WASITUS Rapid Attribution Study:

Human-caused climate change increases potential for flooding in south-eastern counties of Ireland as rainfall intensifies

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Maynooth University
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Human-caused climate change increases potential for flooding in south-eastern counties of Ireland as rainfall intensifies

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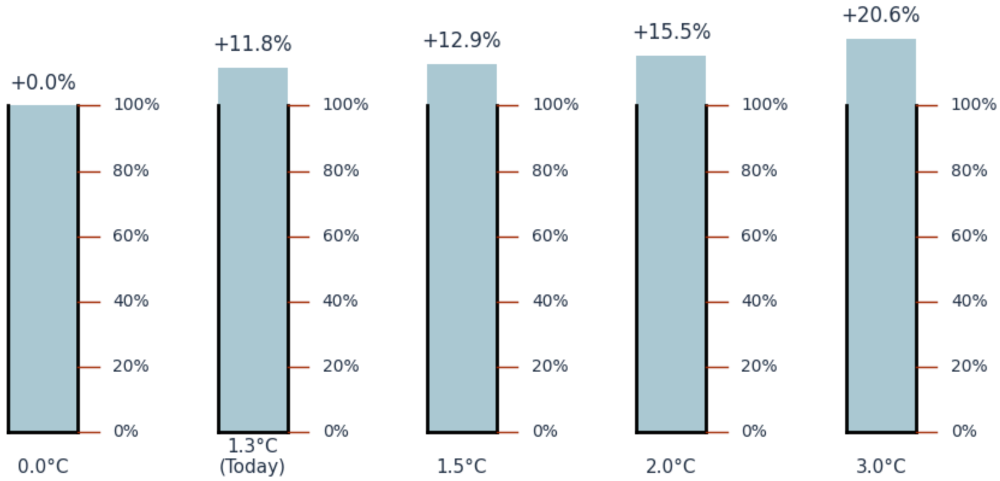
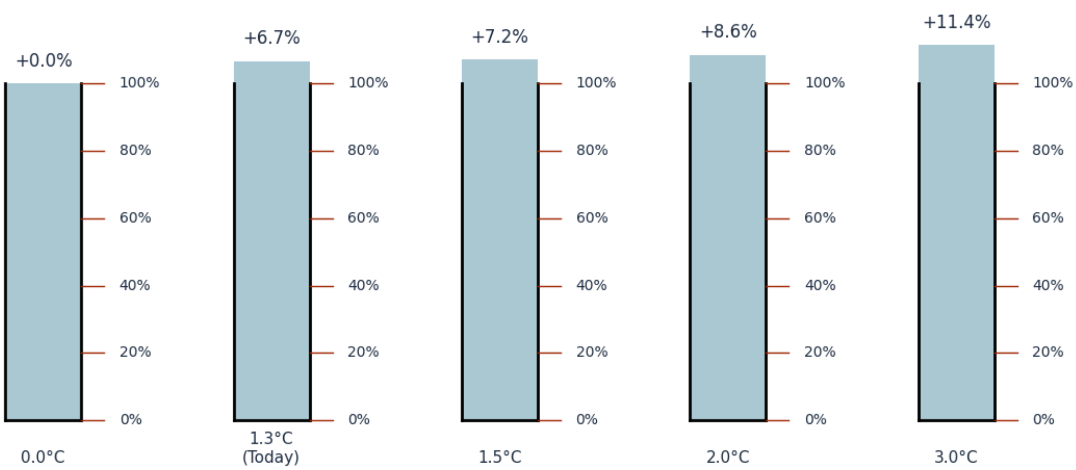
Main findings

- Analysis of hydrometric data shows that Storm Claudia caused significant but not exceptional flooding, with several rivers in Wexford and Wicklow recording their highest or second-highest peaks, although on short records; longer-term records show the event had a return period of roughly 20–30 years, indicating it was moderately rare rather than extreme.
- In comparison to a pre-industrial climate, the magnitude of the rainfall associated with the 2-day event in Dublin, Wexford and Wicklow has increased by nearly 12%.
- With further global warming we expect similar 2-day rainfall events to have a further 1%, 3%, and 8% increase in magnitude from today for climates 1.5°C, 2.0°C, and 3.0°C warmer than pre-industrial levels respectively.
- In comparison to a pre-industrial climate, the magnitude of the rainfall associated with the 30-day event in Dublin, Carlow, Kildare, Kilkenny, Laois, Louth, Meath, Wexford, and Wicklow has increased by nearly 7%.
- With further global warming we expect similar 30-day rainfall events to have a further 0.5%, 2%, and 4.5% increase in magnitude from today for climates 1.5°C, 2.0°C, and 3.0°C warmer than pre-industrial levels respectively.
- Both the 2-day and 30-day rainfall events have already become twice as likely as would have been the case in a pre-industrial climate. On a warmer planet, with 3.0°C of global warming, we would expect similar 2-day rainfall events to happen once every 1-2 years and 30-day rainfall events to happen once every 2 years.

Predicted changes in magnitude for a 2-day intense rainfall event in counties Dublin, Wexford, and Wicklow.



Predicted changes in magnitude for a 30-day intense rainfall event in counties Dublin, Carlow, Kildare, Kilkenny, Laois, Louth, Meath, Wexford, and Wicklow.



1 Introduction

On the Friday 14th and Saturday 15th of November 2025 large amounts of rainfall, associated with Storm Claudia, fell primarily across the south east of Ireland. Both orange and yellow rainfall and wind weather warnings were issued on Thursday the 13th by Met Éireann for the following two days. An orange rainfall warning was put in place for counties Dublin, Wexford and Wicklow from 2pm on the 14th to 11am on the 15th. Yellow rainfall warnings were also put in place for counties Carlow, Cork, Kerry, Kildare, Kilkenny, Limerick, Louth, Meath, Tipperary and Waterford lasting for 24 hours with varying start times.

The rainfall event experienced in Ireland was associated with storm Claudia. Claudia was named by the Spanish Meteorological Agency (AEMET) on Monday 10th November for wind and rain impacts expected over the Canary Islands on Tuesday 11th and through the rest of the week over western parts of the Iberian Peninsula

The low pressure that became Storm Claudia moved off the east coast of North America on Sunday 9th November. It moved to the south of a large complex low pressure system over the mid North Atlantic and engaged with the jet stream. Storm Claudia then moved to the northern side of the jet stream, merging and becoming the dominant low on Monday 10th as it moved closer to northwest Europe. At the same time the jet stream buckled and became more meridional (north to south oriented), with a ridge developing over the western North Atlantic and a deep trough developing over the eastern North Atlantic by Tuesday 11th. The trough stretched all the way south to the Canary Islands with an active cold front from storm Claudia causing the rare wind and rain impacts there.

The more blocked weather pattern that developed with the meridional orientated jet stream led to the low pressure system associated with storm Claudia stalling to the west of the Bay of Biscay between Tuesday 11th and Sunday 16th. During this period a warm and moist tropical maritime airmass, originating over waters with sea surface temperatures well above average, was drawn northwards to the east of the stalled low pressure system towards Ireland and the UK. This brought several active weather fronts and pulses of heavy rain northwards across Ireland between Tuesday 11th and Thursday 13th, with the heaviest rain in the midlands, south and east, as is typical when low pressure is positioned to the southwest of Ireland.

Meanwhile, the ridge that developed over the western North Atlantic pushed north and merged with high pressure over Greenland which intensified and began to slowly push southwards over the mid North Atlantic on Wednesday 12th, drawing a cold Arctic airmass south on its eastern side towards Ireland and the UK.

By Friday 14th the cold Arctic airmass moving south and the warm tropical maritime airmass moving north clashed over Ireland and the UK creating a large temperature gradient between the North of Ireland and the UK and the south of Ireland and the UK, with stalled weather fronts in between stretching east to west across the southern half of Ireland, Wales and England. The cold Arctic air moving south undercut the warm moist airmass moving north creating extra lift along the stalled frontal zone. This led to an intensification of the rainfall along the stalled frontal zone on Friday 14th and Saturday 15th, resulting in high rainfall totals in places, especially for the southeast of Ireland, Wales and parts of England.

A notable feature of this event was the development of very strong northeasterly winds on Friday 14th and Saturday 15th, caused by a tightening in the isobars between the high pressure system sinking south from the north and the stalled low pressure system associated with storm Claudia. This setup concentrated the heaviest rainfall on the eastern slopes of the Wicklow, Wexford and south Dublin hills, which is unusual for heavy rainfall events in Ireland.

This rainfall event was particularly concerning due to the recent high rainfall levels across the country that had left a substantial amount of land saturated, and river levels higher than normal. Provisionally, November (up until the end of the 18th) had seen high rainfall totals: between 63.3mm experienced at Markree, Co Sligo and 189.9mm at Johnstown Castle, Co Wexford. The highest daily reading from the Met Éireann synoptic network occurred during this 2-day rainfall event, on the 14th (00-00 UTC), with 66.9mm recorded at Johnstown Castle. This is equivalent to 58% of that station's average total November rainfall (measured against the 1991-2020 long term average) occurring in just 24 hours. In addition, Ireland experienced above average rainfall in the previous few months. September experienced 144% of average rainfall levels and October experienced 123% of average levels.

The majority of November saw widespread rainfall on a synoptic scale, with extremes experienced regionally. Nationally, the wettest day occurred on the 11th, where many stations recorded totals between 20-40mm over the course of the day. The 12th and 13th saw more modest levels of rainfall, concentrated to the west and northwest of the country. By the 18th, rainfall nationally had reached 92% (128.8mm) of the area gridded average for the month of November. Figure 1.1 shows the total monthly rainfall in mm from the 1st to the 13th, before the 2-day rainfall event, and from the 1st to the 18th, up to and including the rainfall event. As can be seen from the two images, rainfall in the south and east of the country significantly increased as a result of this rainfall event.

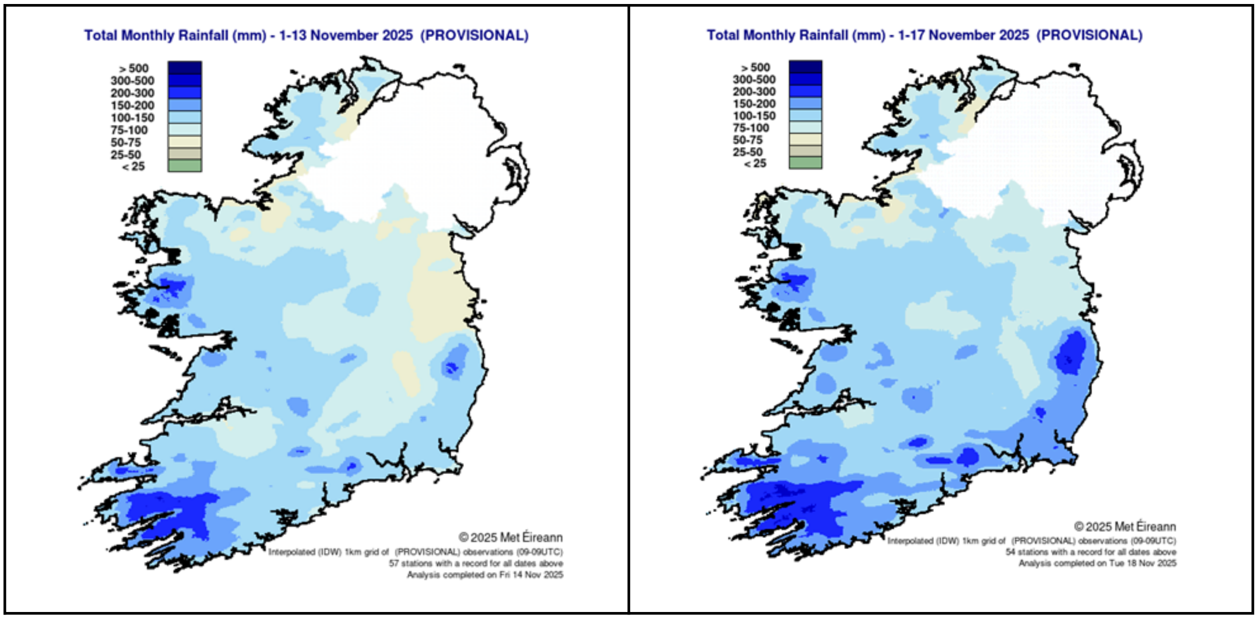
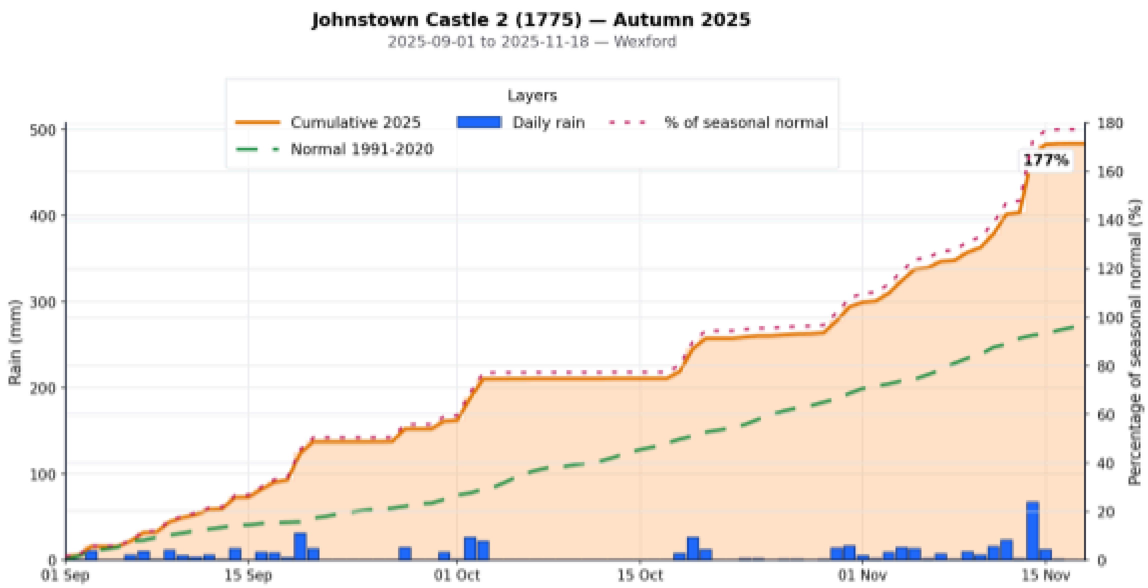


Figure 1.1: Total monthly rainfall in mm. Left: from the 1st to the 13th, before the 2-day rainfall event. Right: from the 1st to the 18th, up to and including the rainfall event.

Figure 1.2 highlights the cumulative rainfall totals from 1st of September through until the 18th of November for Johnstown Castle, Co Wexford and Dublin Airport, Co Dublin. The cumulative rainfall in November 2025 is shown in orange and can be easily compared to the 1991-2020 normal rainfall levels for November, which are shown in a dashed green. Daily rainfall levels are shown using blue histograms. The dashed red line on both graphs represents the "% of seasonal normal". This compares the cumulative rainfall at a given station, e.g. Johnstown Castle (top), in November 2025, with the long-term average for the same dates (1991- 2020). A value of 100% represents normal seasonal rainfall, while values above this indicate wetter-than-normal conditions. Here, 177% means rainfall is 77% above normal. At Johnstown Castle, the cumulative rainfall rose from roughly 420 - 430 mm on 13th November to about 490 - 500 mm on 14th November, indicating a significant one-day increase of around 70 - 80 mm.



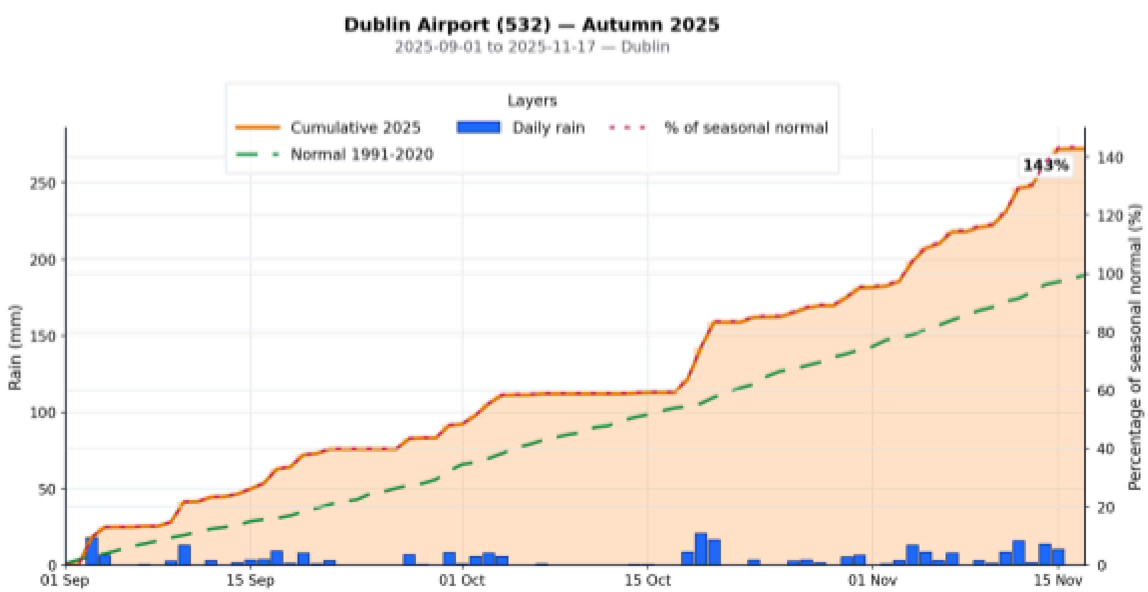


Figure 1.2: Cumulative rainfall totals from 1st of September through until the 18th of November for Johnstown Castle, Co Wexford and Dublin Airport, Co Dublin. Similar, higher than average cumulative rainfall levels were found across the affected areas of the south and east of Ireland.

1.1 High level rainfall events in an Irish context

Extreme rainfall events in Ireland occur over a variety of temporal and spatial scales (Wang et al., 2006). Due to Ireland's relatively good data quality, and long term history of taking meteorological measurements, many of these rainfall extremes have been recorded and provide valuable insight into how the climate has changed over time (Murphy et al., 2019). Table 1.1 below highlights a number of these extreme rainfall events on an annual, monthly, daily and sub-daily scale, with focus where appropriate on extremes in the month of November.

Highest Annual Total	3964.9mm	Ballaghbeama Gap, Co Kerry	1960
Highest Monthly Total	943.5mm	Gernapeka, Cork	December 2015
Wettest November on Record (gridded data)	-	National area-average series (84-years)	November 2009
Provisional Highest November 7-day Total	148mm	Newport, Co Mayo	Week ending 18th November 2015
Highest Daily November Total	167.1mm	Killarney, Co Kerry	9th November 1941
Highest Hourly Total	52.2mm	Clonroche, Co Wexford	27th June 1986

Table 1.1: Relevant rainfall extremes in an Irish context. To see a further and more detailed list of rainfall extremes, visit Met Éireann's 'Weather Extreme Records for Ireland'.

Various studies over the last approximately 10 years have looked at using rainfall records, like those in Table 1.1, to assess changes in Ireland's average rainfall, and the occurrence and intensity of rainfall extremes. According to Ireland's Climate Change Assessment Report, Ireland's average rainfall has increased by 7% over the period 1991-2020 when compared to the annual average of 1186mm over the period 1961-1990. This observed shift in rainfall follows the Clausius-Clapeyron principle, which suggests for every one degree rise in global temperatures, the atmosphere can hold 7% more water (Trenberth, 2011; Adam, 2023).

