west and when considering the whole country. The models ACCESS1.3, HadAM3P-N96 and HadGEM2-ES have a consistently negative bias across the two different spatial scales. The highest positive bias in Ireland corresponds to the model CSIRO Mk3.6.0 (0.032 mm d⁻¹). In the north-west area, the highest bias is present in the CanESM2 model (0.041 mm d⁻¹). In both the east (0.027 mm d⁻¹) and the central southern (0.037 mm d⁻¹), the highest bias is present in the CAM-5.1.1 model. In terms of absolute values, the ACCESS1 model in the east area shows the highest difference with the observed values.

For the overall country, the model HadGEM3-N-216, which has prescribed values of SST, has the lowest bias, corresponding to a positive bias of 0.0017 mm d⁻¹ (Figure 4.11).

4.9.2 Model bias, November precipitation

The bias results for the November rainfall anomalies show higher variability than for the annual values of the anomalies (Figures 4.12 and 4.13). Examining the variability of all-island annual precipitation anomalies (Figure 4.12) and all-island November precipitation anomalies (Figure 4.13) shows an apparent difference between runs representing ALL/HIST forcings and those representing only NAT forcings. However, for annual precipitation, none of the distributions of the historical and natural experiments can be said to be drawn from independent distributions, at the 95% significance level (p-value > 0.5) (Figure 4.14). Statistical testing of the distributions of November precipitation of the natural and historical experiments does not indicate that NAT and HIST are independent populations. Therefore, it cannot be said, on the basis of these results, that there exists an anthropogenic influence on November precipitation (Figure 4.15).

4.10 Discussion and Conclusions

Model precipitation is not directly comparable with observations. A more rigorous approach would be to upscale daily gridded precipitation fields at ~1 km resolution to the coarser model grid scale, as gridded datasets are more suitable for calculating anomalies and trends. This would allow comparison of values that have similar spatial representativeness.

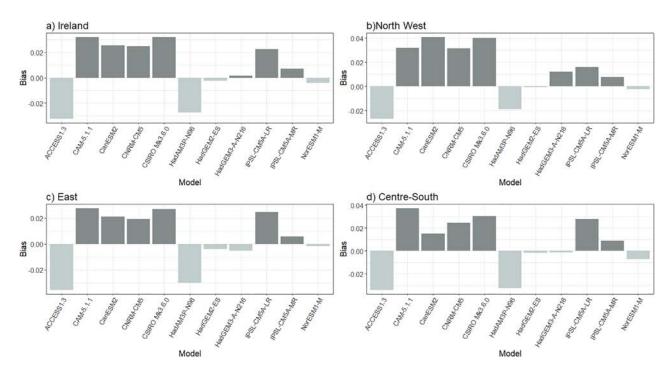


Figure 4.11. Bias of model datasets with respect to observations for annual precipitation anomalies (all-station average, mm d⁻¹).

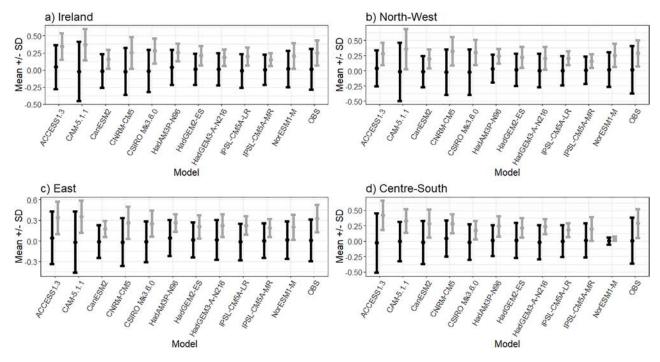


Figure 4.12. All-island average annual precipitation anomalies relative to 1961-1990 LTA \pm standard deviation range for several model datasets and observations. Black lines illustrate NAT forcings (or pre-1970 observations) and grey lines indicate HIST forcings (or post-1970 observations).

With regard to annual total precipitation, none of the distributions of the historical and natural experiments can be said to be from independent distributions, at a 95% significance level (*p*-value > 0.5).

Some further conclusions are presented below.

 There is a consistent positive bias for most of the historical experiments for the annual precipitation anomalies with respect to the LTA 1981–2010.