Further evidence of hydroclimatic change in Ireland was discovered with the development of a continuous 305-year rainfall record (1711-2016) by Murphy et al., (2018). Trends towards wetter conditions were identified, with a notable finding being that the period between 2006-2015 was the wettest 10-year period in over three centuries. From a rainfall extreme perspective, Ryan et al., (2021) examined long-term trends in extreme precipitation indices in Ireland and found increases in precipitation intensity, especially in the east and southeast of the country. Murphy et al. (2023) found that about 30% of long-term daily rainfall stations in Ireland show the emergence of a climate change signal, relative to the early industrial period (1850-1900), in a variety of intensity metrics. Regression of these indices onto global mean surface temperature shows increases per degree of global warming that are consistent with the Clausius-Clapeyron principle (Murphy et al., 2023). Another important factor when discussing precipitation extremes in Ireland is the influence of the North Atlantic storm track, which lies directly over the British-Irish Isles (Matthews et al., 2015). Extra-tropical cyclones can often be pushed towards Ireland bringing unsettled, lower pressure weather fronts, typically congruent with extreme precipitation events, as was evident during the 2013-2014 winter season (Matthews et al., 2014). There remains limited evidence to suggest extra-tropical cyclones or storms will impact Ireland more frequently in the future or will be more intense in the future as stated by Ireland's

Climate Change Assessment Report. However, what is more evident is the projected increase of rainfall extremes. Nolan and Flanagan, (2020) found considerable increases in the average number of “very wet days”, defined as daily precipitation greater than 30mm, by 21% and 31% with respect to RCP4.5 and RCP8.5 scenarios (2041-2060). Autumn and Winter months saw the greatest increase, 25% and 42% for Autumn and 33% and 61% for winter, with respect to RCP4.5 and RCP8.5 scenarios (2041-2060).

It is important to understand the changes in extreme rainfall due to their influence on flooding (Nolan and Flanagan, 2020). Wetter antecedent conditions (i.e. saturated soils in the lead up to a flood), plus an increase in short duration precipitation extremes (i.e. the flood triggering event), lead to a greater risk of flooding (Bloschl et al., 2019). An example of this was the catastrophic 2023 flood event in Midleton, Co Cork. An attribution report assessing the degree to which human-induced climate change influenced the likelihood and intensity of the extreme rainfall event was undertaken. The 2-day precipitation event was brought about by Storm Babet as it moved past the south coast of Ireland (Met Office, 2023). Soils were already heavily saturated due to above average precipitation in the months preceding the event. These conditions lead to high river flows upstream from Midleton which ultimately caused severe flooding of the town and surrounding area. The attribution report found that climate change had made the 2-day October extreme rainfall event more than twice as likely and had increased in intensity by 13% compared to a pre-industrial climate. In a 2°C warmer world (compared to pre-industrial), a similarly extreme 2-day rainfall event in October was projected to further increase in likelihood and intensity.

1.2 Event Definition

Two different event definitions are used to examine the high rainfall levels that lead to flooding in parts of the south-east of Ireland on the 14th and 15th of November 2025.

First, to better understand the heavy rainfall that lead directly to flooding and surface water along the south-east coast, we examine the 2-day event. This is analysed over the three counties that were encompassed by the orange weather warning: Dublin, Wexford and Wicklow. 2-day rainfall extremes are examined for Ireland’s wettest months which consists of the months October, November, December, and January. This will henceforth be referred to as Rx2day.

Second, to better understand the wet conditions during the period preceding the event, we examine the 30-day yearly maximum rainfall levels. This is analysed over nine counties that not only experienced high rainfall levels, but whose rivers lead into the three counties under the orange rainfall warning. They are: Dublin, Carlow, Kildare, Kilkenny, Laois, Louth, Meath, Wexford, and Wicklow. This event will henceforth be referred to as Rx30day.

Both geographical study areas can be seen in Figure 1.3 outlined in red.

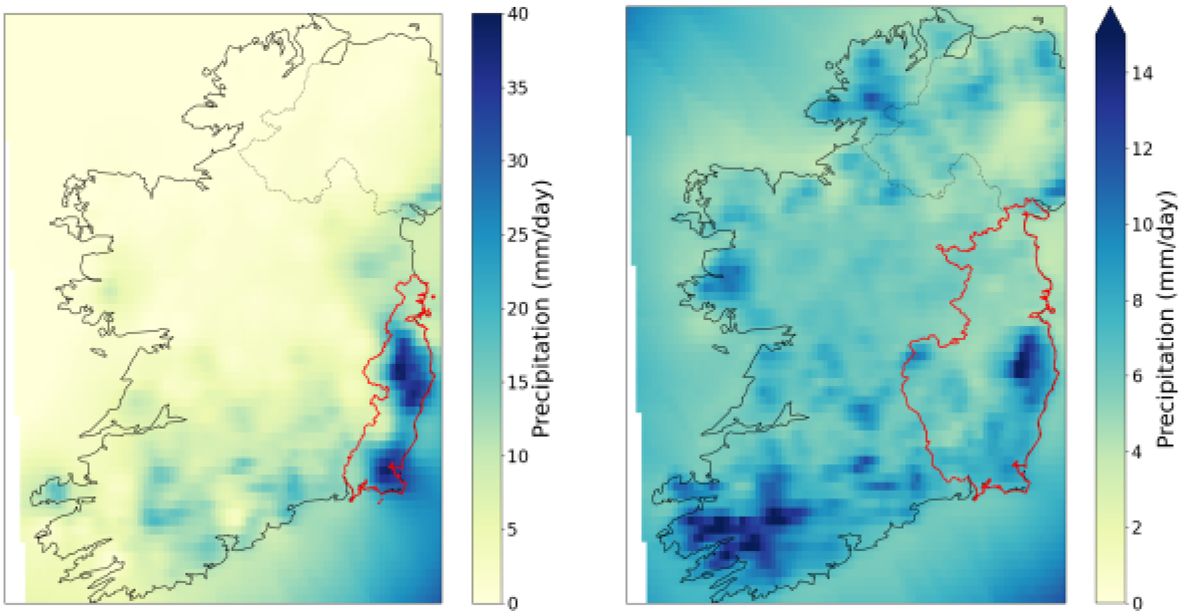


Figure 1.3: Left: Geographical area studied in Rx2day. Right: Geographical area studied in Rx30day. Maps created from Met Éireann's gridded product.

2 Data and methods

In this report, we study the influence of anthropogenic climate change by comparing the likelihood and intensity of similar 2-day and 30-day rainfall totals at present with those in a 1.3°C cooler climate. We also extend this analysis into the future by assessing the influence of a further 0.2°C, 0.7°C, and 1.7°C of global warming from the present. This is in line with 1.5°C and 2°C of global warming which constitutes the long-term temperature goal of the Paris Agreement[1] and 3°C of global warming which is highly likely over the course of this century under current policies (*UNEP, 2024*).

[1] *Article 2*

1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:

(a) Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change; [...]

2.1 Observational data

- **ERA5** - The European Centre for Medium-Range Weather Forecasts's 5th generation reanalysis product, ERA5, is a gridded dataset that combines historical observations into global estimates using advanced modelling and data assimilation systems (Hersbach et al., 2020). We use precipitation data from this product at a resolution of 0.25°×0.25°, from the years 1950 to present.
- **MSWEP** - The Multi-Source Weighted-Ensemble Precipitation v2.8 dataset (updated from Beck et al., 2019) is fully global, available at 3-hourly intervals and at 0.1° spatial resolution, available from 1979 to ~3 hours from real-time. This product combines gauge-, satellite-, and reanalysis-based data, including ERA5.
- **E-OBS** - This is a gridded land-only observation dataset of Europe, formed from the interpolation of station-derived meteorological observations (Cornes et al., 2018). We use version 31.0e of this dataset, at spatial resolution 0.1° × 0.1° gridded precipitation, from 1950-present.
- **Met Éireann** - The Irish national meteorological service, provides a gridded product at 1×1km resolution covering 1941 to the present, with provisional grids for 2025. Interpolation methods were used to calculate the precipitation grid point values with inputs from observations recorded at Met Éireann stations.

As a measure of anthropogenic climate change we use the (low-pass filtered) global mean surface temperature (GMST), where GMST is taken from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Science (GISS) surface temperature analysis (GISTEMP, Hansen et al., 2010 and Lenssen et al. 2019).

2.2 Model and experiment descriptions

- **Euro-CORDEX** - the Coordinated Regional Climate Downscaling Experiment (CORDEX)- European Domain with 0.11° resolution (EUR-11, Jacob et al., 2014; Vautard et al., 2021). The ensemble consists of 11 regional climate models each of which are driven by 8 GCMs. These simulations are composed of historical simulations from 1950 or 1970 up to 2005, and extended to the year 2100 using the RCP8.5 scenario.

2.3 Statistical methods

The methods for observational and model analysis, and for model evaluation and synthesis, follow the World Weather Attribution Protocol, described in Philip et al., (2020), with supporting details found in van Oldenborgh et al., (2021), Ciavarella et al., (2021) and WWA, 2021. The key steps, presented in sections 3-6, are: (3) trend estimation from observations; (4) model evaluation; (5) multi-method multi-model attribution; and (6) synthesis of the attribution statement. In addition, section (7) presents the societal impacts of the extreme weather event and section 8 gives a brief conclusion.

We calculate the return periods, Probability Ratio (PR; the factor-change in the event's probability) and change in intensity of the event under study to compare the climate of now and the climate of the past, defined respectively by the GMST values of now and of the pre-industrial past (1850-1900, based on the Global Warming Index).

To statistically model both rainfall events, we use a nonstationary GEV distribution. In both cases, the distribution is assumed to scale exponentially with the covariates, with the dispersion (the ratio between the standard deviation and the mean) remaining constant over time. The parameters of the statistical model are estimated using maximum likelihood. Next, results from observations and models that pass the validation tests are synthesised to produce a single attribution statement.

3 Observational analyses: return period and trend

In this section, trends in observational datasets (the gridded data products set out in section 2.1) are calculated and compared. We analyse the area average Rx2day and Rx30day for all four gridded datasets and calculate the return period, change in intensity and probability ratio (along with the 95% confidence interval) between the current climate of 2025 and a past climate, that is 1.3°C cooler, by fitting the data to a nonstationary GEV distribution.

3.1 Rx2day - Analysis of 2-day precipitation event

The time series for Rx2day are shown in figure 3.1 for the four gridded data products, with the fitted GMST-dependent trend overlaid. The four datasets exhibit slightly contrasting trends with either slight increases or no change in rainfall levels. In ERA5, the event has a return period of 4 years (bootstrapped 95% confidence interval (CI): 3, 10), in MSWEP, 3 years (95% CI: 1, 7), and Met Éireann 2 years (95% CI: 1.5, 3). We therefore use a return period of 3 years to represent this event in the full attribution analysis.

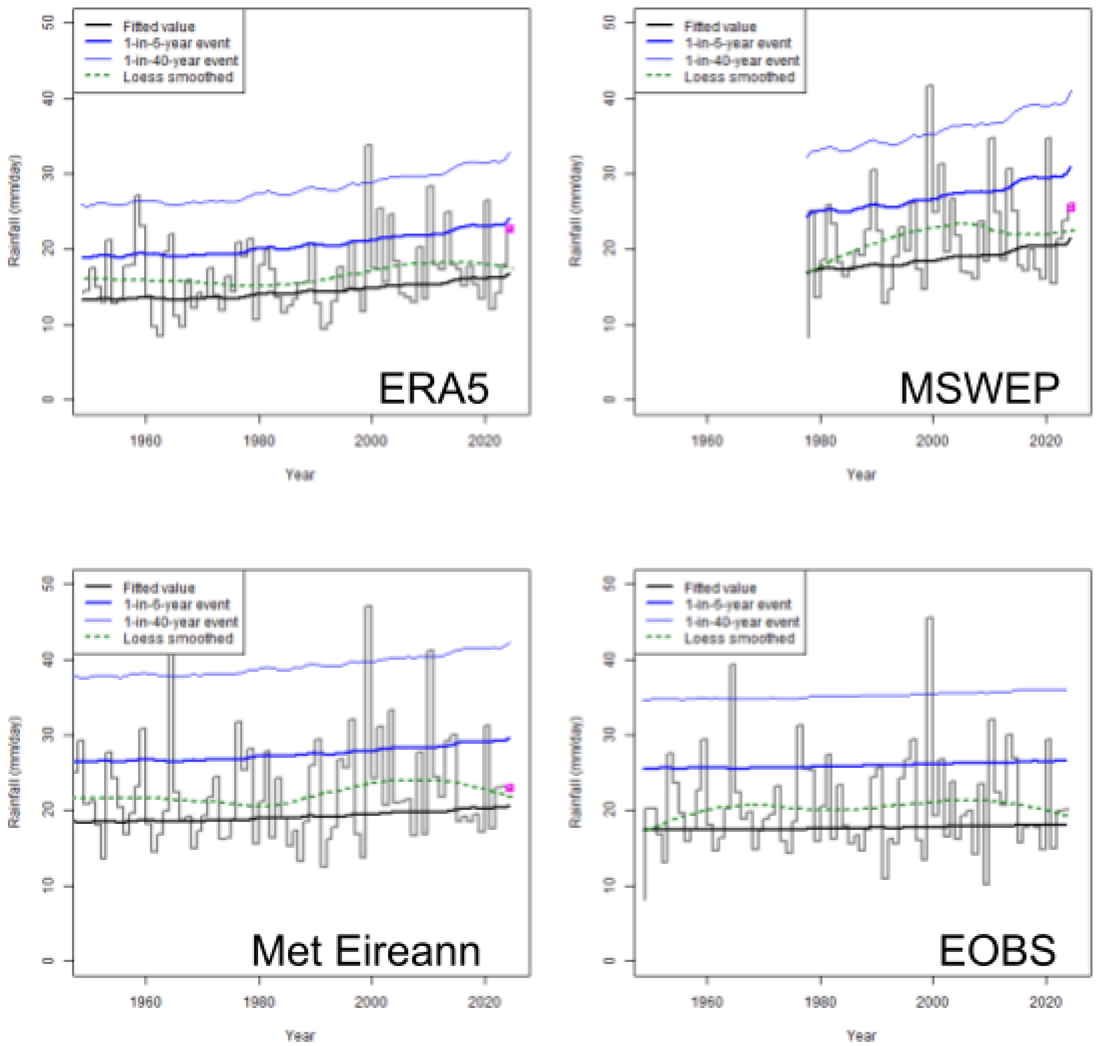


Figure 3.1: Time series of Rx2day over our smaller study region, with fitted model overlaid. The pink dot marks the 2025 event (not yet available in EOBS); the heavy black line indicates the mean of the fitted GEV model, and the blue lines indicate the expected return levels of 6- and 40-year events. The green line is a nonparametric Loess smoother.

The fitted linear trend is plotted against the GMST covariate, rather than time as above, in figure 3.2. In ERA5, the 2-day heavy rainfall event over Dublin, Wexford and Wicklow was found to have increased in magnitude by 29% (95% CI: 3%, 61%) with respect to the pre-industrial baseline. In MSWEP, by 34% (95% CI: -9%, 107%), in Met Éireann, by 13% (95% CI: -4%, 36%), and in EOBS, by 5% (95% CI: -19%, 34%).

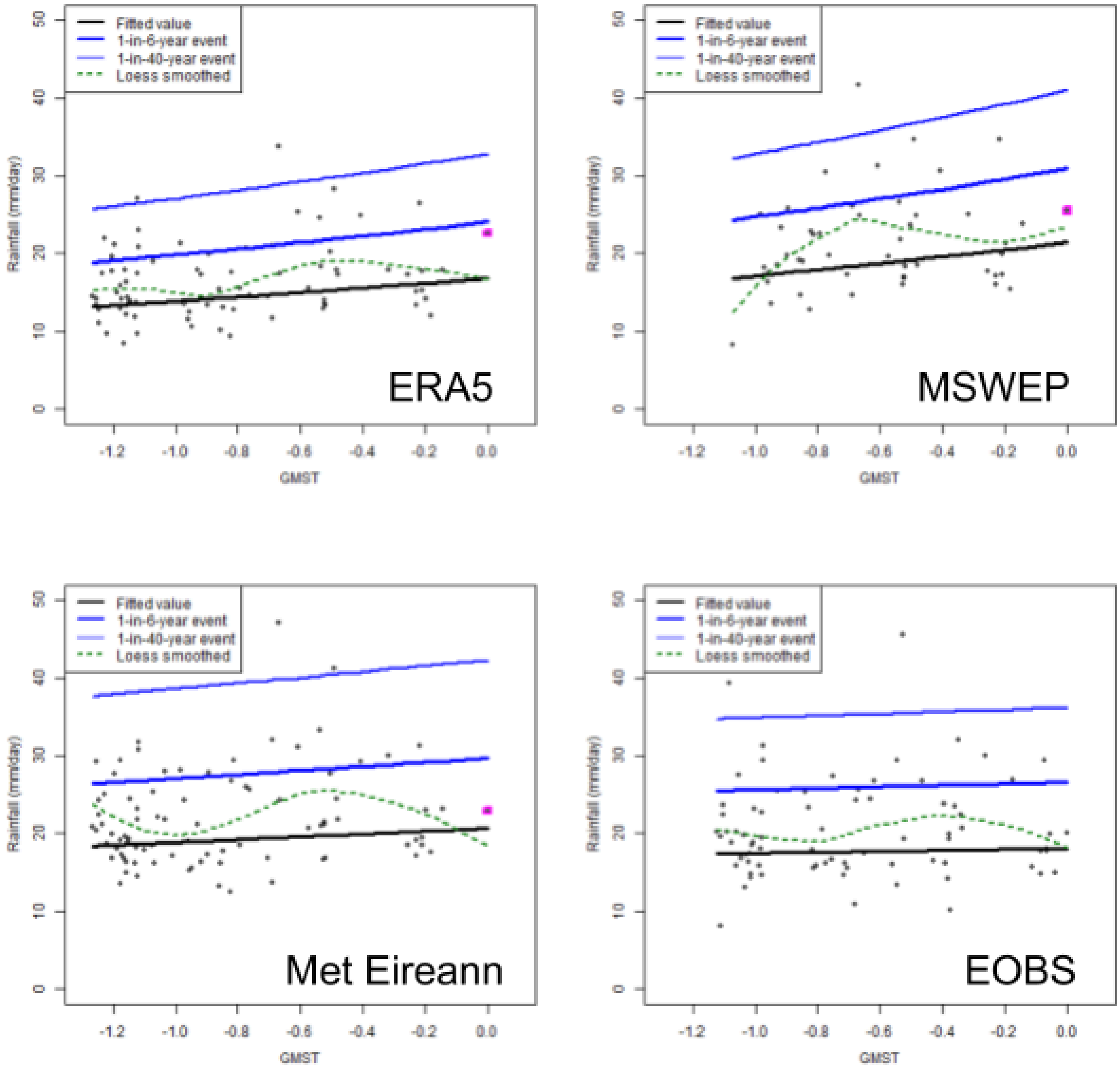


Figure 3.2: Linear trend in Rx2day over our smaller study region as a function of GMST (shown as a difference from the 2025 GMST) in three gridded observational data products. The pink dot marks the 2025 event (not yet available in EOBS); the thick black line denotes the nonstationary location of the fitted Gaussian distribution, and the blue lines show estimated 6- and 40-year return levels. The vertical lines represent a bootstrapped 95% confidence interval for the GEV parameter in the 2025 climate (GMST anomaly = 0) and a hypothetical 1.3ºC cooler climate.

The modelled change in return levels associated with a 1.3°C increase in GMST from the pre-industrial to the current climate are shown in figure 3.3. For all data sets there is some separation between the return levels in the current climate (red) and the past climate (blue). The best estimate of the probability ratio - that is, the factor change in the probability of such an event occurring - is 4 for ERA5, 4 for MSWEP, 1.5 for Met Éireann, and 1.2 for EOBS. These results, along with the estimated return periods and changes in intensity for all datasets, are summarised in Table 3.1.

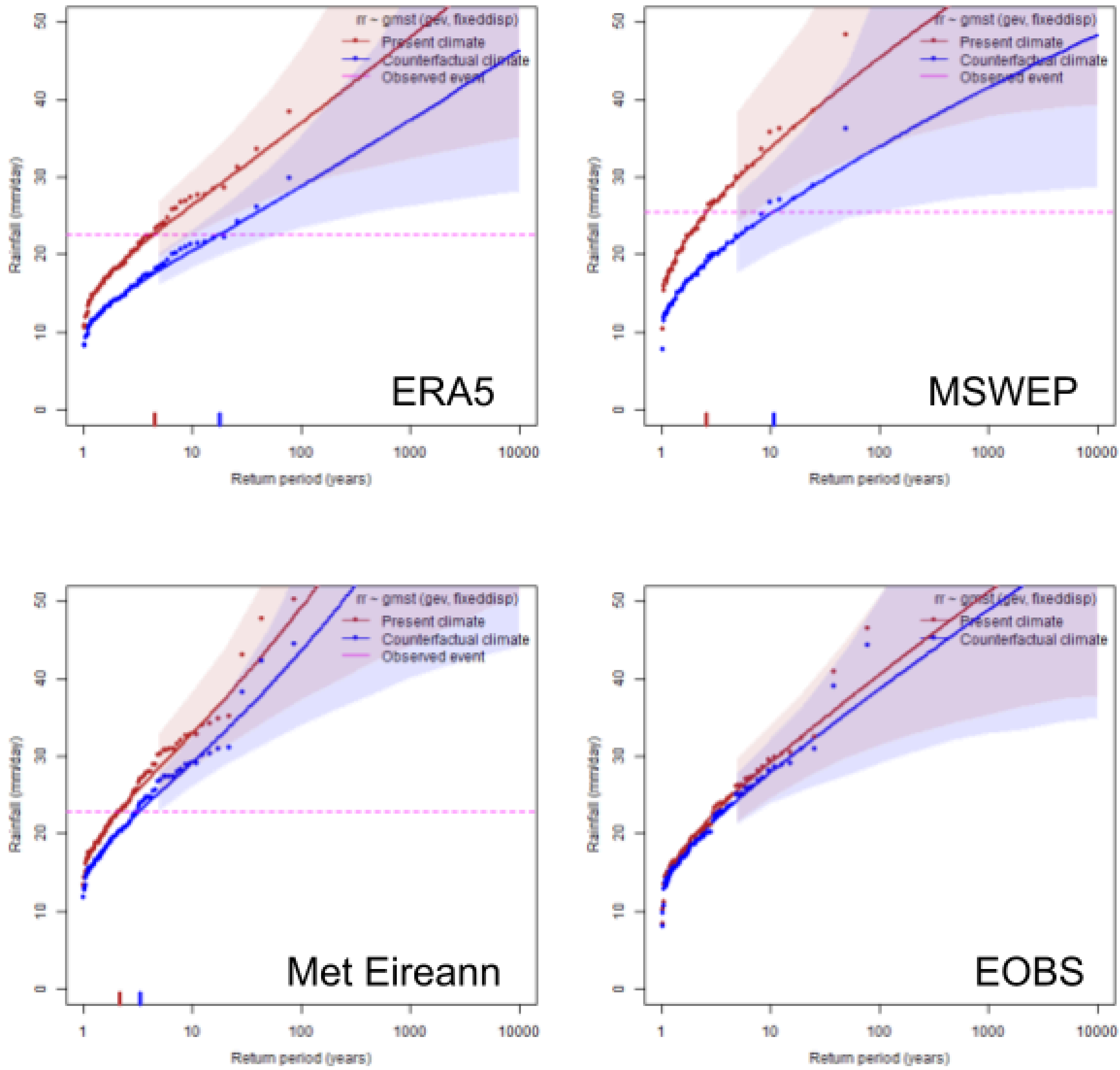


Figure 3.3: Expected return levels of Rx2day over Ireland in the 2025 climate (red lines) and in a 1.3°C cooler counterfactual climate (blue line), estimated from the statistical model described in section 2.3. Shaded regions represent 95% confidence intervals obtained via a bootstrapping procedure. The pink line shows the magnitude of the 2025 event analysed here (not yet available in EOBS). Red and blue ticks at the x axis indicate the estimated return level of the event in the 2025 climate and counterfactual climate.

Rx2day	Observed (mm)	Return period (years)	Change in magnitude (%)	Probability ratio
ERA5	22.6	4.4 (2.5 to 10.3)	**28.5 (2.8 to 60.8)**	**4.0 (1.2 to 16.3)**
MSWEP	25.5	2.6 (1.4 to 6.9)	33.7 (-9.0 to 107)	4.1 (0.6 to 56.8)
Met Éireann	22.9	2.1 (1.5 to 3.3)	12.8 (-4.2 to 35.8)	1.5 (0.8 to 2.9)
EOBS	22.6	3	4.8 (-19.1 to 34.0)	1.2 (0.4 to 3.5)

*Table 3.1: Summary of fitted model results for Rx2day: event magnitude; return period of 2025 Rx2day in the 2025 climate; change in Rx2day and percentage change in magnitude (probability ratio) associated with 1.3°C of global warming. Figures in parenthesis indicate 95% confidence interval obtained via bootstrapping. Statistically significant changes are highlighted in **bold**.*

3.2 Rx30day - Analysis of preceding precipitation

The time series for Rx30day are shown in figure 3.4 for the four gridded data products, with the fitted GMST-dependent trend overlaid. The four datasets exhibit reasonable agreement with an increase in rainfall levels over time, although this is less clear in EOBS. In ERA5, the event has a return period of 4 years (bootstrapped 95% confidence interval (CI): 2, 9), in MSWEP, 2 years (95% CI: 1, 9), and Met Éireann 3 years (95% CI: 2, 11). We therefore use a return period of 3 years to represent this event in the full attribution analysis.

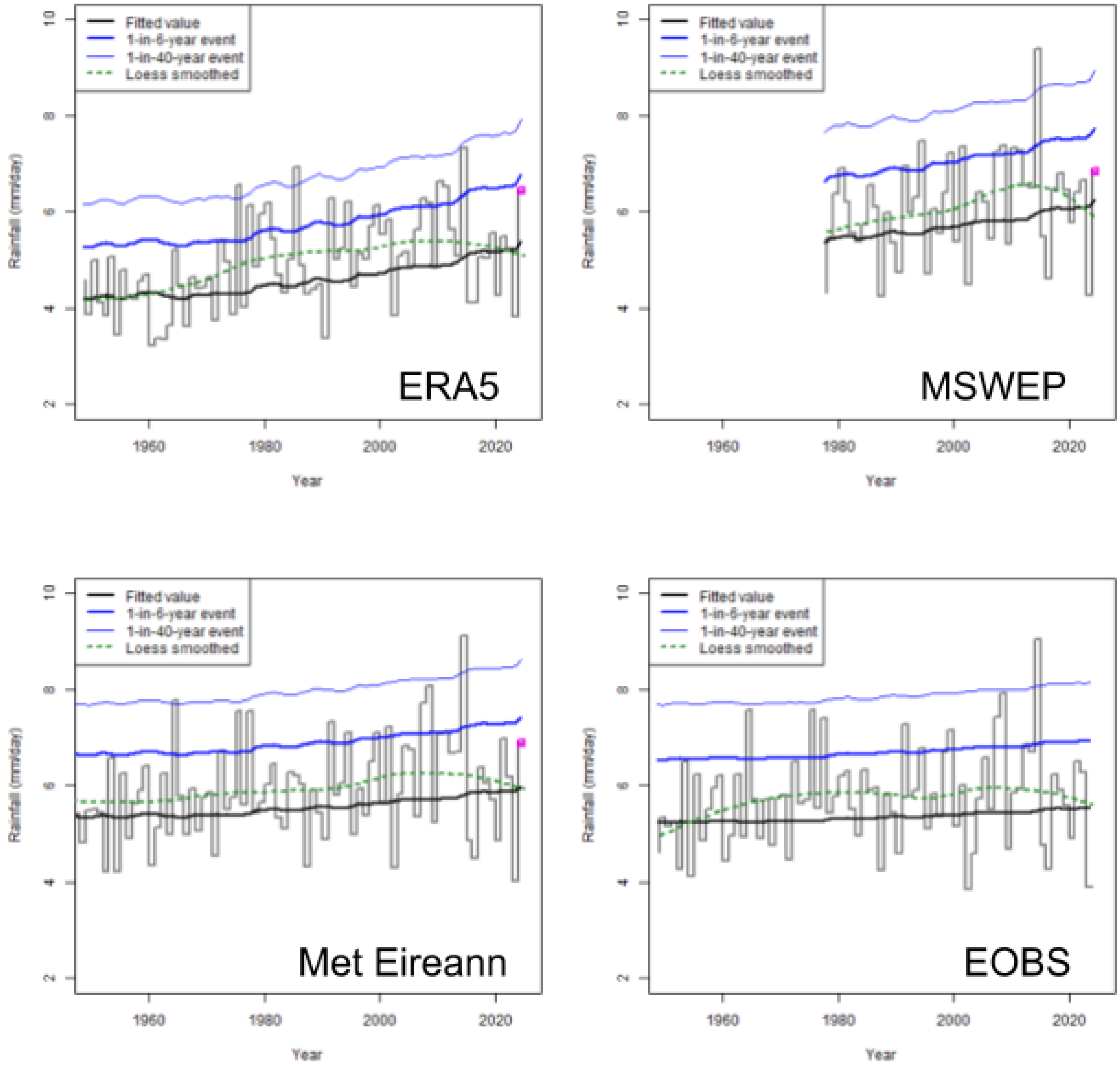


Figure 3.4: Time series of Rx30day over our larger study region, with fitted model overlaid. The pink dot marks the 2025 event (not yet available in EOBS); the heavy black line indicates the mean of the fitted GEV model, and the blue lines indicate the expected return levels of 6- and 40-year events. The green line is a nonparametric Loess smoother.

The fitted linear trend is plotted against the GMST covariate, rather than time as above, in figure 3.5. In ERA5, the 30-day heavy rainfall event over Dublin, Wexford and Wicklow was found to have increased in magnitude by 30% (95% CI: 13%, 52%) with respect to the pre-industrial baseline. In MSWEP, by 21% (95% CI: -9%, 62%), in Met Éireann, by 13% (95% CI: -6%, 33%), and in EOBS, by 7% (95% CI: -12%, 30%).

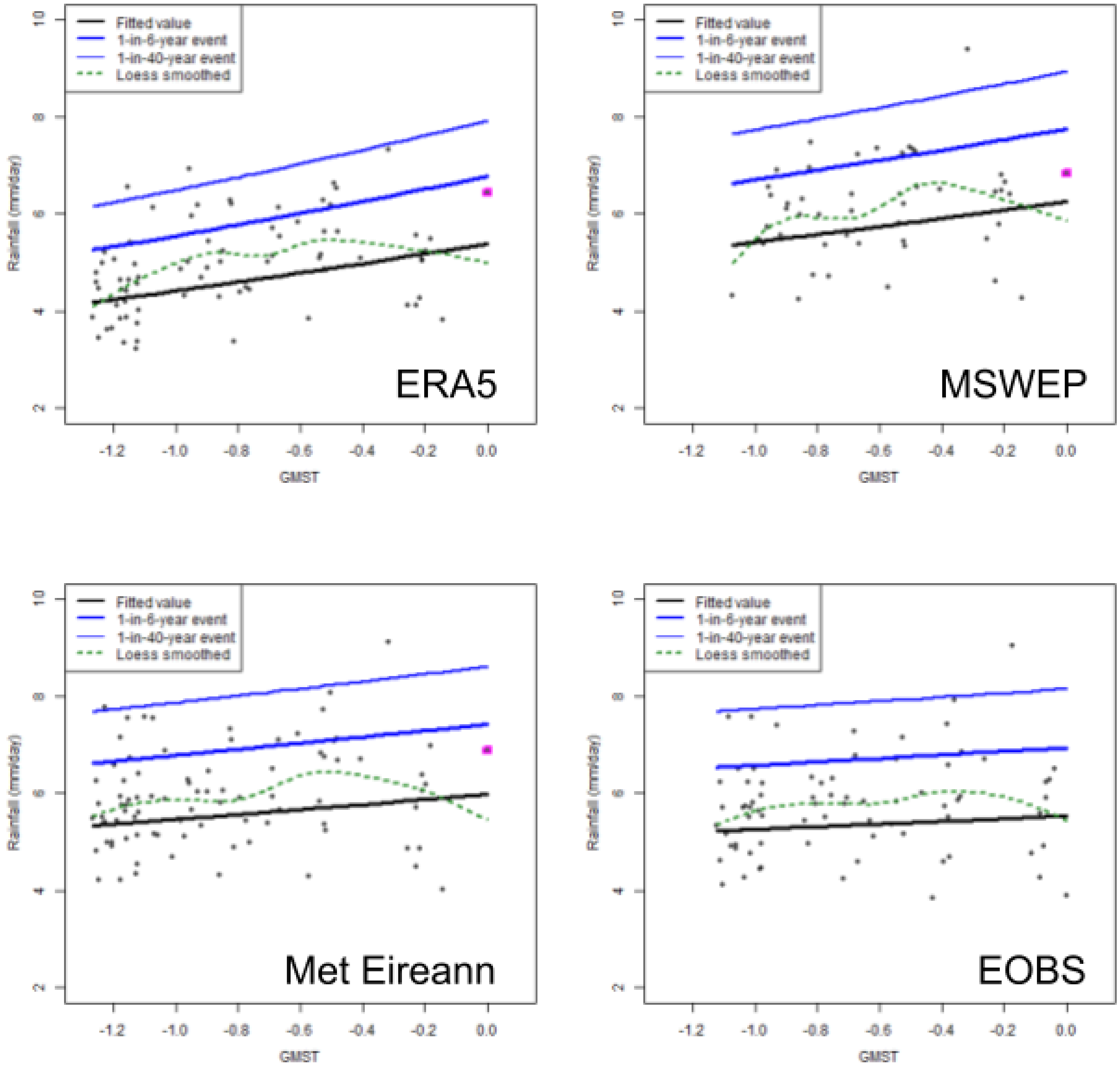


Figure 3.5: Linear trend in Rx30day over our larger study region as a function of GMST (shown as a difference from the 2025 GMST) in three gridded observational data products. The pink dot marks the 2025 event (not yet available in EOBS); the thick black line denotes the nonstationary location of the fitted Gaussian distribution, and the blue lines show estimated 6- and 40-year return levels. The vertical lines represent a bootstrapped 95% confidence interval for the GEV parameter in the 2025 climate (GMST anomaly = 0) and a hypothetical 1.3ºC cooler climate.

The modelled change in return levels associated with a 1.3°C increase in GMST from the pre-industrial to the current climate are shown in figure 3.6. For all data sets there is a separation between the return levels in the current climate (red) and the past climate (blue). The best estimate of the probability ratio - that is, the factor change in the probability of such an event occurring - is 27 for ERA5, 5 for MSWEP, 3 for Met Éireann, and 1.5 for EOBS. These results, along with the estimated return periods and changes in intensity for all datasets, are summarised in Table 3.2.

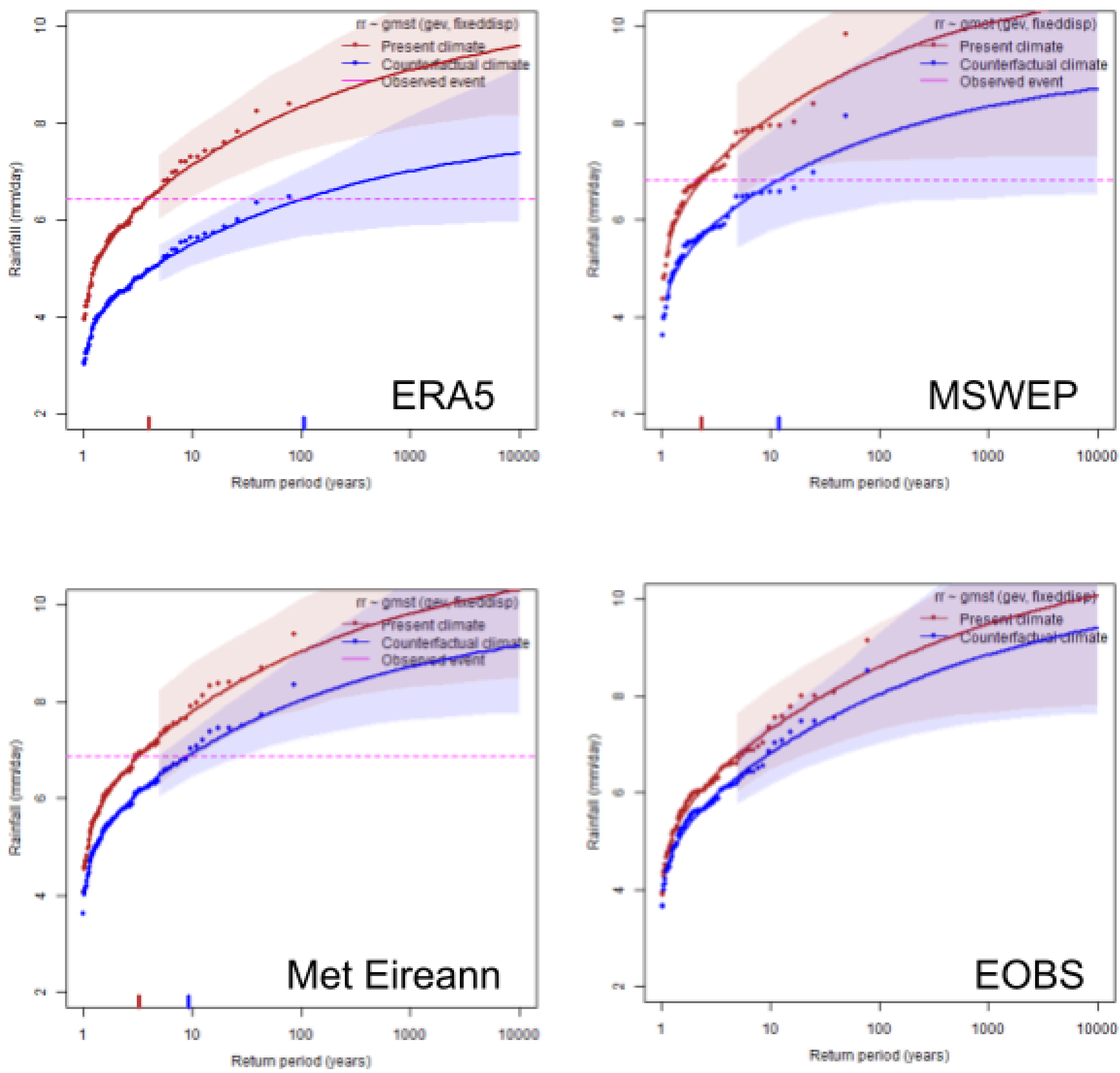


Figure 3.6: Expected return levels of Rx30day over Ireland in the 2025 climate (red lines) and in a 1.3°C cooler counterfactual climate (blue line), estimated from the statistical model described in section 2.3. Shaded regions represent 95% confidence intervals obtained via a bootstrapping procedure. The pink line shows the magnitude of the 2025 event analysed here (not yet available in EOBS). Red and blue ticks at the x axis indicate the estimated return level of the event in the 2025 climate and counterfactual climate.

Rx30day	Observed (mm)	Return period (years)	Change in magnitude (%)	Probability ratio
ERA5	6.44	3.9 (2.1 to 9.4)	**29.8 (12.9 to 51.8)**	**26.9 (4.4 to Infinity)**
MSWEP	6.8	2.3 (1.3 to 8.5)	20.6 (-8.8 to 62.2)	5.1 (0.4 to Infinity)
Met Éireann	6.9	3.2 (1.7 to 11.1)	12.6 (-5.8 to 32.6)	2.9 (0.6 to 13.3)
EOBS	6.3	3	7.1 (-11.6 to 29.9)	1.6 (0.4 to 7.7)

*Table 3.2: Summary of fitted model results for Rx30day: event magnitude; return period of 2025 Rx30day in the 2025 climate; change in Rx30day and percentage change in magnitude (probability ratio) associated with 1.3°C of global warming. Figures in parenthesis indicate 95% confidence interval obtained via bootstrapping. Statistically significant changes are highlighted in **bold**.*

3.3 Analysis of contributing factors to flooding

As a result of relatively persistent rainfall from mid October, and short periods of heavy rainfall in the lead up to the 2-day extreme (Figure 3.7), soils were already heavily saturated by the 14th and 15th of November. Poorly drained soil readings from the synoptic stations within the worst affected counties were at or close to maximum saturation (maximum saturation defined as -10mm) by the time of the 2-day extreme rainfall event (Figure 3.8).