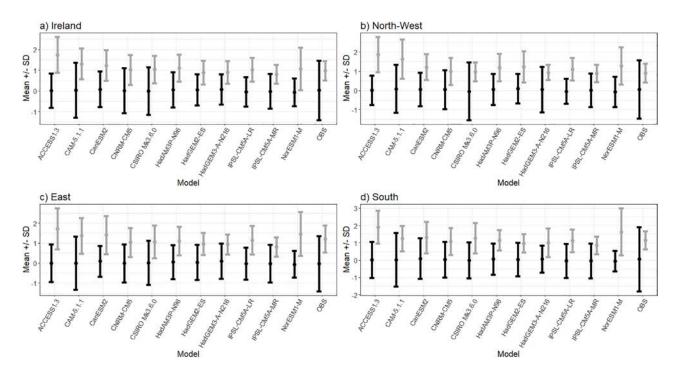


Figure 4.13. All-island average November precipitation anomalies relative to 1961–1990 LTA ± standard deviation range for several model datasets and observations. Black lines illustrate NAT forcings (or pre-1970 observations) and grey lines indicate HIST forcings (or post-1970 observations).

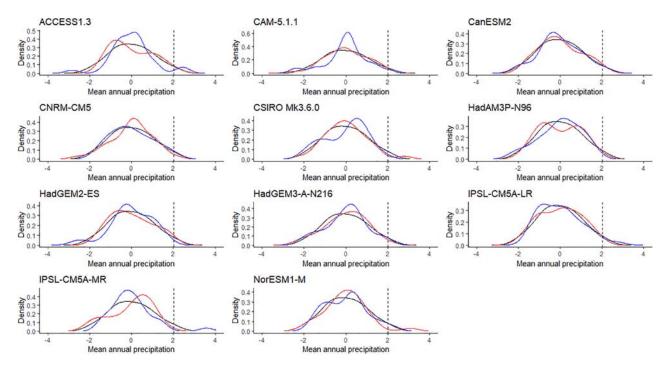


Figure 4.14. Distributions of annual precipitation anomalies in observations (black) and model runs for HIST (red) and ALL (blue) forcings.

- This is observed at two different spatial scales: all-Ireland and for each one of the three spatial clusters.
- In all three areas, the lowest positive bias of the annual precipitation anomalies was displayed by the IPSL-CM5A-MR model, with values between 0.006 and 0.009 mmd⁻¹.

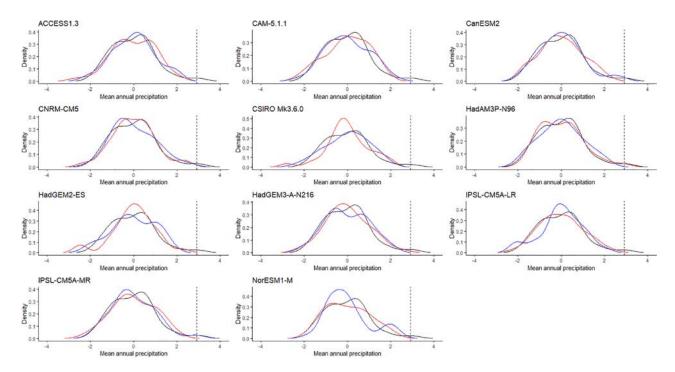


Figure 4.15. Distributions of November precipitation anomalies in observations (black) and model runs for HIST (red) and ALL (blue) forcings.

- For the whole country, the model HadGEM3-N-216 has the lowest bias owing to the prescribed SSTs, demonstrating a positive bias of 0.0017 mm d⁻¹.
- The distributions of the natural and historical experiments are not considered independent populations (for annual and November values).
 There is no statistically significant difference between the distributions.
- The November distributions of the ALL forcing and natural experiments are not statistically independent populations.
- There is no statistically significant difference between distributions of natural and historical forcings for the CMIP5 experiments.

 The results for the two comparison periods of the EURO-CORDEX simulations are similar to those from the natural and historical runs of the CMIP5 datasets, that is, there is no statistically significant difference.

In summary, a strategy for attribution of extreme precipitation events in Ireland has been outlined and applied to a case study. The case study has not resulted in positive attribution results, but it does demonstrate some of the challenges in PEA, particularly for extreme precipitation events.