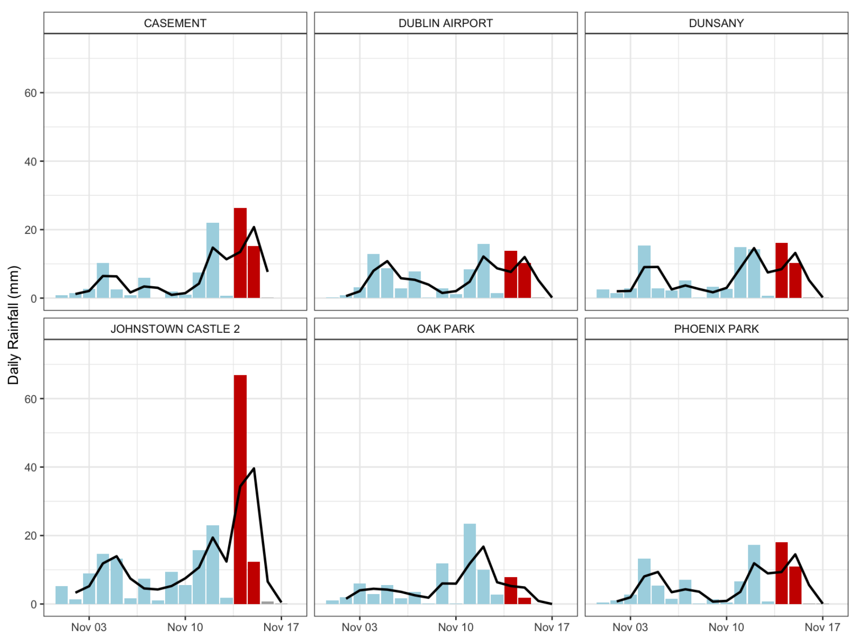


Figure 3.7: Daily rainfall totals for synoptic stations located within heavily affected counties from 1st - 17th November. Blue bars represent rainfall prior to the 2-day extreme, Red bars represent the 2-day extreme (14th-15th) and grey bars represent rainfall after the event. The black line represents the 2-day rolling average.

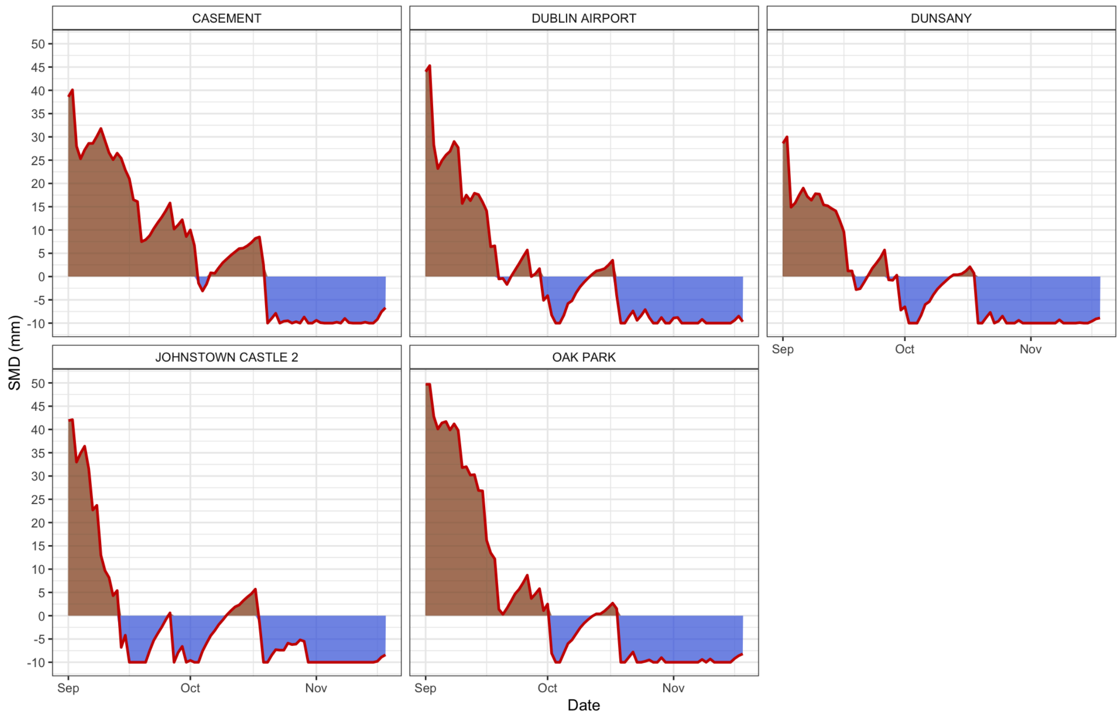


Figure 3.8: Daily soil moisture deficit levels (poorly drained soils) for synoptic stations located within heavily affected counties from 1st September through till 18th November. Brown areas represent the periods when soil moisture was at or above field capacity (>=0mm). Blue areas represent the periods when soils became saturated (<0mm).

Furthermore, the river levels had responded to the recent rainfall and were already out of bank or approaching out of bank for large parts of the country, see figure 3.9 River Level Status on the 14th of November 2025. As a result, when the 2-day rainfall event occurred, soils were unable to absorb or store much, if any, of the water. Much of this excess water would have taken the form of surface runoff, rapidly entering water bodies, raising the already high levels in the rivers. This undoubtedly contributed to the flooding experienced.

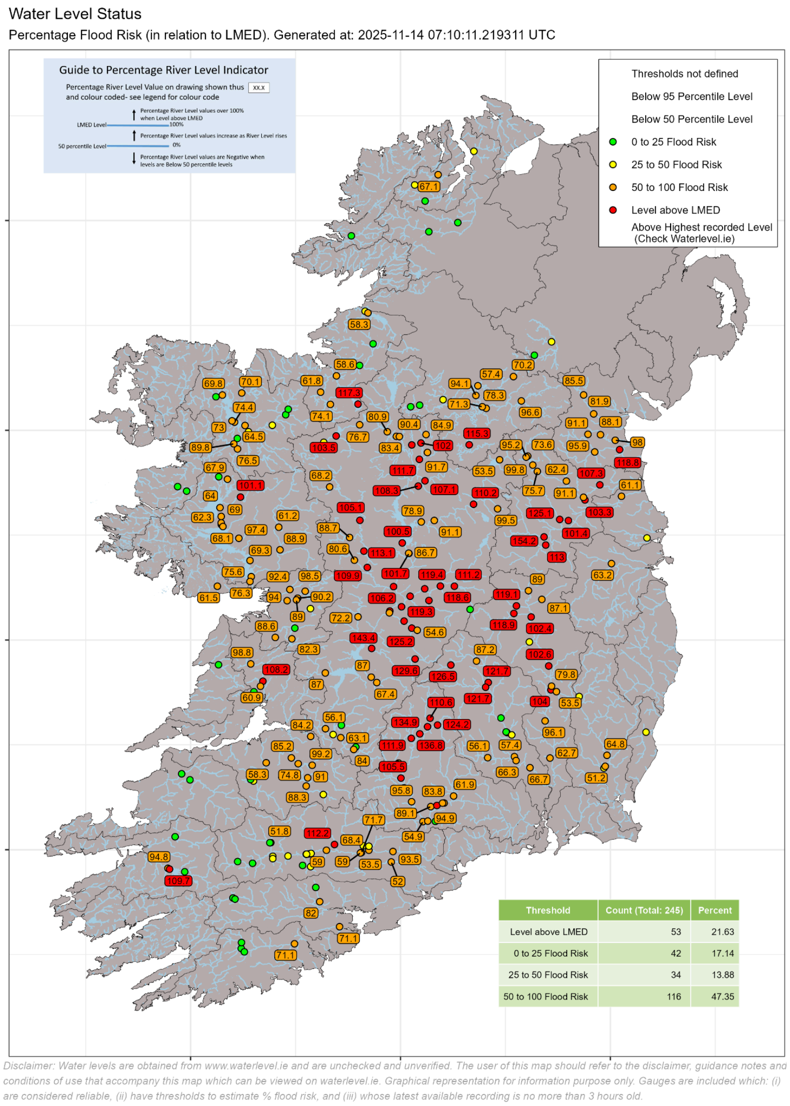


Figure 3.9: River Level Status on the 14th of November 2025.

From a hydrological perspective, Storm Claudia was also noteworthy in parts of the midlands, east and southeast. The riverwater levels by lunchtime on the 16th of November showed the response to the rainfall in the southeast and east of the county, see figure 3.10. The rainfall earlier in the week had the river levels high and the key catchments impacted were the Nore, Suir, Barrow, Slaney, Owenavorragh and Avoca. At the time of the Rx2day event, the antecedent rainfall was still travelling down the catchments. In some cases, it takes the river rise due to rainfall in the upper section of the rivers 3 to 4 days to get to the sea.

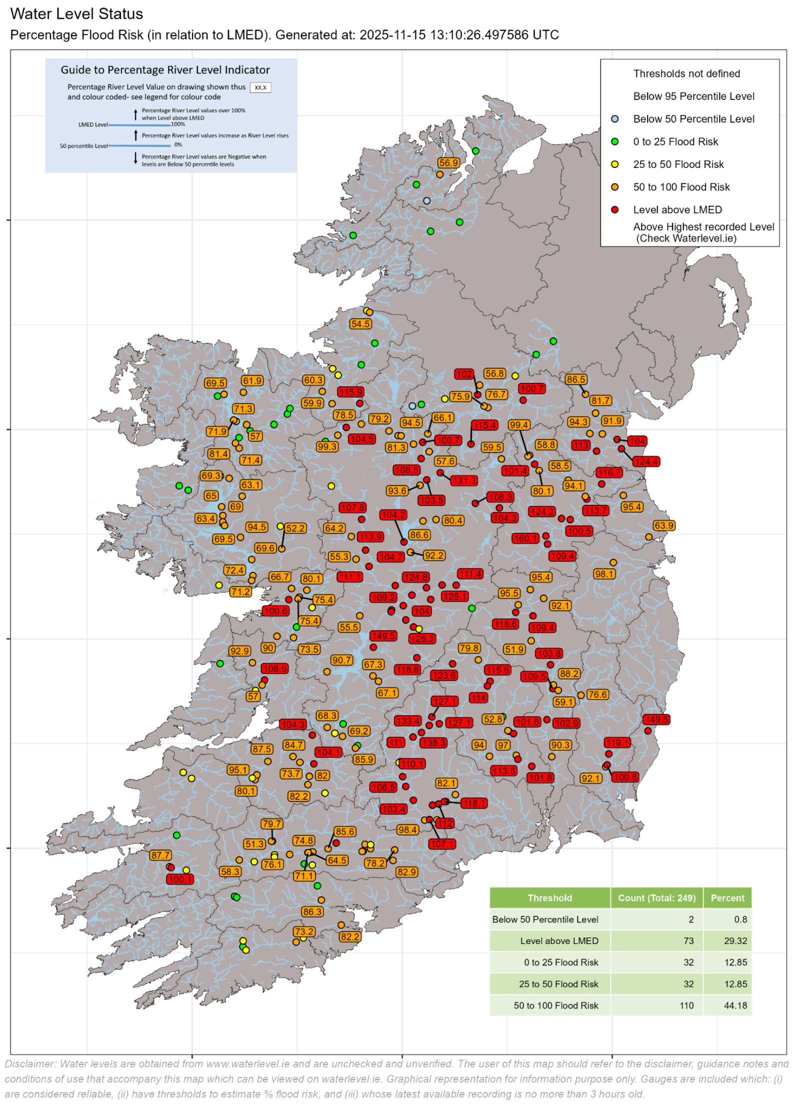


Figure 3.10 Water Level Status at 13:00 on the 16th of November.

It is worth noting that the flooding experienced in the near-coast river stretches could have been substantially worse if this extreme rainfall event occurred at the same time as a Spring High Tide. Spring tides occur when the Earth, Sun and Moon are all aligned (Full Moon & New Moon), causing a “bulge” or rise in the oceans and high tides. The opposite of this is referred to as a neap tide, which occurs when the Sun and Moon are at right angles to each other (First & Third Quarters). A neap tide lowers the effect of a high tide and reduces the risk of flooding. During the Rx2day event, the lunar phase was transiting from a Third Quarter (12th) to a New Moon (20th), meaning high tides had only begun to rise from their minimum neap tide extent. These lower end tidal conditions acted to “pull” water out of the rivers, effectively reducing flooding. Had it been a New Moon or Full Moon, the spring high tide would have acted to block or “push” water back inland increasing the extent of flooding. In particular, towns like Enniscorthy in Co. Wexford are the main beneficiaries of escaping high spring tides during the period of this high rainfall event.

Ireland has been "increasingly lucky" with the timing of past extreme storm and precipitation events in the fact they have not occurred during a spring high tide. However, it is only a matter of time before this does happen, potentially resulting in far worse impacts.

3.4 Flooding attribution - case study

The compound effect of the heavy rainfall falling at the same time as the antecedent rainfall flowed downstream was clearly observed in Wexford. Bridgetown and Ballycanew in Co. Wexford experienced flooding from their local rivers. At Goff's Bridge near Bridgetown, the flood event was the highest peak flow in a dataset extending to the late 1970s (though with significant missing data). At Ballycanew, hydrometric records for the Owenavorragh are short (~10 years), with the flood associated with Storm Claudia being the highest recorded at that gauge to date. Figure 3.11 shows the evolution of the flood peak over the past 3-months and within the context of the full record using stage (height above sea level) data from the EPA Hydrodata website.

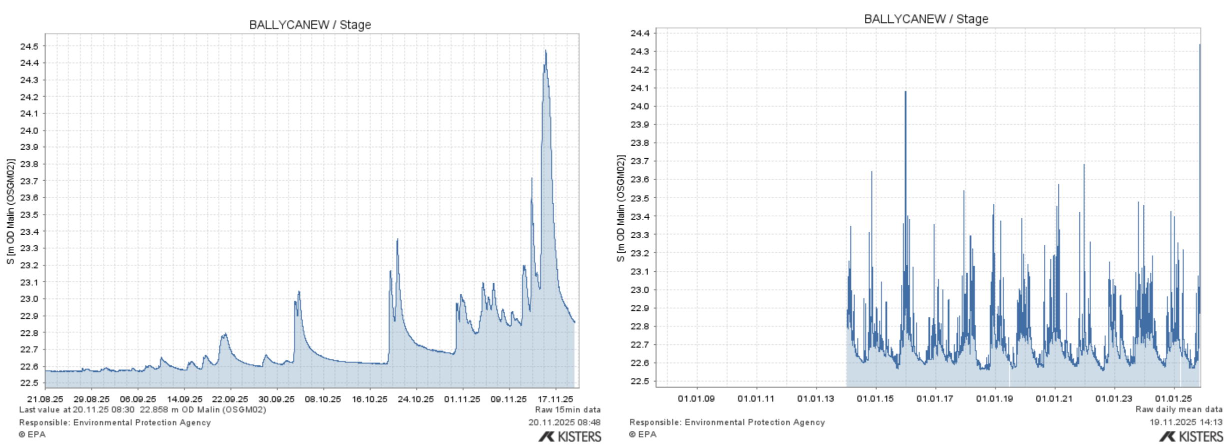


Figure 3.11 River Stage for the Owenavorragh River at Ballycanew for the 3 months previous to the flood event associated with Storm Claudia (left), and the context of the flood in terms of the full record at Ballycanew (right). Source: https://epawebapp.epa.ie/hydronet/#11004

Further downstream on the Owenavorragh (the gauge at Bolaney), the longer term and more complete record spans 54 years (1972-2025), thus allowing a more robust assessment of the extreme nature of the flood event. Annual Maximum data were downloaded from waterlevel.ie for the gauge. The flood associated with Storm Claudia is the second highest flood peak in the record (approximating 77 cubic meters per second (cumecs)). The flood event associated with 'Hurricane Charlie' in 1986 (Hydrological Year 1985) is by far the largest flood in the record (120.7 cumecs).

Using the Storm Claudia event as the assumed annual maximum for the hydrological year 2025, extreme flows were modelled using a stationary Gumbel distribution to estimate a return period for the event. Preliminary investigation using the Generalised Extreme Value (GEV) distribution gave a shape parameter very close to zero, indicating Gumbel type behaviour. Parameters of the Gumbel distribution were estimated by maximum likelihood using the gum.fit function in the *ismev* package in R (Location = 43.239 cumecs; Scale = 11.034 cumecs), while uncertainty in the return level estimates were quantified using a non-parametric bootstrap (2000 resamples). For comparison, the empirical plotting positions were also computed using the Weibull formula.

For the Owenavorragh at Bolaney, under the fitted Gumbel distribution this corresponds with an exceedance probability of approximately 0.046 and a return period of about 22 years, with 95 percent confidence intervals spanning roughly 11 to 56 years. The corresponding return period using the GEV distribution was 21.4 years, see figure 3.12. The estimated return period using the Weibull formula (i.e. using just the empirical or recorded data with no distribution fitting) is 27.5 years. These results indicate that while the flood event associated with Storm Claudia was a moderately rare extreme event, and although causing significant flood impacts for communities, it was not an exceptionally rare flood event.

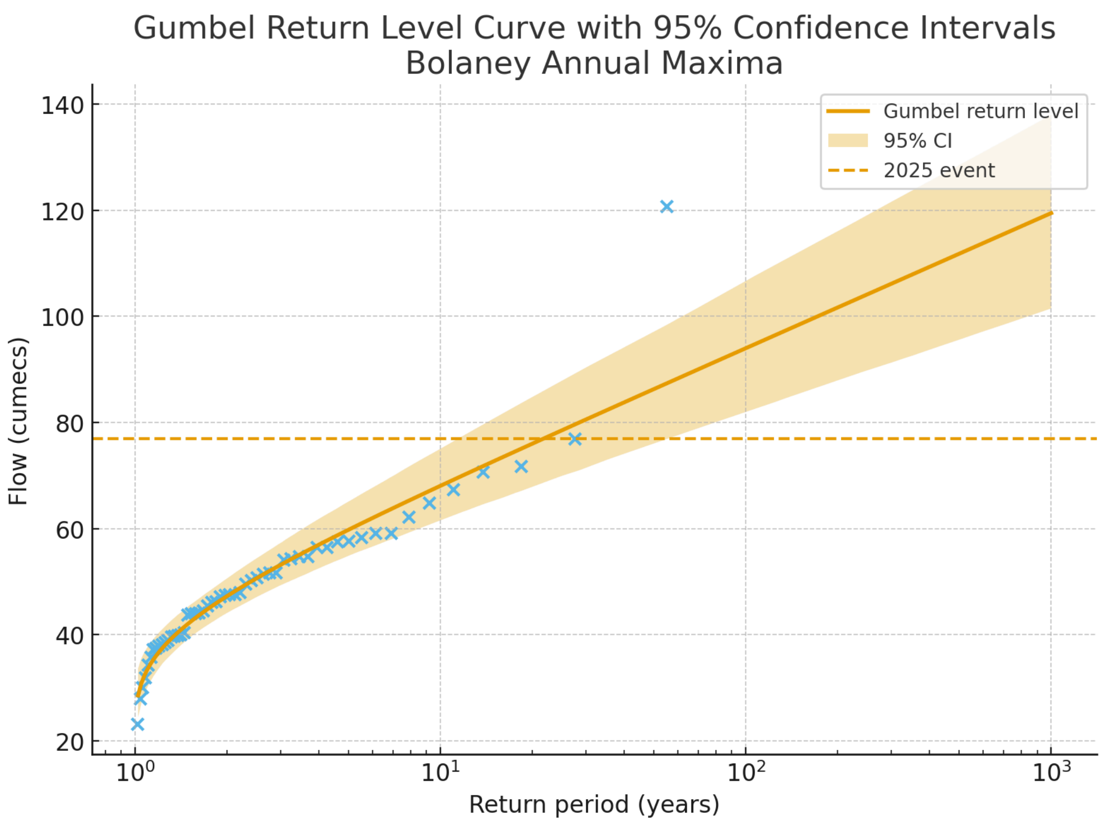


Figure 3.12 Return level plot fitted to the annual maximum series for the Owenavorragh at Bolaney (1972-2025). The blue crosses represent past annual maxima, with the dashed horizontal line indicating the November 2025 flood associated with Storm Claudia. Note that for this analysis this flood is assumed as the peak for Hydrological year 2025 (which has only recently commenced and is not guaranteed). Evident from the plot is the extreme nature of the floods associated with Hurricane Charlie in August 1986 (Hydrological year 2025).

The flood event associated with Storm Claudia was also noteworthy in rivers draining the Wicklow mountains. For instance, for the Avonmore river and the Dodder at Glenasmole it was the second highest flood peak in records extending over the last ~20 years. This reaffirms the standing of the flood event as moderately rare, rather than exceptional.