5 Tools for End-to-end Attribution of Hydrological Impacts: Selection and Evaluation

The study of Schaller *et al.* (2016) on the southern England floods of 2014 extended the attribution methodology to include the *impact* of an extreme weather event (precipitation) in the form of flooding. In this study, modelled precipitation and temperature from weather@home RCMs were coupled to a semi-distributed conceptual rainfall runoff model of the Thames catchment (Crooks and Naden, 2007).

Over the last 50 years, many different hydrological rainfall runoff models (also called catchment hydrological models) have been developed (Devi et al., 2015). One objective of catchment modelling is to gain an understanding of the hydrological phenomena operating in a catchment and how changes (e.g. in climate or land use) in a catchment may affect the catchment behaviour. Rainfall runoff models are classified based on the extent or paucity of the models' input data and parameters and on the extent of physical principles applied in the model. Models may be fully distributed, semi-distributed or lumped.

In distributed models, the parameters are a function of space and time and can contain extensive detail of the catchment topography, soils and land cover, etc. The catchment is divided into small units, usually square cells or triangulated irregular network (TIN), so that the parameters, inputs and outputs can vary spatially. These physically based models are highly demanding in terms of parameters, as they try to resolve water and energy budgets or hydrological processes to eventually estimate the runoff in each cell or TIN.

Semi-distributed models divide the catchment into subcatchments with uniform characteristics and a unique discharge point that can be either a node or another subcatchment. These models are not as complex as the fully distributed models and not as simple as the lumped models (Pina *et al.*, 2016). In lumped models the entire river catchment is taken as a single unit and spatial variability is disregarded; hence the outputs are generated without considering the spatial processes (Sitterson *et al.*, 2017).

Rainfall runoff models can also be classified into three categories based on their underlying physics (Wheater *et al.*, 1993):

- physically based or mechanistic models (white-box models) based on the mathematical equations of the underlying physical processes and discretised physical equations of motions;
- metric or empirical models (black-box models) that derive information from observational data (e.g. rainfall, river flow, river height) without considering the physical and hydrological processes of the catchment but using the statistical properties of the long time series of rainfall or flow;
- conceptual or parametric models (grey-box models), which can be considered a combination of a physically based model (white box model) and an empirical model (black box model), relying on a simplified representation of the physical system, and can be calibrated using historical data (Leahy et al., 2008).

The two most important inputs required for all models are rainfall and catchment data. Along with these, watershed characteristics such as soil properties, vegetation cover, watershed topography, soil moisture content and characteristics of ground water aquifers may also be considered. The best model is the one that is parsimonious, i.e. gives results as close as possible to the reality using the fewest parameters and the lowest model complexity. Parsimony is always desirable in hydrological modelling, but it is particularly important when models are used for extreme event attribution. Owing to the large number of simulations that may be required to handle ensembles of climate data, and the resulting computational and data-handling requirements, lightweight models with minimal inputs are best suited to attribution studies. Calibration is another aspect of hydrological modelling that needs to be specifically considered in the context of attribution studies, as calibrating models separately for different sets of climatic data (e.g. NAT and ALL forcings) may introduce bias into the results.

5.1 Rainfall Runoff Model Assessment

5.1.1 **GEOtop**

Several models were considered for this exercise. including the fully distributed model GEOtop (Endrizzi et al., 2017). GEOtop is a physically based, fully distributed hydrological model that analyses the complete water cycle and energy budget in a catchment. GEOtop is open source software available for Linux, Mac and Windows platforms. This model's inputs are topographical and meteorological data. Furthermore, GEOtop can incorporate complex topography. It considers the catchment a digital elevation model (DEM), which allows modelling of the incident radiation on the topographical surface, both shortwave (including shadowing) and longwave (sky view factor). GEOtop is a spatially distributed model, so it divides the catchment into cells or pixels. Initial experiments with GEOtop provided good simulation results, but the large data requirements make it impracticable for attribution studies.