4 Model evaluation

In the subsections below we show the results of the model evaluation. The climate models are evaluated against the observations in their ability to capture:

1. Seasonal cycles: For this, we qualitatively compare the seasonal cycles in model outputs against observations-based cycles. We discard the models that exhibit ill-defined peaks in their seasonal cycles.
2. Spatial patterns: Models that do not match the observations in terms of the large-scale temperature patterns are excluded.
3. Parameters of the fitted statistical models: The statistical fit parameters must lie within the equivalent observational parameter uncertainty range (good), or their uncertainty ranges must overlap (reasonable).

The models are labelled as 'good', 'reasonable', or 'bad' based on their performances in terms of the three criteria discussed above. A model is given an overall rating of 'good' if it is rated 'good' for all characteristics. If there is at least one 'reasonable' the overall rating is 'reasonable', and if there is at least one 'bad' the overall rating is 'bad'. Only models that are labelled as 'good' overall are used in the final analysis.

Tables showing how the respective models chosen are shown in Tables A.1 and A.2 in the appendix. Visuals for choosing the seasonal cycles and spatial patterns are shown in Figures A.1 - A.4 respectively.

5 Multi-method multi-model attribution

Before any synthesis of the models can be carried out, the models that passed the evaluation in section 4 must be gathered and their results combined for the synthesis outlined in section 6. Tables 5.1 and 5.2 below show the probability ratios and changes in intensity ΔI for models that passed model evaluation, alongside those from observational data products. This is calculated for both past to present and present to future (1.5°C, 2°C, and 3°C of global warming).

		Preindustrial - Present (1.3 ˚C)		Present - Future (1.5 ˚C)		Present - Future (2.0 ˚C)		Present - Future (3.0 ˚C)	
Model / Observations	**Threshold for return period**	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**
eobs	22.64	1.2 (0.39...3.48)	4.75 (-19.09...34.05)						
era5	22.61	3.96 (1.19...16.	28.49 (2.79...60.						

		34)	8)						
me	22.94	1.55 (0.85…2.89)	12.82 (-4.23…34.76)						
MSWEP	25.54	4.09 (0.62…56.82)	33.71 (-8.97…107.46)						
CNRM-CM5_r1_ALARO-0	26.49	0.99 (0.35…4.64)	-0.07 (-12.28…8.8)	1.17 (1.05…1.3)	1.76 (0.53…2.63)	1.67 (1.17…2.26)	6.03 (1.83…8.89)	3.04 (1.44…4.94)	14.03 (4.37…20.25)
CNRM-CM5_r1_HIRHAM5	32.26	0.83 (0.49…1.16)	-3.08 (-13.55…2.54)	1.1 (1.06…1.11)	1.4 (0.95…1.67)	1.37 (1.22…1.44)	4.82 (3.29…5.72)	2.08 (1.59…2.29)	11.31 (7.81…13.34)
CNRM-CM5_r1_RACMO22E	25.08	0.5 (0.36…1.63)	-7.1 (-10.41…4.24)	1.05 (1.03…1.14)	0.45 (0.37…0.98)	1.19 (1.12…1.52)	1.57 (1.3…3.38)	1.49 (1.32…2.45)	3.77 (3.13…8.02)
EC-EARTH_r1_COSMO-crCLIM-v1-1	31.42	4.45 (2.34…11.11)	20.16 (12.75…34.73)	1.13 (1.11…1.16)	1.42 (1.17…1.71)	1.49 (1.41…1.62)	4.87 (4.02…5.86)	2.41 (2.16…2.85)	11.42 (9.49…13.65)
EC-EARTH_r1_RACMO22E	27.12	2.06 (0.86…2.88)	7.92 (-1.62…12.06)	1.13 (1.12…1.19)	1.91 (1.85…2.53)	1.53 (1.46…1.79)	6.52 (6.33…8.58)	2.61 (2.39…3.56)	15.11 (14.68…19.58)
EC-EARTH_r12_COSMO-crCLIM-v1-1	30.82	1.85 (0.62…3.97)	11.26 (-8.62…23)	1.07 (1.05…1.09)	1.27 (0.88…1.9)	1.28 (1.19…1.36)	4.38 (3.03…6.49)	1.8 (1.52…2.05)	10.32 (7.2…15.03)
EC-EARTH_r12_RACMO22E	32.32	4.37 (3.43…43.58)	24.43 (23.11…51.09)	1.05 (1.04…1.09)	0.81 (0.68…1.91)	1.18 (1.16…1.35)	2.82 (2.35…6.53)	1.49 (1.41…2.06)	6.71 (5.6…15.12)
EC-EARTH_r12_WRF361H	38.22	5.12 (1.17…18.71)	32.34 (2.3…89.48)	1.05 (1.02…1.13)	0.92 (0.42…2.27)	1.19 (1.08…1.51)	3.17 (1.44…7.72)	1.51 (1.2…2.57)	7.54 (3.47…17.72)
EC-EARTH_r3_COSMO-crCLIM-v1-1	28.57	0.94 (0.6…1.75)	-1.08 (-10.05…7.97)	1.02 (0.98…1.08)	0.38 (-0.43…1.09)	1.08 (0.92…1.29)	1.32 (-1.5…3.75)	1.21 (0.81…1.79)	3.17 (-3.69…8.85)
EC-EARTH_r3_RACMO22E	29.24	1.23 (0.45…9.42)	2.98 (-10.92…19.45)	1.06 (1.02…1.15)	0.88 (0.42…2.04)	1.21 (1.08…1.58)	3.03 (1.47…6.97)	1.58 (1.2…2.75)	7.21 (3.52…16.07)
HadGEM2-ES_r1_COSMO-crCLIM-v1-1	26.8	0.77 (0.24…1.43)	-3.36 (-19.77…6.74)	1 (0.99…1.04)	0.02 (-0.26…0.45)	1 (0.95…1.13)	0.08 (-0.92…1.56)	1.01 (0.89…1.35)	0.2 (-2.26…3.74)
HadGEM2-ES_r1_RACMO22E	28.62	1.59 (0.76…1.98)	6.99 (-4.08…11.88)	1.03 (1.01…1.04)	0.47 (0.2…0.68)	1.1 (1.04…1.14)	1.63 (0.71…2.37)	1.27 (1.1…1.36)	3.9 (1.71…5.65)
HadGEM2-ES_r1_WRF361H	35.95	3.27 (1.3…5.54)	19.02 (5.93…25.49)	0.98 (0.95…1)	-0.31 (-0.98…0.02)	0.92 (0.82…1)	-1.09 (-3.47…0.06)	0.82 (0.61…1.01)	-2.68 (-8.66…0.16)
IPSL-CM5A-MR_r1_WRF381P	23.93	0.29 (0.24…0.48)	-20.84 (-25.71…-11.65)	1 (0.98…1.01)	-0.02 (-0.32…0.19)	1 (0.94…1.04)	-0.07 (-1.11…0.65)	0.99 (0.87…1.1)	-0.18 (-2.72…1.58)
MIROC5_r1_WRF361H	37.62	9.04 (3.78…157.59)	29.95 (27.98…48.87)	1.14 (1.09…1.19)	1.95 (1.28…2.06)	1.57 (1.35…1.77)	6.64 (4.39…7.02)	2.78 (2.01…3.46)	15.38 (10.33…16.19)

MPI-ESM-LR_r1_CCLM4-8-17	30.97	2.79 (2.27…9.06)	14.46 (8.61…22.46)	1.07 (1.01…1.09)	1.02 (0.16…1.28)	1.27 (1.04…1.33)	3.52 (0.56…4.41)	1.75 (1.1…1.96)	8.34 (1.35…10.38)
MPI-ESM-LR_r1_COSMO-crCLIM-v1-1	33.41	1.66 (1.52…10.22)	8.59 (6.35…31.33)	1.08 (1.08…1.13)	1.3 (1.11…1.77)	1.32 (1.29…1.53)	4.47 (3.85…6.07)	1.92 (1.81…2.59)	10.51 (9.09…14.1)
MPI-ESM-LR_r2_COSMO-crCLIM-v1-1	37.98	3.49 (2.97…136.9)	25.54 (22.04…38.79)	1.05 (1.01…1.08)	1.06 (0.24…1.52)	1.2 (1.05…1.31)	3.65 (0.84…5.22)	1.55 (1.13…1.91)	8.63 (2.03…12.21)
MPI-ESM-LR_r3_COSMO-crCLIM-v1-1	32.31	8381.13 (1.4…39.07)	24.92 (-3.33…19.52)	1.14 (1.07…1.22)	1.82 (1.01…2.41)	1.56 (1.26…1.9)	6.24 (3.47…8.19)	2.69 (1.7…3.82)	14.48 (8.22…18.74)
NorESM1-M_r1_COSMO-crCLIM-v1-1	29.78	0.63 (0.51…1.3)	-9.99 (-15.38…7.2)	1.03 (1…1.09)	0.54 (-0.04…1.48)	1.1 (0.99…1.33)	1.89 (-0.12…5.07)	1.25 (0.99…1.93)	4.53 (-0.3…11.86)
NorESM1-M_r1_WRF381P	26.25	1.49 (0.36…12.64)	5.59 (-13.3…27.69)	1.09 (1.04…1.11)	1.6 (0.83…1.9)	1.36 (1.16…1.42)	5.49 (2.88…6.5)	2.04 (1.44…2.28)	12.81 (6.85…15.06)

Table 5.1: Event magnitude, probability ratio and change in intensity for 3-year return period for Rx2day for observational datasets and each model that passed the evaluation tests. (a) from pre-industrial climate to the present, (b) from the present to 1.5°C above pre-industrial climate (c) from the present to 2.0°C above pre-industrial climate, and (d) from the present to 3.0°C above pre-industrial climate.

		Preindustrial - Present (1.3 ˚C)		**Present - Future (1.5 ˚C)**		**Present - Future (2.0 ˚C)**		**Present - Future (3.0 ˚C)**	
Model / Observations	**Threshold for return period 50 yr**	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**
eobs	6.33	1.64 (0.41…7.75)	7.09 (-11.63…29.86)						
era5	6.44	26.9 (4.38…Inf)	29.79 (12.85…51.82)						
me	6.89	2.86 (0.59…13.26)	12.57 (-5.8…32.6)						
MSWEP	6.84	5.09 (0.4…Inf)	20.64 (-8.77…62.18)						
CNRM-CM5_r1_ALARO-0	7.21	1.89 (1.34…3.9)	4.97 (2.18…9.95)	1.18 (1.1…1.25)	1.35 (0.9…1.59)	1.75 (1.4…2.07)	4.65 (3.11…5.46)	3.42 (2.2…4.7)	10.93 (7.37…12.75)
CNRM-CM5_r1_CCLM4-8-17	7.03	11 (2.22…133.74)	14.71 (1.46…27.61)	1.06 (1.03…1.12)	0.53 (0.26…0.9)	1.23 (1.11…1.45)	1.86 (0.91…3.1)	1.63 (1.29…2.3)	4.46 (2.19…7.36)
EC-EARTH_r1_COSMO-crCLIM-v1-1	6.02	0.86 (0.71…3.9)	-0.86 (-1.93…6.46)	1.14 (1.13…1.18)	0.84 (0.88…1.04)	1.55 (1.53…1.7)	2.9 (3.05…3.61)	2.59 (2.59…3.07)	6.9 (7.25…8.54)

EC-EARTH_r1_RACMO22E	6.84	3.89 (1.56…4.89)	7.25 (2.91…9.62)	1.18 (1.15…1.24)	1.11 (1.22…1.53)	1.74 (1.62…2.01)	3.83 (4.22…5.26)	3.27 (3.04…4.27)	9.05 (9.95…12.29)
EC-EARTH_r12_COSMO-crCLIM-v1-1	6.79	3.51 (2.35…6.73)	11.21 (5.89…17.24)	1.06 (1.04…1.09)	0.57 (0.43…0.91)	1.24 (1.16…1.36)	2 (1.49…3.15)	1.66 (1.42…2.01)	4.78 (3.59…7.47)
EC-EARTH_r12_WRF361H	6.56	0.36 (0.21…0.48)	-6.74 (-11.96…-4.7)	0.95 (0.9…1.01)	-0.42 (-0.78…0.05)	0.85 (0.69…1.02)	-1.47 (-2.75…0.17)	0.66 (0.37…1.05)	-3.6 (-6.81…0.4)
EC-EARTH_r3_COSMO-crCLIM-v1-1	6.23	0.7 (0.33…1.34)	-3.45 (-10.04…2.61)	1.02 (1.01…1.08)	0.22 (0.05…0.57)	1.09 (1.02…1.29)	0.77 (0.18…1.98)	1.22 (1.04…1.8)	1.86 (0.44…4.75)
EC-EARTH_r3_RACMO22E	6.49	0.46 (0.37…0.82)	-5.8 (-7.01…-1.35)	1.06 (1.03…1.12)	0.43 (0.2…0.73)	1.22 (1.1…1.45)	1.49 (0.7…2.55)	1.6 (1.26…2.28)	3.58 (1.7…6.07)
HadGEM2-ES_r1_WRF361H	7.57	1.62 (0.75…3.06)	4.3 (-2.53…10.62)	1 (1…1.04)	0 (0.03…0.52)	1 (1.01…1.15)	0.01 (0.11…1.8)	1 (1.02…1.4)	0.03 (0.26…4.32)
IPSL-CM5A-MR_r1_RACMO22E	7.05	1.16 (0.88…4.21)	1.04 (-1.04…8.96)	1.05 (1.04…1.1)	0.35 (0.27…0.64)	1.19 (1.14…1.37)	1.2 (0.95…2.23)	1.49 (1.36…2.06)	2.9 (2.29…5.33)
MIROC5_r1_CCLM4-8-17	7.88	6.75 (7.85…157.32)	16.87 (14.14…24.6)	1.04 (0.98…1.09)	0.45 (-0.19…0.89)	1.16 (0.95…1.33)	1.57 (-0.66…3.07)	1.42 (0.87…1.94)	3.76 (-1.63…7.29)
MPI-ESM-LR_r2_COSMO-crCLIM-v1-1	7.18	3.3 (1.62…Inf)	5.92 (2.18…17.47)	1.08 (1.05…1.12)	0.7 (0.45…1.09)	1.31 (1.17…1.47)	2.43 (1.58…3.77)	1.86 (1.45…2.43)	5.81 (3.78…8.91)
MPI-ESM-LR_r3_COSMO-crCLIM-v1-1	7.09	3.25 (0.37…2.2)	6.44 (-6.67…4.1)	1.12 (1.06…1.16)	0.78 (0.35…0.93)	1.45 (1.22…1.61)	2.72 (1.21…3.2)	2.31 (1.58…2.81)	6.47 (2.92…7.6)

Table 5.2: Event magnitude, probability ratio and change in intensity for 3-year return period for Rx30day for observational datasets and each model that passed the evaluation tests. (a) from pre-industrial climate to the present, (b) from the present to 1.5°C above pre-industrial climate (c) from the present to 2.0°C above pre-industrial climate, and (d) from the present to 3.0°C above pre-industrial climate.

6 Hazard synthesis

For the event definitions described above we evaluate the influence of anthropogenic climate change on the events by calculating the probability ratio as well as the change in intensity using observations and climate models. Models which do not pass the evaluation described above are excluded from the analysis. The aim is to synthesise results from models that pass the evaluation, along with the observation-based products, to give an overarching attribution statement.

Figures 6.1 - 6.4 show the changes in probability and intensity for the observations (blue) and models (red). Before combining them into a synthesised assessment, first, a representation error is added (in quadrature) to the observations, to account for the difference between observations-based datasets that cannot be explained by natural variability. This is shown in these figures as white boxes around the light blue bars. The dark blue bar shows the average over the observation-based products. Next, a term to account for intermodel spread is added (in quadrature) to the natural variability of the models. This is shown in the figures as white boxes around the light red bars. The dark red bar shows the model average, consisting of a weighted mean using the (uncorrelated) uncertainties due to natural variability plus the term representing intermodel spread (i.e., the inverse square of the white bars).

Observation-based products and models are combined into a single result in two ways. Firstly, we neglect common model uncertainties beyond the intermodel spread that is depicted by the model average and compute the weighted average of models (dark red bar) and observations (dark blue bar): this is indicated by the magenta bar. As, due to common model uncertainties, model uncertainty can be larger than the intermodel spread, secondly, we also show the more conservative estimate of an unweighted, direct average of observations (dark blue bar) and models (dark red bar) contributing 50% each, indicated by the white box around the magenta bar in the synthesis figures.

Results are shown in Tables 6.1 - 6.4, where differences are presented for changes both between the past, 1.3°C cooler climate, and today's climate, and between the present and a future, 0.2°C, 0.7°C, and 1.7°C warmer climate (1.5°C, 2°C, and 3°C of global warming since pre-industrial times). By combining evidence from the synthesis of model results for the past, projections for the future, and established physical understanding, we derive a best-estimate attribution of the event.

6.1 Rx2day - Analysis of 2-day precipitation event

Figures 6.1 and 6.2 show the synthesised changes in magnitude for a 1-in-3-year 2-day intense rainfall event in counties Dublin, Wexford, and Wicklow, for the wettest months October, November, December, and January. These changes are associated with 1.3°C of warming from the pre-industrial period to 2025, and a further 0.2°C, 0.7°C, and 1.7°C of warming from 2025 to different times throughout the century under current policies. All models estimate similar ranges of warming.

In comparison to a pre-industrial climate, the rainfall associated with this 2-day event has increased by nearly 12% (95% CI: -17, 51), results can be seen in Table 6.1. It must be noted, however, that observational data suggests a much higher increase in rainfall than the climate models. Although it cannot be said for certain, it is possible that climate models may be underpredicting changes in rainfall magnitude both to date and, by extension, into the future. In addition, there is expected to be a further 1%, 3%, and 8% increase in rainfall magnitudes from 2025 levels for similar events, respectively, for climates 1.5°C, 2.0°C, and 3.0°C warmer than pre-industrial levels. However, it is important to stress that there are considerable uncertainties in these estimates and that much greater changes cannot be precluded.

Likelihood changes are also calculated, and their results shown in Table 6.2. In comparison to a pre-industrial climate, the similar 2-day intense rainfall event in counties Dublin, Wexford and Wicklow have already become twice as likely. In pre-industrial times 2-day heavy rainfall in this region would've been expected to occur once every 6 years but they are now expected to occur once every 3 years. For climates 1.5°C, 2.0°C, and 3.0°C warmer than pre-industrial levels, similar rainfall events will become 1.1, 1.2, and 1.7 times more likely than today (or 13, 15.5 and 20.5 times more likely than pre-industrial). This means that with 3.0°C of global warming we would expect similar rainfall events to happen once every 1-2 years.