5.1.2 *tRIBS*

The TIN-based Real-time Integrated Basin Simulator (tRIBS) is a physically based distributed model developed for real-time continuous hydrological forecasting at the Ralph M. Parsons Laboratory, Massachusetts Institute of Technology (Vivoni and Ivanov, 2002), and is suitable for small to mid-size catchments (Wolock, 1995). tRIBS uses different types of geographical information system (GIS)-based input data such as the topography and soil and land use data to characterise the catchment; water table depth to initialise soil moisture; radar rainfall as precipitation input; and meteorological station data for modelling inter-storm periods.

5.1.3 TopModel

TopModel is a semi-distributed conceptual rainfall runoff model that uses the topographical information of the catchment area as a DEM and soil transmissivity to generate the runoff at the catchment outlet based on the theory of hydrological similarity between points in a catchment based on a measure called the topographical index (TI). The simplicity of the model

comes from the use of this index, which is an index of hydrological similarity (Beven, 2008). TI is the ratio of drained area per unit contour length to the local slope angle of the location, and represents the relation between the tendency of water to accumulate at any point in the catchment and the tendency for gravitational forces to move that water downslope.

5.1.4 The probability distributed model

The probability distributed model (PDM) is a conceptual rainfall runoff model developed by Moore (2007). This model is suitable for a variety of catchments, and has minimal data and computational requirements - much less than GEOtop. PDM has a large number of model options; the "standard" model is suitable for most practical purposes. Rainfall and potential evapotranspiration data are used as inputs to produce runoff at any point of the catchment, which is controlled by the absorption capacity (of the canopy, surface and soil). PDM considers each point of a catchment as a single storage unit with a specific storage capacity (depth) that can be described by a Pareto distribution. PDM is therefore a "lumped" model and is more straightforward to parameterise and run for attribution studies.

5.2 Case Study Application of PDM – Munster Blackwater

5.2.1 The Munster Blackwater catchment

The Munster Blackwater catchment (Blackwater catchment hereafter) is located in the south-east of Ireland (Figure 5.1). The catchment is relatively broad and flat, where the river flows from west to east, passing through the urban centres of Mallow and Fermoy to then turn south at Cappoquin and finally discharge into the sea at Youghal (Nicholson, 2012). Four subcatchments were considered for the exercise: Duarrigle, Dromcummer (11 rain gauges), Mallow Rail Bridge (15 rain gauges) and Killavullen (17 gauges) (Figure 5.1). The period 2010–2017 was chosen owing to the availability of good-quality data, and the year 2014 was selected for more in-depth analysis. The model was run for each one of the three subcatchments and the performance of the model evaluated.

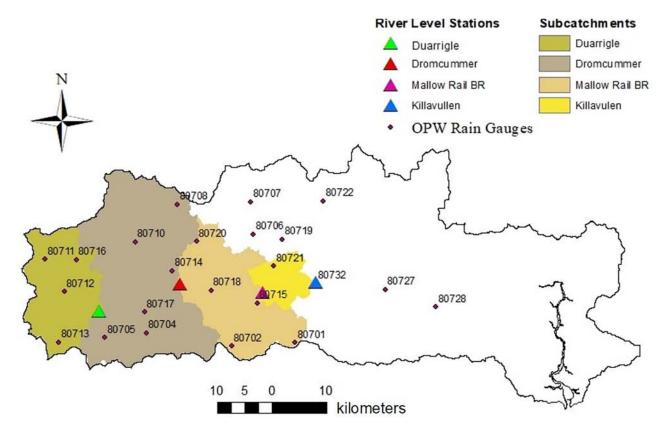


Figure 5.1. Munster Blackwater catchment, showing locations of river level gauging stations, rain gauges and subcatchments.

5.2.2 Model validation

Annual maxima of flows at Mallow Rail Bridge were inspected in order to select suitable events for validation (Table 5.1).

5.2.3 High-flow event from 3 to 5 February 2014

The model was run (with calibration parameters) for the event between 3 and 5 February 2014 in three

Table 5.1. Times and magnitudes of Mallow Rail Bridge annual maxima of river flow in each year during 2010–2017

Date and time	Observed river flow (m ³ s ⁻¹)
13/01/2010, 00:30	504
30/11/2011, 01:15	388
08/06/2012, 10:30	369
30/12/2013, 14:30	463
03/02/2014, 19:30	367
30/12/2015, 17:45	518
02/01/2016, 07:45	524
22/10/2017, 07:00	336

subcatchments as validation (i.e. no change to the parameters as used in the calibration run). Table 5.2 shows the summary of each model run performance. The resulting hydrograph for Dromcummer is illustrated in Figure 5.2. This indicates that the shape of the computed flow in Dromcummer is similar to the shape of the observed flow, with the observed peak flows seeming to be wider and decreasing more rapidly than the modelled flow. The goodness-of-fit (R^2) of the model is 93%, which indicates that the estimations of the magnitude of the computed flows are close to the observed flows for most of the time.