Rx2day	**Change in magnitude (%)**			
	Already occurred (+1.3°C)	Projected further change (+1.5°C)	Projected further change (+2.0°C)	Projected further change (+3.0°C)
Observations	19.4 (-15.0, 69.6)	-	-	-
Models	7.70 (-17.1, 40.2)	-	-	-
Synthesis	11.8 (-16.5, 50.8)	0.97 (-0.34, 2.32)	3.33 (-1.09, 8.02)	7.83 (-2.30, 19.0)

Table 6.1: Summary of synthesised changes in magnitude for Rx2day, presented in Figures 6.1 and 6.2. The projected temperatures are for °C warmer than pre-industrial time (1.3°C cooler than today's climate). *Statistically significant changes are highlighted in **bold**.*

Rx2day	**Probability ratio**			
	Already occurred (+1.3°C)	Projected further change (+1.5°C)	Projected further change (+2.0°C)	Projected further change (3.0°C)
Observations	2.34 (0.41, 15.6)	-	-	-
Models	2.00 (0.18, 21.4)	-	-	-
Synthesis	2.21 (0.30, 17.7)	1.06 (0.97, 1.17)	1.24 (0.91, 1.70)	1.65 (0.82, 3.34)

Table 6.2: Summary of synthesised changes in the probability ratio for Rx2day, presented in Figures 6.1 and 6.2. The projected temperatures are for °C warmer than pre-industrial time (1.3°C cooler than today's climate). *Statistically significant changes are highlighted in **bold**.*

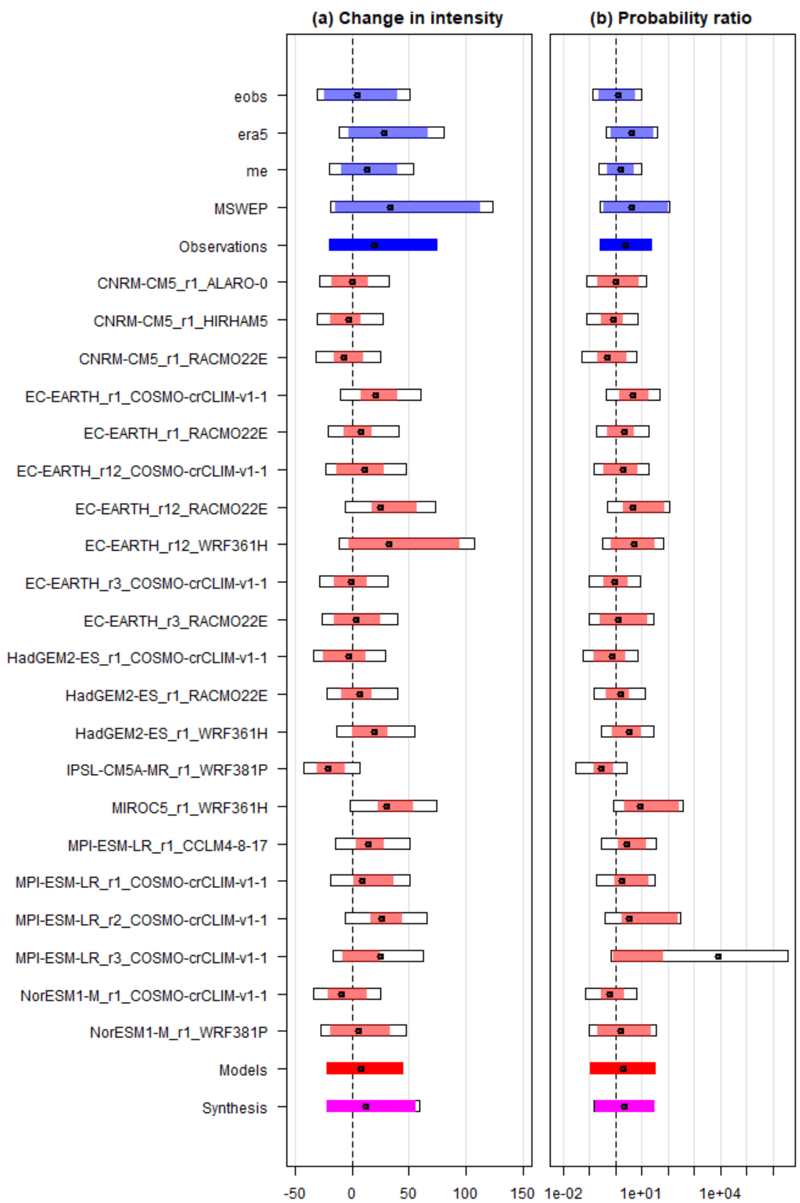


Figure 6.1: Synthesised changes for a 1-in-3-year (section 3.1) Rx2day event due to GMST. Changes in intensity (left) and PR (right) are shown for a historical period comparing the past 1.3°C cooler climate with the present.

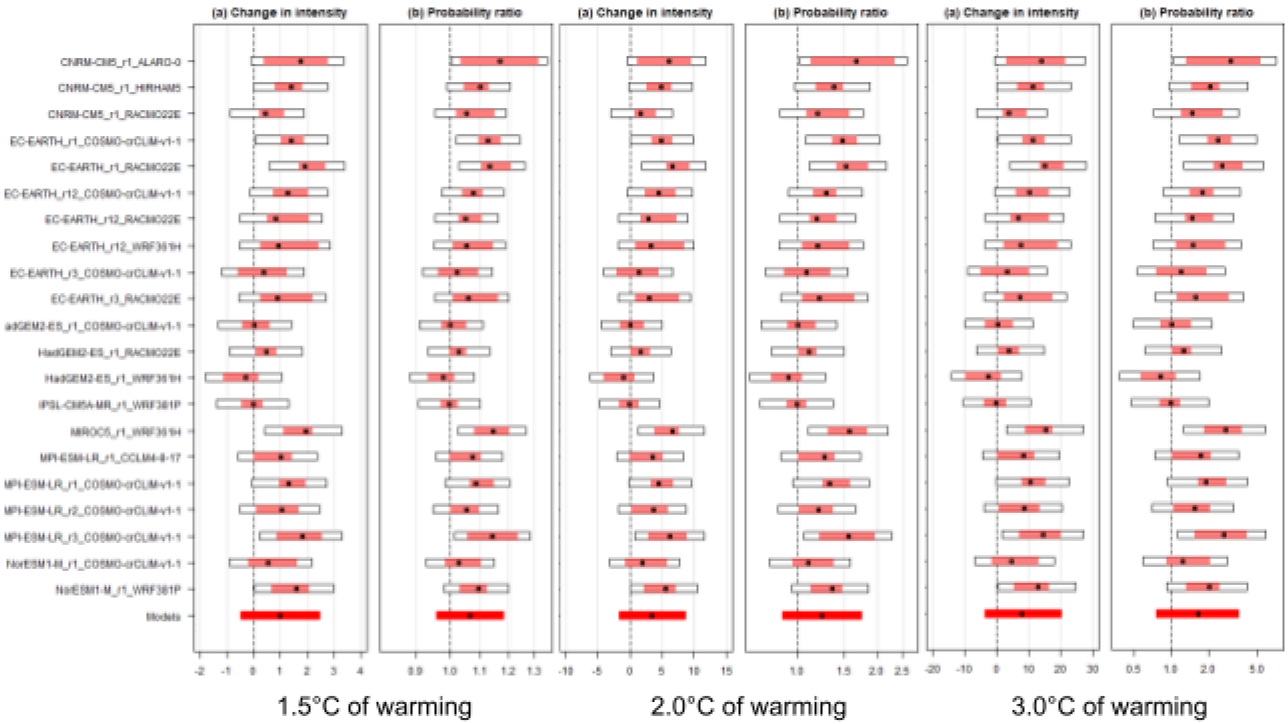


Figure 6.2: Synthesised changes for a 1-in-3-year (section 3.1) Rx2day event due to GMST. Changes in intensity (left) and PR (right) are shown for a future period, based on model projections only, comparing the present and a future warmed climate.

6.2 Rx30day - Analysis of precursor conditioning to the 2-day precipitation event

Figures 6.3 and 6.4 show the synthesised changes in magnitude for a 1-in-3-year 30-day intense rainfall event in counties Dublin, Carlow, Kildare, Kilkenny, Laois, Louth, Meath, Wexford, and Wicklow. Similar to that which preceded the Rx2day event. These changes are associated with 1.3°C of warming from the pre-industrial period to 2025, and a further 0.2°C, 0.7°C, and 1.7°C of warming from 2025 to different times throughout the century under current policies. All models estimate similar ranges of warming.

In comparison to a pre-industrial climate, the rainfall associated with this 30-day rainfall has increased to nearly 7% (95% CI: -10, 27), results can be seen in Table 6.3. It must be noted, however, that observational data suggests a much higher increase in rainfall than the climate models suggesting some disagreement between the two. In addition, there is expected to be a further 0.5%, 1.9%, and 4.5% increase in rainfall magnitudes from 2025 levels, respectively, for climates 1.5°C, 2.0°C, and 3.0°C warmer than pre-industrial levels.

Likelihood changes are also calculated, and their results shown in Table 6.2. In comparison to a pre-industrial climate, the similar 30-day intense rainfall event in counties Dublin, Carlow, Kildare, Kilkenny, Laois, Louth, Meath, Wexford, and Wicklow have become twice as likely. In pre-industrial times 30-day heavy rainfall in this region would've been expected to occur once every 6.5 years but they are now expected to occur once every 3 years. For climates 1.5°C, 2.0°C, and 3.0°C warmer than pre-industrial levels, similar rainfall events will become 1.1, 1.3, and 1.7 times more likely than today(or 7, 8.5 and 11.5 times more likely than pre-industrial). This means that with 3.0°C of global warming we would expect similar rainfall events to happen once every 2 years.

Rx30day	**Change in magnitude (%)**			
	Already occurred (+1.3°C)	Projected further change (+1.5°C)	Projected further change (+2.0°C)	Projected further change (+3.0°C)
Observations	17.2 (-9.32, 52.1)	-	-	-
Models	3.71 (-9.91, 19.4)	-	-	-
Synthesis	6.65 (-10.4, 27.2)	0.54 (-0.31, 1.42)	1.87 (-1.02, 4.94)	4.46 (-2.3, 11.9)

Table 6.3: Summary of synthesised changes in magnitude for Rx30day, presented in Figures 6.3 and 6.4. The projected temperatures are for °C warmer than pre-industrial time (1.3°C cooler than today's climate). *Statistically significant changes are highlighted in **bold**.*

Rx30day	**Probability ratio**			
	Already occurred (+1.3°C)	Projected further change (+1.5°C)	Projected further change (+2.0°C)	Projected further change (3.0°C)
Observations	5.04 (0.25, 547)	-	-	-
Models	1.65 (0.22, 15.4)	-	-	-
Synthesis	2.15 (0.22, 43.1)	1.07 (0.95, 1.21)	1.27 (0.85, 1.9)	1.72 (0.72, 4.14)

Table 6.4: Summary of synthesised changes in the probability ratio for Rx30day, presented in Figures 6.3 and 6.4. The projected temperatures are for °C warmer than pre-industrial time (1.3°C cooler than today's climate). *Statistically significant changes are highlighted in **bold**.*

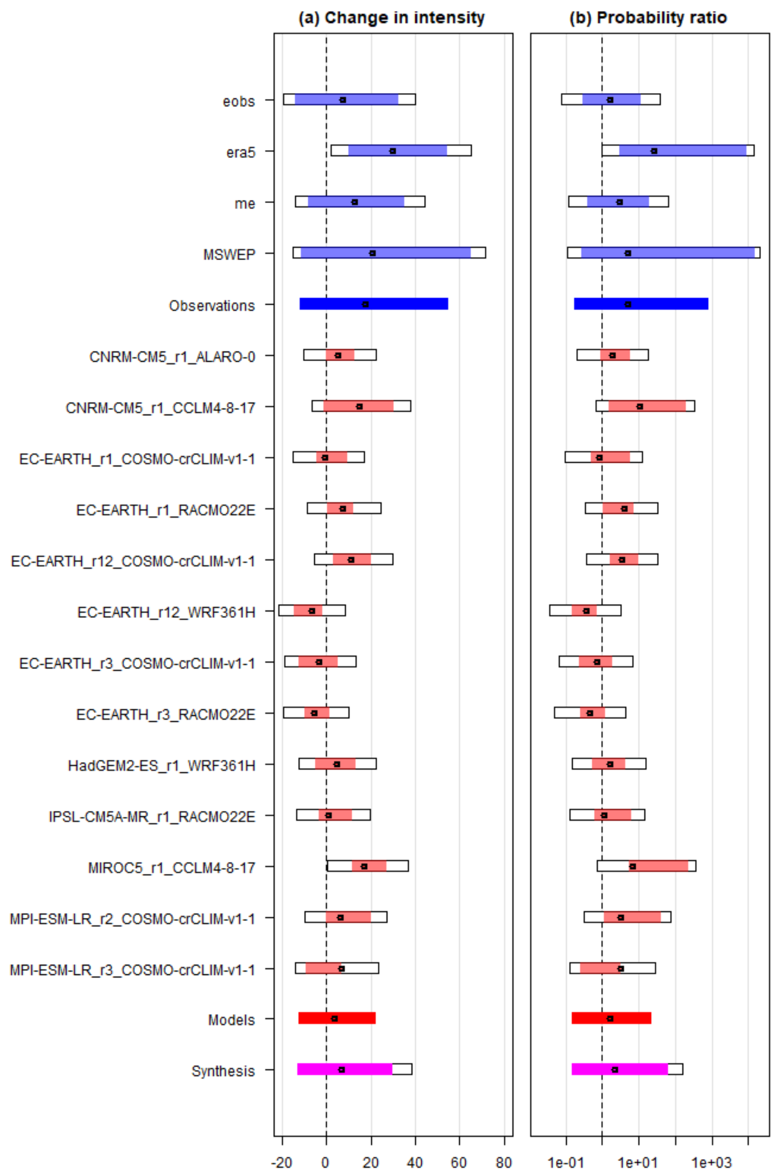


Figure 6.3: Synthesised changes for a 1-in-3-year (section 3.2) Rx30day event due to GMST. Changes in intensity (left) and PR (right) are shown for a historical period comparing the past 1.3°C cooler climate with the present.

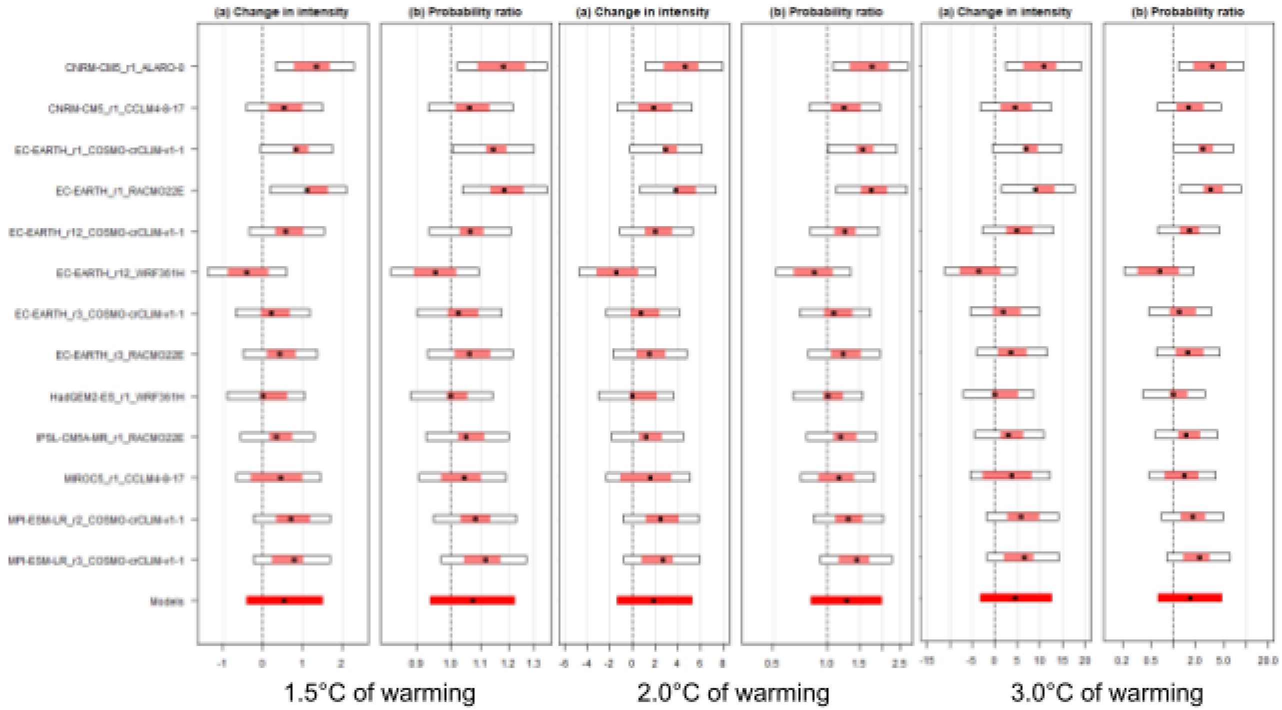


Figure 6.4: Synthesised changes for a 1-in-3-year (section 3.2) Rx30day event due to GMST. Changes in intensity (left) and PR (right) are shown for a future period, based on model projections only, comparing the present and a future warmed climate.

7 Societal impacts

The extreme rainfall event associated with Storm Claudia produced widespread social disruption across multiple counties. Communities in Wexford experienced significant inundation as saturated catchments and rivers already at capacity led to the flooding of at least 18 properties in Wexford, half of which were in Bridgetown following a canal breach, with further damage reported in Gorey, Ballycanew, Castlebridge, Blackwater, and Courtown. Thousands of farms, businesses and households were left without power, particularly in counties Offaly and Kildare.

Transport was also disrupted, with road closures due to fallen trees and flooding (R741 north of Castlebridge was deemed "Impassable"). The Rosslare rail line was delayed due to high water levels, while Stena line resorted to stopping one of its ferries mid-crossing between Dublin and Holyhead due to the unsafe conditions and subsequently cancelled the departure of several other ferries. Both Stena and Irish Ferries had sailings which were stuck outside Holyhead from about 11am to 6am the next morning, see figure 7.1. The closure was pre-emptive following the extreme damage to the port infrastructure caused by Storm Darragh last December.

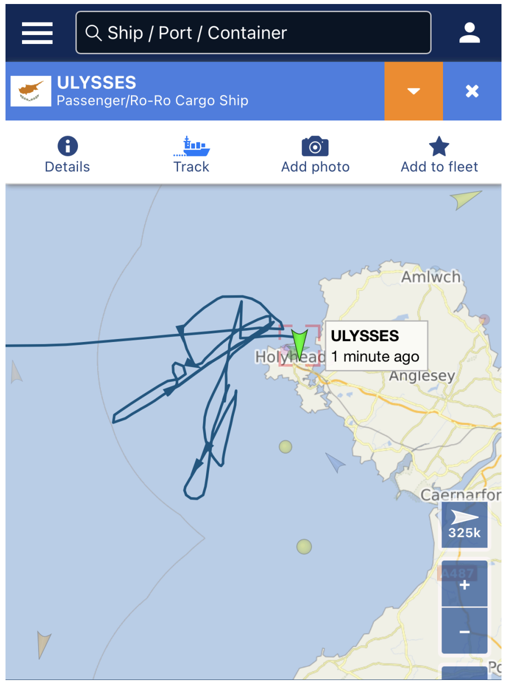


Figure 7.1: Image from vesselfinder.com of Ulysses journey from 11am on the 14th to 6am on the 15th of November.

Several primary schools located in Dublin took the decision to close early on Friday to avoid the worst conditions.

he first day of the Navan Racing Festival was cancelled due to much of the track becoming water-lodged following 23mm of rainfall. Farmers were advised by the department of Agriculture, Food and the Marine to move machinery and livestock to higher ground ahead of the worst conditions. Figure 7.2 depicts the large amount of agricultural land and businesses affected by the bursting of the banks of the Owenavarragh River at Ballycanew in Co. Wexford.

Figure 7.2: Flooding at Ballycanew Co. Wexford (Owenavarragh River). Photos taken with thanks from Fionntán Ó Súilleabháin TD facebook post.

Fortunately, while parks, playgrounds and racecourses flooded across the affected counties, further significant flooding was averted due to recent flood relief works on the river Poddle and Dodder in south Dublin. As can be seen in figure 7.3 the water levels of the river Dodder rose quite high but did not break their banks due to recent works.

Figure 7.3: Image highlights the high river level experienced on the Dodder river in Dublin on the 15th of November.

Similar impacts were felt across the UK, with parts of Wales experiencing the worst impacts. In particular, the town of Monmouth saw evacuation orders as residents were rescued from their flooded homes.

8 Conclusion

Storm Claudia dropped large amounts of rainfall on Dublin, Wexford, and Wicklow on the 14th and 15th of November 2025. In the heart of the rainfall, Johnstown Castle recorded 58% of average November totals in just 24 hours.

Understanding how rainfall intensities are set to change is important for real world flood risk management and emergency response. A short flooding attribution showed that antecedent wet conditions strongly amplified the flooding, as heavy rainfall over previous weeks primed catchments and contributed substantially to the flood severity, underscoring the importance of compounding effects when assessing and attributing flood events.

Human-caused climate change not only increased the rainfall associated with this 2-day event, but it also increased the rainfall in the preceding 30 days. While similar 2-day rainfall events are expected to become slightly more frequent with global warming, more concerning is that, to date, this rainfall has increased by over 10% in magnitude. With future warming these events are set to become yet more intense. There are similar expectations for the 30-day event which has already been made nearly 7% more intense by climate change.

References

All references are given as hyperlinks in the text.