The model performance at Mallow Rail Bridge is not as good as the model's performance in Dromcummer but is better than the model's performance in Killavullen (Figure 5.3). The shape of computed hydrograph is similar to the shape of observed hydrograph, but it does not show the two successive peaks. In general, the computed flow is underestimated.

Table 5.3 shows the modelled peak flow time and magnitude and the rising rate and falling rate at three subcatchments and indicates that the modelled flow falling limb is more than twice as long as the rising

Table 5.2. Rainfall and modelled and observed flows for the test event between 3 and 5 February 2014 at the three gauging points on the Munster Blackwater catchment

Station	R ²	Rainfall (mm)	Computed baseflow (m³ s ⁻¹)	Observed flow (m³ s ⁻¹)	Computed flow (m³ s ⁻¹)	Potential evaporation (mm)	Actual evaporation (mm)	Net rainfall (mm)
Dromcummer	0.9376	37.04	8.67	30.46	29.34	0.51	0.51	36.53
Mallow Rail Bridge	0.8089	35.52	12.70	31.48	29.68	0.51	0.51	35.01
Killavullen	0.7834	35.97	10.54	25.15	27.15	0.51	0.51	35.46

Note that the observed flows and computed flows are the total flows during the event. The R^2 or coefficient of determination is an indicator of the fraction of the variance in a quantity that is explained by a model, and is dependent on the sum of squares of differences of observed flow and computed flow in each time step. When R^2 is small, it means that the computed flow over a specific duration is not a good representation of the variance of observed flow. Actual evaporation is typically about 90% of potential evaporation, as soil moisture is not frequently limiting, particularly in the west of the catchment. Annual average actual evapotranspiration ranges from 24% of annual precipitation in the west of the catchment to 44% of annual precipitation in the drier eastern section (Mills, 2000).

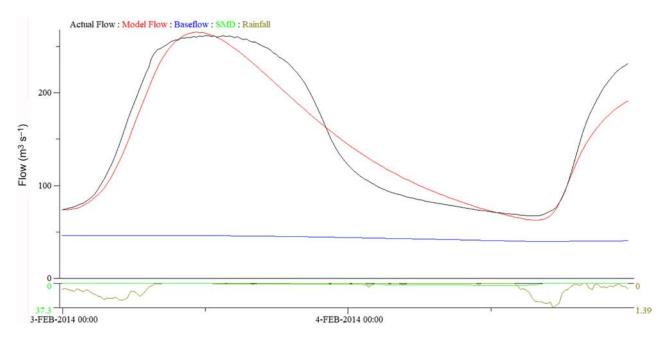


Figure 5.2. PDM simulation for validation. Event of 3–5 February 2014 in Dromcummer, R^2 = 0.9376.

limb. Further research might address the possibility of using the model to detect wider hydrographs.

5.3 Summary of Findings on Hydrological Models for Attribution

There have been very few end-to-end attribution studies of flood events incorporating hydrological models since that of Schaller *et al.* (2016), which used the CLASSIC semi-distributed rainfall runoff model (Crooks and Naden, 2007). Other studies of climate change impact on flooding have used other

semi-distributed models such as HBV-Light (Steele-Dunne et al., 2008).

PDM is a suitable hydrological model for modelling streamflow in Irish river catchments where there is sufficient coverage of rain gauges and available flow records. Once the model is calibrated and parameters are optimised by PDM, streamflow is modelled well, with good performance for both peak flows and low flows (e.g. R^2 =0.9461).

While peak flow magnitudes were modelled well in most cases, the timing of the peaks was not as good as expected. This may be because PDM produced hydrographs that tended to be short duration (narrow)

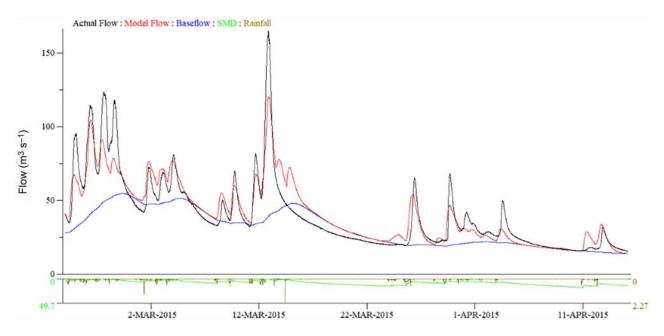


Figure 5.3. Observed and simulated flows at Mallow for several events during March and April 2015.

Table 5.3. Comparison of modelled peak time, flow, and rising and falling limb at three river stations

	Time peak	Flow peak (m³ s ⁻¹)	Rising rate (m³ s ⁻¹ h ⁻¹)	Falling rate (m³ s ⁻¹ h ⁻¹)	Rising limb (h)	Falling limb (h)
Dromcummer	03/02/2014, 11:15	265	17.36	7.25	11:15	28:30
Mallow Rail Bridge	03/02/2014, 15:00	340	20.75	8.14	11:15	27:45
Killavullen	03/02/2014, 16:30	280	4.015	5.29	12:00	26:30

and almost bell-shaped, while the observed peaks tended to be much longer duration (i.e. wider). Some observed peaks at Mallow and Killavullen lasted as long as 12 h, while PDM modelled peaks tended to be shorter by a few hours.

It is important to note that, for attribution studies, exact matching of modelled and observed peak flow values or low values, or even correct timing of flood peaks, is not essential. For climate change attribution studies, changes in quantities such as peak flows or low flows are of greater interest than their absolute values and, in practice, models are often bias corrected prior to use in attribution studies. The frequency of high- or low-flow events is also of interest. The requirements of attribution studies are therefore very different to the more conventional applications of hydrological models such as flood forecasting.

A sensitivity analysis was carried out, which can be viewed as the initial step towards an attribution study using PDM. When rainfall was artificially increased by various amounts ranging from 10% to 30%, the peak flows of high-flow events increased at a slightly

greater rate than the rainfall. For instance, for a 10% increase in rainfall, the streamflow peaks increased by 10.6% (Figure 5.4). Low flows exhibited a much lower sensitivity to total rainfall, increasing at a much lower rate than the rainfall increases.

A model such as PDM requires calibration on past river flows to parameterise the soil storage. This may be seen as a disadvantage for attribution studies, as any calibration exercise carried out using observational data under historical climate conditions could be perceived as being invalid under other climatic scenarios, for example with only natural forcings. However, it is important to note that the goal of the model calibration exercise is to correctly model the soil hydraulics, and soil parameters are unlikely to be strongly dependent on climatic factors. Therefore, provided the model is not applied outside its calibrated range, it should yield useful results for attribution studies.

This work was the subject of Parvaneh Nowbakht's Master of Engineering Science thesis, supported by the project and completed in 2020 (Nowbakht, 2020).

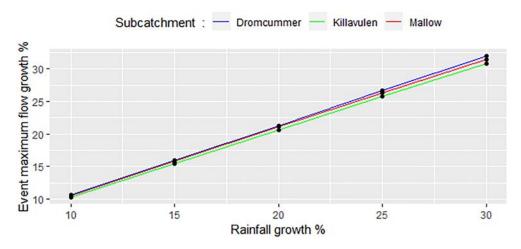


Figure 5.4. Comparison of the ratio of new flow (computed flow with rainfall increases of 10%, 15% and 30%) with old flow (computed flows with actual rainfall) for largest flow (3–5 February 2014) for three subcatchments.

6 Conclusions and Recommendations

Despite the relatively benign climate of Ireland, the hazards of extreme weather events pose a substantial risk to the society, economy and infrastructure of the country. Events in the recent past, such as the "fodder crises" of 2012/13 and 2018 and multiple occurrences of flooding, have shown that extreme weather events have had a significant impact. The financial losses alone from 17 events between 1980 and 2018 amounted to almost €3 billion. Climate change modelling exercises have projected that extreme weather events will increase in frequency and magnitude in the coming decades as the effects of anthropogenic GHG emissions on the global climate system increase. For Ireland, these are likely to include a greater seasonal incidence and severity of regional droughts, impacting agricultural systems and resulting in more frequent flooding in some areas (Desmond et al., 2017). Impacts on public health and energy systems also cannot be ruled out (Nolan, 2009).