Acknowledgements

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Appendix

Model / Observations	Seasonal cycle	Spatial pattern	Disp	Shape	Summary
eobs			0.28 (0.21…0.32)	-0.01 (-0.22…0.18)	
era5			0.25 (0.2…0.28)	0.02 (-0.19…0.18)	
me			0.23 (0.2…0.27)	0.1 (-0.12…0.27)	
MSWEP			0.27 (0.19…0.32)	-0.05 (-0.3…0.35)	
CanESM2_r1_CCLM4-8-17	good	bad	0.23 (0.19…0.23)	-0.13 (-0.34…-0.03)	bad
CanESM2_r1_REMO2015	good	bad	0.33 (0.28…0.34)	0.05 (0.01…0.27)	bad
CNRM-CM5_r1_ALADIN63	bad	good	0.22 (0.2…0.24)	-0.16 (-0.2…-0.11)	bad
CNRM-CM5_r1_ALARO-0	good	good	0.25 (0.23…0.26)	-0.24 (-0.33…-0.15)	good
CNRM-CM5_r1_CCLM4-8-17	good	bad	0.26 (0.21…0.29)	-0.15 (-0.19…-0.02)	bad
CNRM-CM5_r1_HadREM3-GA7-05	reasonable	good	0.25 (0.18…0.28)	0.14 (0.05…0.29)	reasonable
CNRM-CM5_r1_HIRHAM5	good	good	0.28 (0.19…0.29)	-0.01 (-0.24…0.11)	good
CNRM-CM5_r1_RACMO22E	good	good	0.26 (0.2…0.29)	-0.24 (-0.3…0.01)	good
CNRM-CM5_r1_RCA4	bad	good	0.24 (0.19…0.22)	-0.05 (-0.2…0.04)	bad
CNRM-CM5_r1_REMO2015	good	bad	0.34 (0.26…0.38)	-0.02 (-0.13…0.08)	bad
CNRM-CM5_r1_WRF381P	good	bad	0.3 (0.26…0.33)	-0.11 (-0.14…0.16)	bad
EC-EARTH_r1_COSMO-crCLIM-v1-1	good	good	0.25 (0.23…0.27)	-0.04 (-0.12…0.04)	good
EC-EARTH_r1_HIRHAM5	reasonable	good	0.28 (0.22…0.32)	0 (-0.08…0.38)	reasonable
EC-EARTH_r1_RACMO22E	good	good	0.23 (0.22…0.25)	-0.12 (-0.15…0.03)	good

EC-EARTH_r1_RCA4	bad	good	0.23 (0.2…0.25)	0 (-0.11…0.02)	bad
EC-EARTH_r12_CCLM4-8-17	good	bad	0.31 (0.26…0.35)	0.05 (-0.07…0.1)	bad
EC-EARTH_r12_COSMO-crCLIM-v1-1	good	good	0.26 (0.23…0.26)	0.06 (-0.09…0.25)	good
EC-EARTH_r12_HadREM3-GA7-05	reasonable	good	0.27 (0.27…0.28)	0.05 (0.01…0.1)	reasonable
EC-EARTH_r12_HIRHAM5	reasonable	good	0.21 (0.19…0.21)	0.06 (-0.25…0.16)	reasonable
EC-EARTH_r12_RACMO22E	good	good	0.24 (0.22…0.26)	0.04 (-0.05…0.15)	good
EC-EARTH_r12_RCA4	bad	good	0.23 (0.21…0.25)	0.05 (-0.07…0.14)	bad
EC-EARTH_r12_RegCM4-6	good	bad	0.27 (0.21…0.31)	0.05 (-0.06…0.16)	bad
EC-EARTH_r12_REMO2015	good	bad	0.31 (0.28…0.33)	0.03 (0.09…0.2)	bad
EC-EARTH_r12_WRF361H	good	good	0.26 (0.21…0.32)	0.08 (0.08…0.48)	good
EC-EARTH_r12_WRF381P	good	reasonable	0.29 (0.28…0.33)	-0.02 (-0.18…0.01)	reasonable
EC-EARTH_r3_COSMO-crCLIM-v1-1	good	good	0.28 (0.26…0.29)	0.01 (-0.06…0.13)	good
EC-EARTH_r3_HIRHAM5	reasonable	good	0.27 (0.24…0.29)	0.02 (-0.04…0.07)	reasonable
EC-EARTH_r3_RACMO22E	good	good	0.26 (0.21…0.29)	-0.04 (-0.2…0.2)	good
EC-EARTH_r3_RCA4	bad	good	0.27 (0.19…0.29)	0 (-0.01…0.36)	bad
HadGEM2-ES_r1_ALADIN63	bad	good	0.22 (0.21…0.22)	0.07 (-0.04…0.11)	bad
HadGEM2-ES_r1_CCLM4-8-17	good	reasonable	0.24 (0.23…0.27)	0.13 (-0.03…0.23)	reasonable
HadGEM2-ES_r1_COSMO-crCLIM-v1-1	good	good	0.24 (0.2…0.26)	-0.08 (-0.26…0.14)	good
HadGEM2-ES_r1_HadREM3-GA7-05	reasonable	good	0.26 (0.24…0.28)	0.12 (-0.11…0.18)	reasonable
HadGEM2-ES_r1_HIRHAM5	reasonable	good	0.29 (0.25…0.32)	-0.1 (-0.21…0.04)	reasonable
HadGEM2-ES_r1_RACMO22E	good	good	0.23 (0.2…0.23)	0.01 (-0.16…0.13)	good
HadGEM2-ES_r1_RCA4	bad	good	0.23 (0.2…0.24)	0.02 (-0.19…0.17)	bad
HadGEM2-ES_r1_RegCM4-6	reasonable	bad	0.25 (0.21…0.26)	0.06 (0.02…0.24)	reasonable
HadGEM2-ES_r1_REMO2015	good	bad	0.27 (0.25…0.27)	-0.03 (-0.1…0.07)	bad

HadGEM2-ES_r1_WRF361H	good	good	0.25 (0.22…0.25)	0.02 (-0.03…0.22)	good
HadGEM2-ES_r1_WRF381P	reasonable	good	0.25 (0.21…0.28)	0.14 (0.03…0.25)	reasonable
IPSL-CM5A-MR_r1_HIRHAM5	bad	bad	0.25 (0.2…0.27)	0.01 (-0.08…0.2)	bad
IPSL-CM5A-MR_r1_RACMO22E	reasonable	good	0.28 (0.23…0.3)	-0.05 (-0.15…0.16)	reasonable
IPSL-CM5A-MR_r1_RCA4	bad	good	0.27 (0.22…0.32)	0 (-0.07…0.21)	bad
IPSL-CM5A-MR_r1_REMO2015	good	bad	0.28 (0.25…0.29)	-0.01 (-0.04…0.22)	bad
IPSL-CM5A-MR_r1_WRF381P	good	good	0.29 (0.28…0.33)	-0.04 (-0.23…0)	good
MIROC5_r1_CCLM4-8-17	good	bad	0.25 (0.22…0.28)	-0.06 (-0.13…-0.02)	bad
MIROC5_r1_REMO2015	good	bad	0.29 (0.27…0.33)	-0.04 (-0.23…0.03)	bad
MIROC5_r1_WRF361H	good	good	0.25 (0.24…0.26)	-0.03 (-0.12…0.14)	good
MPI-ESM-LR_r1_ALADIN63	bad	good	0.22 (0.17…0.23)	-0.13 (-0.64…0.05)	bad
MPI-ESM-LR_r1_CCLM4-8-17	good	good	0.23 (0.2…0.25)	-0.02 (-0.13…0.07)	good
MPI-ESM-LR_r1_COSMO-crCLIM-v1-1	good	good	0.26 (0.24…0.27)	0.03 (-0.11…0.01)	good
MPI-ESM-LR_r1_HadREM3-GA7-05	bad	good	0.24 (0.2…0.26)	-0.19 (-0.29…0.05)	bad
MPI-ESM-LR_r1_HIRHAM5	bad	good	0.24 (0.21…0.26)	0 (-0.07…0.09)	bad
MPI-ESM-LR_r1_RACMO22E	reasonable	good	0.23 (0.21…0.27)	-0.04 (-0.2…0.08)	reasonable
MPI-ESM-LR_r1_RCA4	bad	good	0.21 (0.2…0.22)	-0.16 (-0.51…-0.14)	bad
MPI-ESM-LR_r1_RegCM4-6	good	bad	0.22 (0.2…0.24)	-0.01 (-0.17…0.14)	bad
MPI-ESM-LR_r1_REMO2009	good	bad	0.23 (0.22…0.24)	-0.13 (-0.24…-0.02)	bad
MPI-ESM-LR_r2_COSMO-crCLIM-v1-1	good	good	0.23 (0.2…0.27)	0.12 (-0.14…0.15)	good
MPI-ESM-LR_r2_RCA4	bad	good	0.22 (0.2…0.27)	-0.07 (-0.14…-0.05)	bad
MPI-ESM-LR_r2_REMO2009	good	bad	0.21 (0.17…0.22)	0.13 (0.07…0.36)	bad
MPI-ESM-LR_r3_COSMO-crCLIM-v1-1	good	good	0.25 (0.19…0.25)	-0.29 (-0.29…0.01)	good
MPI-ESM-LR_r3_RCA4	bad	good	0.28 (0.25…0.3)	-0.05 (-0.23…0.03)	bad

MPI-ESM-LR_r3_REMO2015	good	bad	0.22 (0.18…0.23)	0.18 (0.07…0.49)	bad
NorESM1-M_r1_ALADIN63	bad	good	0.28 (0.25…0.27)	0 (-0.4…0.05)	bad
NorESM1-M_r1_COSMO-crCLIM-v1-1	good	good	0.25 (0.23…0.29)	0.17 (0.07…0.26)	good
NorESM1-M_r1_HadREM3-GA7-05	bad	bad	0.29 (0.27…0.32)	0.1 (0.09…0.19)	bad
NorESM1-M_r1_HIRHAM5	bad	good	0.25 (0.18…0.29)	0.16 (0.13…0.31)	bad
NorESM1-M_r1_RACMO22E	bad	good	0.24 (0.21…0.24)	0.21 (-0.01…0.36)	bad
NorESM1-M_r1_RCA4	bad	good	0.28 (0.25…0.3)	-0.07 (-0.15…0)	bad
NorESM1-M_r1_RegCM4-6	good	bad	0.32 (0.26…0.34)	-0.15 (-0.2…-0.01)	bad
NorESM1-M_r1_REMO2015	good	bad	0.31 (0.25…0.32)	0.04 (-0.09…0.21)	bad
NorESM1-M_r1_WRF381P	good	good	0.26 (0.23…0.3)	-0.05 (-0.11…0.03)	good

Table A.1: Evaluation results of the climate models considered for attribution analysis of Rx2day over the study region. Results of a visual evaluation of the seasonal cycle and spatial pattern are given. For each model, the best estimate of the Sigma parameter is shown, and a 95% confidence interval is given for each, obtained via bootstrapping. The qualitative evaluation is shown in the right-hand column.

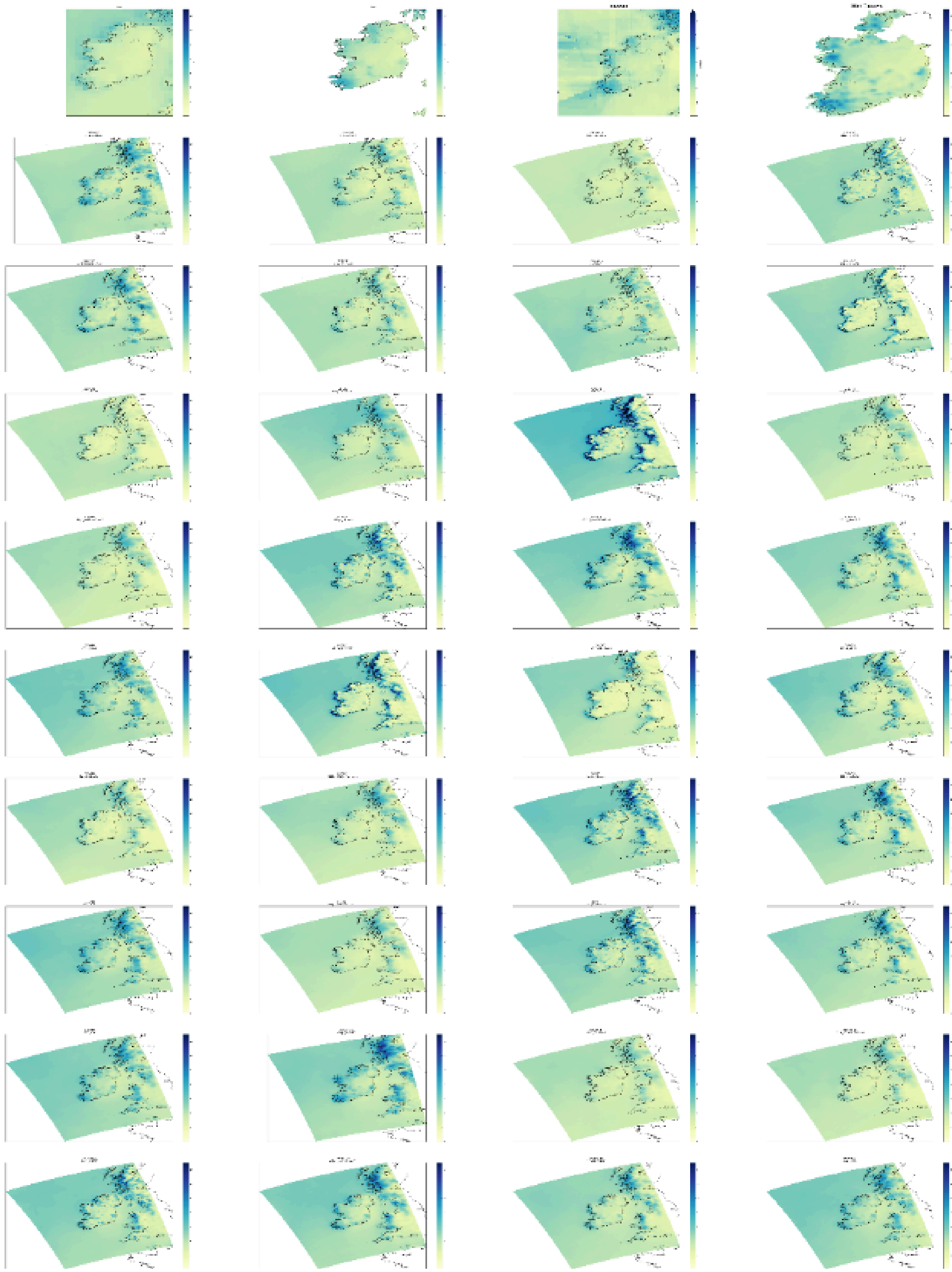
Model / Observations	***Seasonal cycle***	***Spatial pattern***	***Sigma***	***Shape***	***Summary***
eobs			*0.17 (0.14…0.19)*	*-0.16 (-0.33…0)*	
era5			*0.18 (0.15…0.2)*	*-0.18 (-0.36…-0.07)*	
me			*0.17 (0.14…0.19)*	*-0.19 (-0.37…-0.04)*	
MSWEP			*0.17 (0.13…0.2)*	*-0.21 (-0.75…-0.04)*	
CanESM2_r1_CCLM4-8-17	*bad*	*bad*	*0.12 (0.12…0.12)*	*-0.18 (-0.22…-0.1)*	*bad*
CanESM2_r1_REMO2015	*good*	*bad*	*0.15 (0.11…0.15)*	*-0.34 (-0.38…-0.15)*	*bad*
CNRM-CM5_r1_ALADIN63	*bad*	*good*	*0.14 (0.1…0.15)*	*-0.23 (-0.29…-0.15)*	*bad*
CNRM-CM5_r1_ALARO-0	*good*	*good*	*0.14 (0.12…0.12)*	*-0.1 (-0.11…0.02)*	*good*
CNRM-CM5_r1_CCLM4-8-17	*good*	*good*	*0.14 (0.13…0.15)*	*-0.15 (-0.26…-0.09)*	*good*
CNRM-CM5_r1_HadREM3-GA7-05	*bad*	*good*	*0.17 (0.17…0.2)*	*-0.39 (-0.63…-0.38)*	*bad*

CNRM-CM5_r1_HIRHAM5	*good*	*good*	*0.17 (0.14…0.19)*	*-0.27 (-0.36…-0.23)*	*Insufficient*
CNRM-CM5_r1_RACMO22E	*good*	*good*	*0.12 (0.11…0.12)*	*-0.01 (-0.3…-0.06)*	*bad*
CNRM-CM5_r1_RCA4	*bad*	*good*	*0.16 (0.13…0.17)*	*-0.21 (-0.34…-0.21)*	*bad*
CNRM-CM5_r1_REMO2015	*good*	*bad*	*0.16 (0.14…0.15)*	*-0.08 (-0.13…0)*	*bad*
CNRM-CM5_r1_WRF381P	*good*	*bad*	*0.13 (0.11…0.15)*	*-0.12 (-0.31…-0.1)*	*bad*
EC-EARTH_r1_COSMO-crCLIM-v1-1	*good*	*good*	*0.14 (0.11…0.15)*	*-0.29 (-0.3…-0.1)*	*good*
EC-EARTH_r1_HIRHAM5	*bad*	*reasonable*	*0.15 (0.14…0.17)*	*-0.04 (-0.05…0.02)*	*reasonable*
EC-EARTH_r1_RACMO22E	*good*	*good*	*0.14 (0.11…0.14)*	*-0.21 (-0.23…-0.02)*	*good*
EC-EARTH_r1_RCA4	*bad*	*good*	*0.13 (0.12…0.14)*	*-0.3 (-0.51…-0.13)*	*bad*
EC-EARTH_r12_CCLM4-8-17	*reasonable*	*good*	*0.16 (0.13…0.18)*	*-0.11 (-0.19…0.02)*	*reasonable*
EC-EARTH_r12_COSMO-crCLIM-v1-1	*good*	*good*	*0.14 (0.13…0.17)*	*-0.05 (-0.16…0.06)*	*good*
EC-EARTH_r12_HadREM3-GA7-05	*bad*	*good*	*0.15 (0.13…0.17)*	*-0.24 (-0.36…-0.18)*	*bad*
EC-EARTH_r12_HIRHAM5	*bad*	*good*	*0.11 (0.09…0.11)*	*0.05 (-0.03…0.14)*	*bad*
EC-EARTH_r12_RACMO22E	*good*	*good*	*0.12 (0.11…0.14)*	*-0.17 (-0.33…-0.1)*	*reasonable*
EC-EARTH_r12_RCA4	*bad*	*good*	*0.11 (0.11…0.12)*	*-0.05 (-0.31…-0.07)*	*bad*
EC-EARTH_r12_RegCM4-6	*bad*	*bad*	*0.14 (0.12…0.16)*	*0.01 (-0.51…0.06)*	*bad*
EC-EARTH_r12_REMO2015	*good*	*bad*	*0.17 (0.15…0.18)*	*-0.27 (-0.31…-0.19)*	*bad*
EC-EARTH_r12_WRF361H	*good*	*good*	*0.13 (0.11…0.15)*	*-0.26 (-0.39…-0.1)*	*good*
EC-EARTH_r12_WRF381P	*good*	*reasonable*	*0.13 (0.12…0.16)*	*-0.21 (-0.37…-0.12)*	*reasonable*
EC-EARTH_r3_COSMO-crCLIM-v1-1	*good*	*good*	*0.16 (0.15…0.17)*	*-0.09 (-0.2…-0.05)*	*good*
EC-EARTH_r3_HIRHAM5	*good*	*reasonable*	*0.16 (0.14…0.18)*	*-0.11 (-0.28…-0.04)*	*reasonable*
EC-EARTH_r3_RACMO22E	*good*	*good*	*0.14 (0.12…0.17)*	*-0.2 (-0.27…-0.14)*	*good*
EC-EARTH_r3_RCA4	*bad*	*good*	*0.12 (0.1…0.13)*	*-0.15 (-0.21…0.03)*	*reasonable*
HadGEM2-ES_r1_ALADIN63	*bad*	*good*	*0.16 (0.14…0.17)*	*-0.05 (0.02…0.1)*	*bad*
HadGEM2-ES_r1_CCLM4-8-17	*good*	*bad*	*0.14 (0.13…0.15)*	*0.04 (-0.01…0.12)*	*bad*
HadGEM2-ES_r1_COSMO-crCLIM-v1-1	*good*	*bad*	*0.14 (0.12…0.15)*	*-0.05 (-0.12…0.1)*	*bad*
HadGEM2-ES_r1_HadREM3-GA7-05	*reasonable*	*good*	*0.15 (0.13…0.16)*	*-0.1 (-0.17…-0.06)*	*reasonable*