The science of probabilistic event attribution offers a means to estimate the influence of human activities (chiefly GHG emissions from fossil fuels, industry, land use change and agriculture) on particular types of extreme weather events. When the methodology is used in conjunction with simulations of future climatic conditions under different projections of future GHG emissions, it is possible to take the results further and estimate the future frequency and severity of particular types of events.

Daily time series of precipitation for the Novembers between 1980 and 2012, including observations, and the historical and natural experiments for 11 different models, and standardised daily values of precipitation for each model and experiments, were compared. Distributions of the natural and historical experiments for November are not found to be independent populations. So it cannot be said that there is a statistically significant difference between the modelled distributions, and there is therefore no evidence that anthropogenic emissions have changed the probability of flooding events similar to that seen in November 2009.

Application of PEA to extreme precipitation events in Ireland is made more challenging by the marinedominated climate and relatively small size of Ireland. The influence of SST on the local climate is very strong. Therefore, the representation of SST in the GCMs used for generating attribution datasets has a strong influence on model performance. This emphasises the importance of using datasets based on atmosphere-only GCMs, with prescribed SSTs (and sea ice) for attribution of events in the Irish context. Furthermore, depending on the model's resolution, the entire country may be contained within only four or five GCM grid cells, several of which will be partially made up of sea areas. However, higher resolution downscaled regional climate model datasets have been produced specifically for Ireland (e.g. Nolan, 2015) and demonstrate improved accuracy of simulations for the terrestrial area of Ireland. Paired ensembles of downscaled RCM simulations for Ireland with NAT and ALL forcings would be a valuable addition to the current datasets to support climate change attribution work in Ireland.

PEA is a useful tool to help communicate the impacts of climate change in a way that the general public is likely to understand. This can be done by careful framing of the attribution question, i.e. translating a high-impact event such as an extreme storm into a set of meteorological drivers, and investigating the frequency or severity of similar events in two different sets of simulated worlds – one with human-induced climate change and one without.

The final recommendations arising from this project are:

- For general climate change attribution investigations of Irish extreme weather events, models with prescribed SSTs are recommended on account of the strong marine influence on the climate of Ireland. The HadGEM3-A model runs are available with excellent spatial resolution and have been shown to perform well.
- A recommended alternative approach is to use downscaled EURO-CORDEX simulations, split into two time periods, one representative of recent past conditions (e.g. prior to 1970) and one

- representative of current and/or future conditions (e.g. post 1970).
- For end-to-end attribution of fluvial flooding impacts in Ireland, a lumped hydrological model such as the PDM is recommended. This class of model requires several orders of magnitude fewer input data than the other type of model considered in this study, the fully distributed models such as GEOtop. The lower computational requirements for running lumped models will allow results to be generated more rapidly. This is useful for near-real-time attribution of extreme weather events, and it also permits larger ensembles to be used, allowing greater statistical confidence in the results.
- The wide range of observational datasets
 collected over long durations and with good spatial
 representativeness are useful for validating the
 outputs of models used in attribution studies.
 Further work could be carried out to investigate
 the use of gridded data products produced
 from Met Éireann observations and to generate

- Ireland-specific downscaled HIST and NAT RCM runs specifically for attribution purposes.
- The tools to support near-real-time attribution of extreme weather events are improving and are becoming more accessible, e.g. the outputs of the EUCLEIA project and cloud computing platforms such as Pangeo.²⁴
- Further work is needed to characterise
 multifactorial events, such as the fodder crises of
 2012/13 and 2018, in order to carry out attribution
 studies. The chosen case study event of the 2009
 floods could also be considered a multifactorial
 event, influenced by antecedent precipitation over
 different timescales.
- The inventory of extreme weather events should be extended and maintained, possibly through an open platform supported by the research community and relevant stakeholders such as the Environmental Protection Agency and the OPW. This could be combined with a more formal set of metrics, including a subset of the extreme indices discussed in this report.

²⁴ Pangeo, a community platform for big data geoscience. See https://pangeo.io/

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Abbreviations

CAM Community Atmosphere Model

CLM Community Land Model

CMIP Coupled Model Intercomparison Project

CORDEX Coordinated Regional Downscaling Experiment

DEM Digital elevation model

ETCCDI Expert Team on Climate Change Detection and Indices

FAR Fraction of attributable risk
GCM Global climate model

GHCN Global Historical Climatology Network

GHG Greenhouse gas

HadGEM Hadley Centre Global Environmental Model

LTA Long-term average

NCIC National Climate Information Centre (UK)

OPW Office of Public Works (Ireland)
PDM Probability distributed model
PEA Probabilistic event attribution
RCM Regional climate model

RCP Representative Concentration Pathway

SST Sea surface temperature
TI Topographical index

TIN Triangulated irregular network

Glossary

ALL A set of climate model simulations representing all forcings, anthropogenic and non-

anthropogenic

EURO-CORDEX European branch of the CORDEX model initiative

HIST A set of model simulations representing historical forcings (both natural and anthropogenic)

NAT A set of model simulations representing only "natural" non-anthropogenic forcings

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.

Eolas: Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.

Tacaíocht: Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola (m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- an diantalmhaíocht (m.sh. muca, éanlaith);
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe (OGM);
- foinsí radaíochta ianúcháin (m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha);
- áiseanna móra stórála peitril;
- · scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil (m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí).

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

 Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

 Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn (m.sh. mórphleananna forbartha).

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol (m.sh. Timpeall an Tí, léarscáileanna radóin).
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

ClimAtt: Tools for Climate Change Attribution of Extreme Weather Events



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Identifying Pressures

Extreme weather events, such as heavy or prolonged rainfall events, droughts and heatwaves, have the potential to cause significant social and economic disruption in Ireland. The most damaging impacts of climate change may be due to changes in the frequency or severity of such extreme events, rather than changes in average weather conditions.

It is important that the public and decision-makers understand how climate change is influencing weather variability and extremes. Following the occurrence of an event associated with extreme weather, such as a flood, the media may ascribe the event to climate change, even in the absence of any underlying scientific evidence.

The field of probabilistic event attribution has developed rapidly in the last two decades. It allows for the influence of climate change on specific extreme weather events to be calculated, based on evidence from climate models. This allows for better understanding of the drivers of such events and, more importantly, predictions of how often similar events may occur in future decades as the Irish climate continues to change.

Informing Policy

Policymakers have become familiar with the effects of climate change on mean climatic conditions, for example average monthly temperatures in summer. However, climate change also affects the occurrence of extreme values for rainfall, temperature and other variables. This project found that many of the most damaging extreme weather-related events experienced in Ireland are due to prolonged heavy precipitation or cold spells. The known financial losses from 17 events between 1980 and 2018 amounted to almost €3 billion.

The damage may be mediated by human responses to the events; therefore, having detailed knowledge of the present

and future likelihood of such events occurring will lead to better levels of preparedness and a more resilient society.

A move to evidence-based attribution of the impacts of extreme weather events to climate change will lead to a more informed public debate about the costs of anthropogenic climate change and the risks associated with future occurrences of similar events. It will also provide valuable information to support and future-proof climate adaptation plans and infrastructure, such as flood relief schemes or water supply upgrades.

Developing Solutions

Ireland's climate is heavily influenced by the sea. An appropriate set of climate change attribution data, tools and methods is therefore important in order to investigate the influence of climate change on extreme weather events experienced in Ireland, such as Storm Ophelia in 2017 or the widespread floods of November 2009.

The ClimAtt project has examined the state of the art in climate change attribution of extreme weather events. Met Éireann's observational records have been used to test and validate several climate model datasets for attribution purposes. The most appropriate datasets and methods to use to investigate the influence of climate change on extreme weather events occurring in Ireland have been recommended.

A case study of the November 2009 floods in south-western Ireland found no evidence that the rainfall in the days before that particular event was made more severe, or more likely, as a result of climate change.

Further work should examine the role of climate change in multiple extreme events whose effects may combine over time to create significant damage such as widespread floods, droughts, or deficits in agricultural production.