HadGEM2-ES_r1_HIRHAM5	reasonable	good	0.12 (0.1…0.13)	-0.02 (-0.13…-0.01)	bad
HadGEM2-ES_r1_RACMO22E	good	good	0.13 (0.12…0.13)	0.01 (-0.06…0.06)	reasonable
HadGEM2-ES_r1_RCA4	bad	good	0.15 (0.13…0.15)	-0.17 (-0.27…-0.08)	bad
HadGEM2-ES_r1_RegCM4-6	reasonable	bad	0.16 (0.12…0.17)	-0.07 (-0.2…0.02)	bad
HadGEM2-ES_r1_REMO2015	good	bad	0.16 (0.15…0.17)	-0.15 (-0.27…-0.12)	bad
HadGEM2-ES_r1_WRF361H	good	good	0.17 (0.14…0.19)	-0.13 (-0.17…0.01)	good
HadGEM2-ES_r1_WRF381P	reasonable	good	0.11 (0.11…0.13)	0.06 (-0.09…0.07)	reasonable
IPSL-CM5A-MR_r1_HIRHAM5	good	bad	0.13 (0.1…0.12)	-0.13 (-0.16…-0.03)	bad
IPSL-CM5A-MR_r1_RACMO22E	good	good	0.14 (0.12…0.14)	-0.17 (-0.14…-0.06)	good
IPSL-CM5A-MR_r1_RCA4	bad	good	0.13 (0.11…0.13)	-0.33 (-0.34…-0.28)	bad
IPSL-CM5A-MR_r1_REMO2015	good	bad	0.15 (0.12…0.16)	-0.32 (-0.45…-0.19)	bad
IPSL-CM5A-MR_r1_WRF381P	good	reasonable	0.11 (0.1…0.12)	-0.12 (-0.24…-0.06)	bad
MIROC5_r1_CCLM4-8-17	good	good	0.16 (0.15…0.18)	-0.07 (-0.31…-0.04)	good
MIROC5_r1_REMO2015	good	bad	0.15 (0.14…0.16)	-0.01 (-0.09…0.04)	bad
MPI-ESM-LR_r1_ALADIN63	bad	good	0.13 (0.11…0.13)	-0.27 (-0.31…-0.25)	bad
MPI-ESM-LR_r1_CCLM4-8-17	good	good	0.11 (0.08…0.13)	0.02 (-0.16…0.29)	reasonable
MPI-ESM-LR_r1_COSMO-crCLIM-v1-1	good	good	0.11 (0.09…0.13)	0 (-0.21…0.08)	reasonable
MPI-ESM-LR_r1_HadREM3-GA7-05	bad	good	0.12 (0.11…0.13)	-0.11 (-0.23…-0.11)	bad
MPI-ESM-LR_r1_HIRHAM5	bad	good	0.13 (0.12…0.14)	-0.39 (-0.56…-0.36)	bad
MPI-ESM-LR_r1_RACMO22E	reasonable	good	0.12 (0.1…0.13)	-0.27 (-0.41…-0.16)	bad
MPI-ESM-LR_r1_RCA4	bad	good	0.13 (0.11…0.14)	-0.27 (-0.46…-0.18)	bad
MPI-ESM-LR_r1_RegCM4-6	good	bad	0.17 (0.13…0.18)	-0.3 (-0.38…-0.22)	bad
MPI-ESM-LR_r1_REMO2009	good	bad	0.12 (0.11…0.14)	-0.11 (-0.23…-0.09)	bad
MPI-ESM-LR_r2_COSMO-crCLIM-v1-1	good	good	0.15 (0.14…0.17)	-0.27 (-0.39…-0.13)	good
MPI-ESM-LR_r2_RCA4	bad	good	0.11 (0.1…0.12)	-0.1 (-0.34…-0.06)	bad
MPI-ESM-LR_r2_REMO2009	good	bad	0.14 (0.13…0.15)	-0.08 (-0.1…0.03)	bad
MPI-ESM-LR_r3_COSMO-crCLIM-v1-1	good	good	0.14 (0.11…0.14)	-0.21 (-0.34…-0.1)	good

MPI-ESM-LR_r3_RCA4	*bad*	*good*	*0.13 (0.11…0.14)*	*-0.16 (-0.15…-0.07)*	*bad*
MPI-ESM-LR_r3_REMO2015	*good*	*bad*	*0.13 (0.1…0.14)*	*-0.15 (-0.22…0.06)*	*bad*
NorESM1-M_r1_ALADIN63	*bad*	*good*	*0.12 (0.1…0.14)*	*-0.08 (-0.14…-0.09)*	*bad*
NorESM1-M_r1_COSMO-crCLIM-v1-1	*good*	*good*	*0.11 (0.11…0.12)*	*0.05 (-0.14…0.14)*	*bad*
NorESM1-M_r1_HadREM3-GA7-05	*bad*	*good*	*0.12 (0.11…0.14)*	*0.02 (-0.05…0.14)*	*bad*
NorESM1-M_r1_HIRHAM5	*bad*	*good*	*0.11 (0.1…0.12)*	*-0.1 (-0.16…0.07)*	*bad*
NorESM1-M_r1_RACMO22E	*bad*	*good*	*0.13 (0.11…0.13)*	*-0.28 (-0.36…-0.17)*	*bad*
NorESM1-M_r1_RCA4	*bad*	*good*	*0.13 (0.11…0.15)*	*-0.03 (-0.12…0.17)*	*bad*
NorESM1-M_r1_RegCM4-6	*bad*	*bad*	*0.14 (0.11…0.14)*	*-0.26 (-0.29…-0.14)*	*bad*
NorESM1-M_r1_REMO2015	*bad*	*bad*	*0.13 (0.12…0.14)*	*-0.24 (-0.33…-0.18)*	*bad*
NorESM1-M_r1_WRF381P	*good*	*reasonable*	*0.12 (0.11…0.12)*	*-0.23 (-0.33…-0.19)*	*bad*

Table A.2: Evaluation results of the climate models considered for attribution analysis of Rx2day over the study region. Results of a visual evaluation of the seasonal cycle and spatial pattern are given. For each model, the best estimate of the Sigma parameter is shown, and a 95% confidence interval is given for each, obtained via bootstrapping. The qualitative evaluation is shown in the right-hand column.



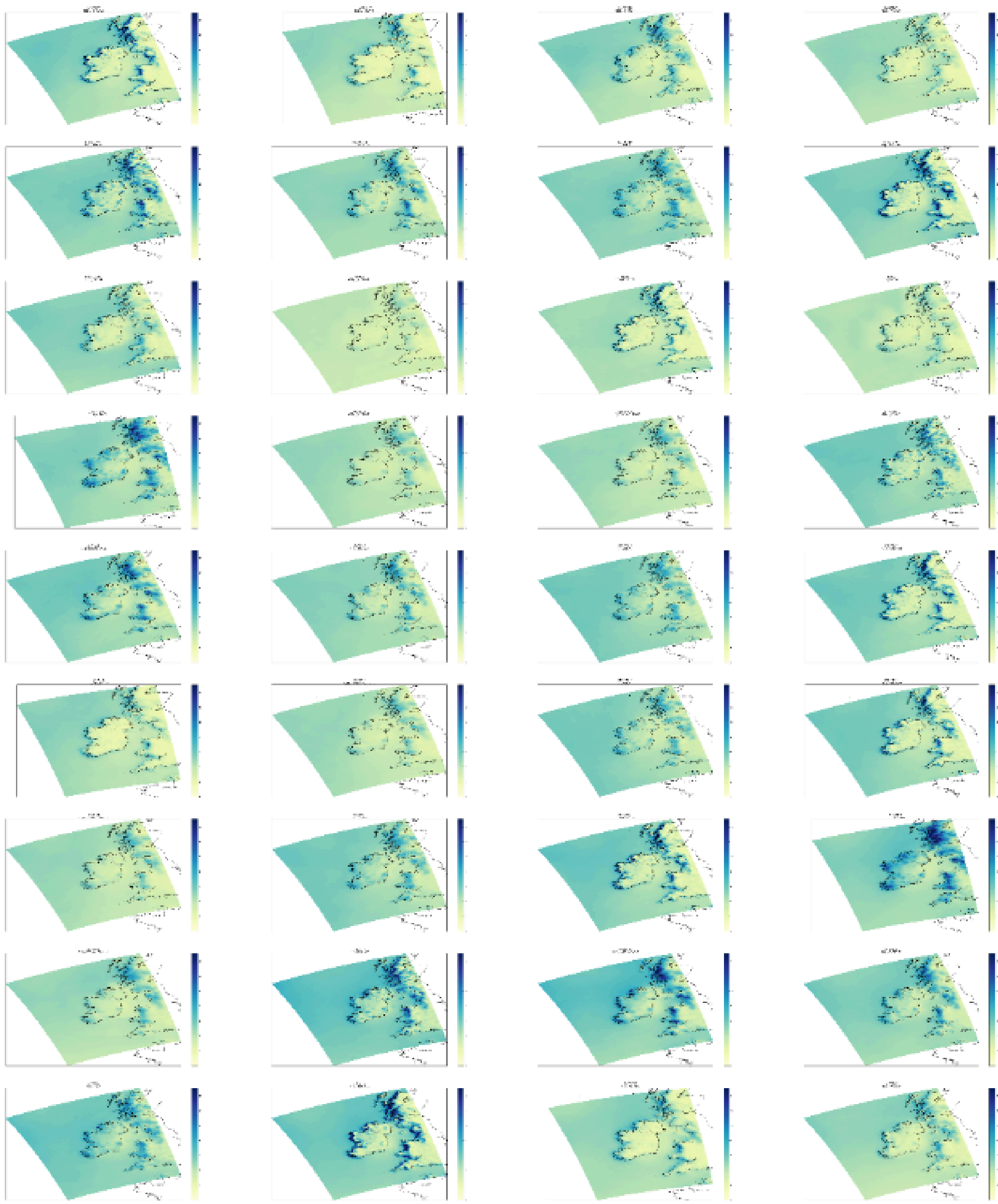


Figure A.1: Spatial patterns of 2-day precipitation in observations and CORDEX models.

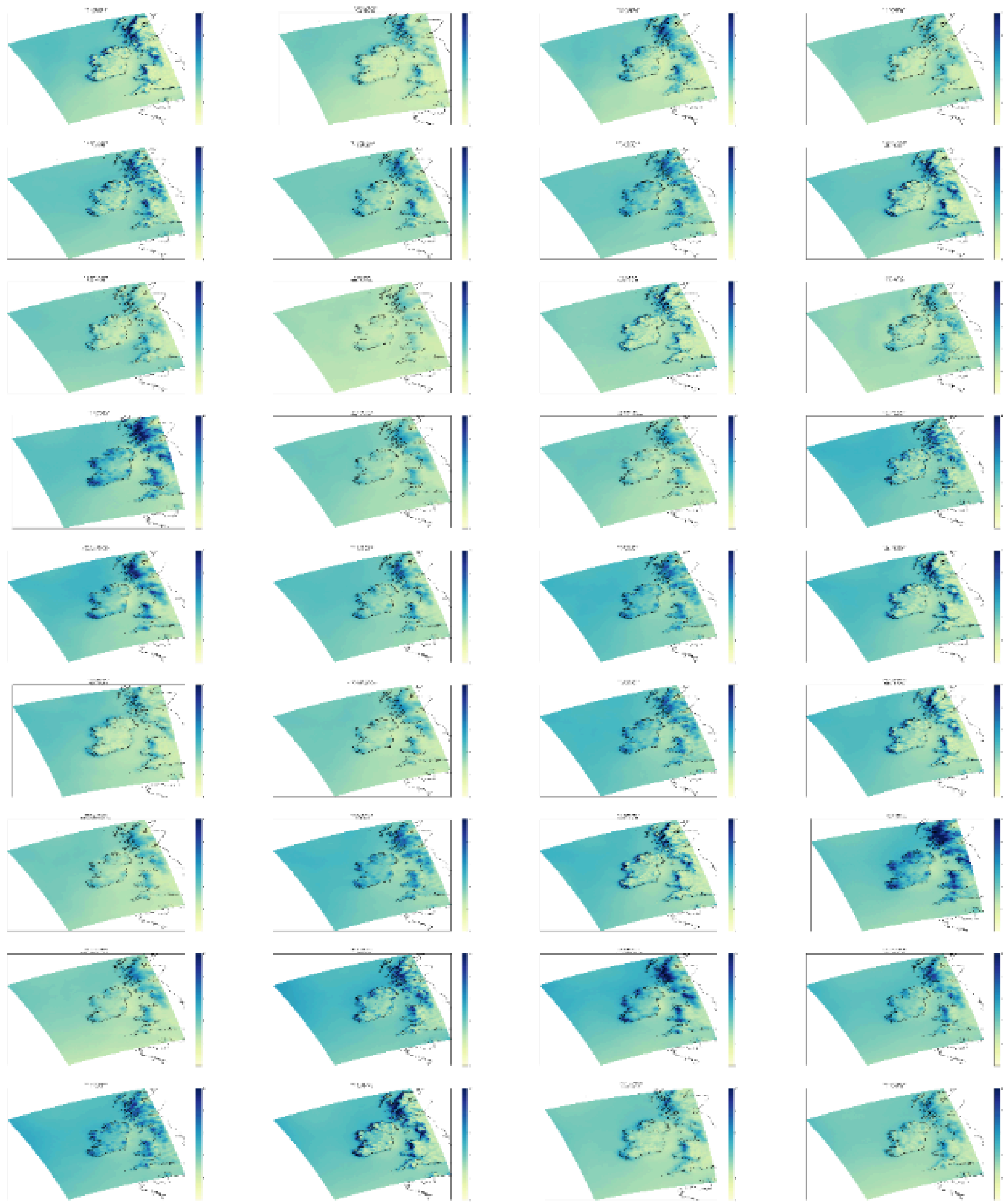
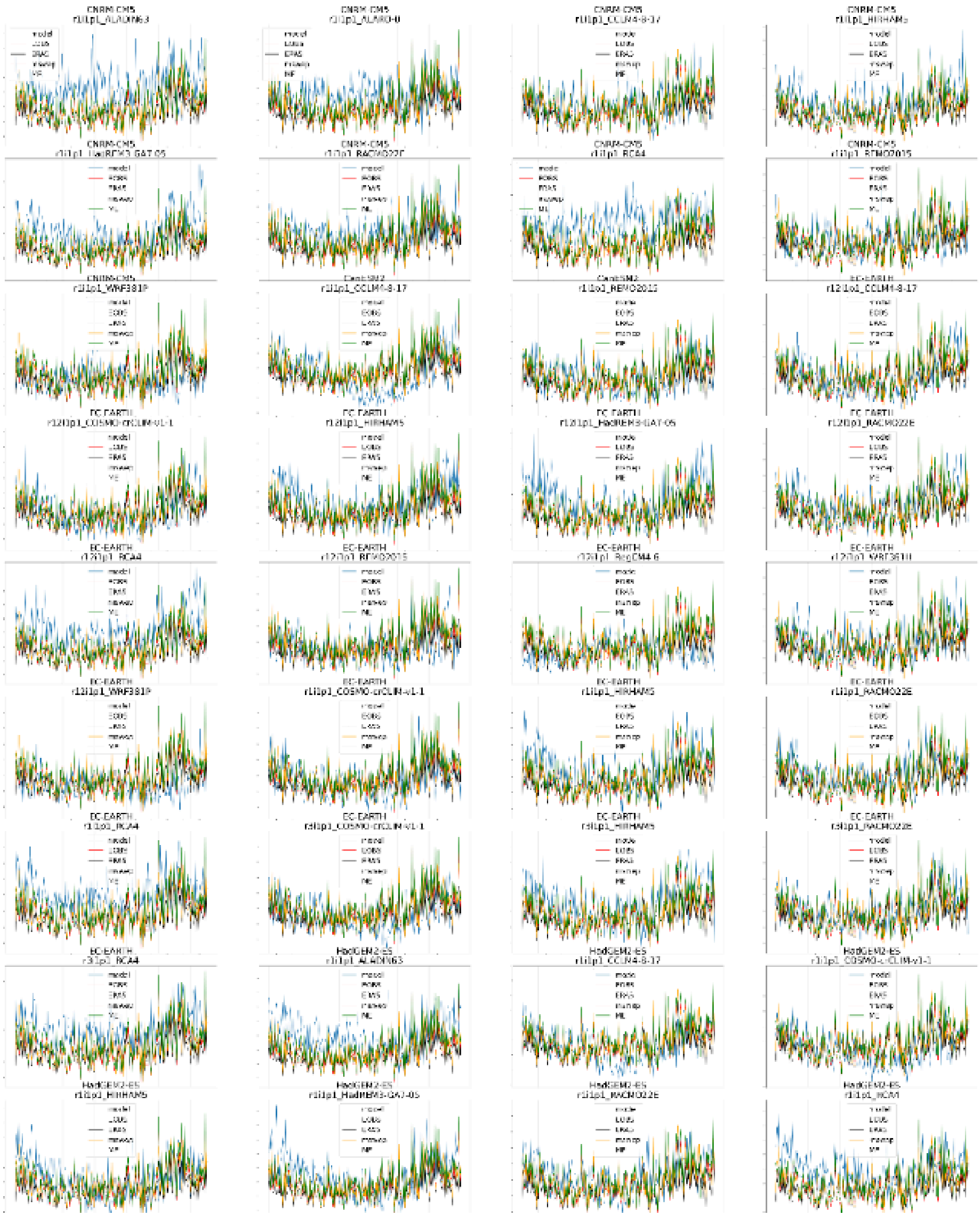


Figure A.2: Spatial patterns of 30-day precipitation in observations and CORDEX models.


CNRM-CM5
r1i1p1_ALADIN63
CNRM-CM5
r1i1p1_ALARO-0
CNRM-CM5
r1i1p1_CCLM4-8-17
CNRM-CM5
r1i1p1_HIRHAM5
CNRM-CM5
r1i1p1_HadREM3-GA7-05
CNRM-CM5
r1i1p1_RACMO22E
CNRM-CM5
r1i1p1_RCA4
CNRM-CM5
r1i1p1_REMO2015
CNRM-CM5
r1i1p1_WRF381P
CanESM2
r1i1p1_CCLM4-8-17
CanESM2
r1i1p1_REMO2015
EC-EARTH
r12i1p1_CCLM4-8-17
EC-EARTH
r12i1p1_COSMO-crCLIM-v1-1
EC-EARTH
r12i1p1_HIRHAM5
EC-EARTH
r12i1p1_HadREM3-GA7-05
EC-EARTH
r12i1p1_RACMO22E
EC-EARTH
r12i1p1_RCA4
EC-EARTH
r12i1p1_REMO2015
EC-EARTH
r12i1p1_RegCM4-6
EC-EARTH
r12i1p1_WRF361H
EC-EARTH
r12i1p1_WRF381P
EC-EARTH
r1i1p1_COSMO-crCLIM-v1-1
EC-EARTH
r1i1p1_HIRHAM5
EC-EARTH
r1i1p1_RACMO22E
EC-EARTH
r1i1p1_RCA4
EC-EARTH
r3i1p1_COSMO-crCLIM-v1-1
EC-EARTH
r3i1p1_HIRHAM5
EC-EARTH
r3i1p1_RACMO22E
EC-EARTH
r3i1p1_RCA4
HadGEM2-ES
r1i1p1_ALADIN63
HadGEM2-ES
r1i1p1_CCLM4-8-17
HadGEM2-ES
r1i1p1_COSMO-crCLIM-v1-1
HadGEM2-ES
r1i1p1_HIRHAM5
HadGEM2-ES
r1i1p1_HadREM3-GA7-05
HadGEM2-ES
r1i1p1_RACMO22E
HadGEM2-ES
r1i1p1_RCA4

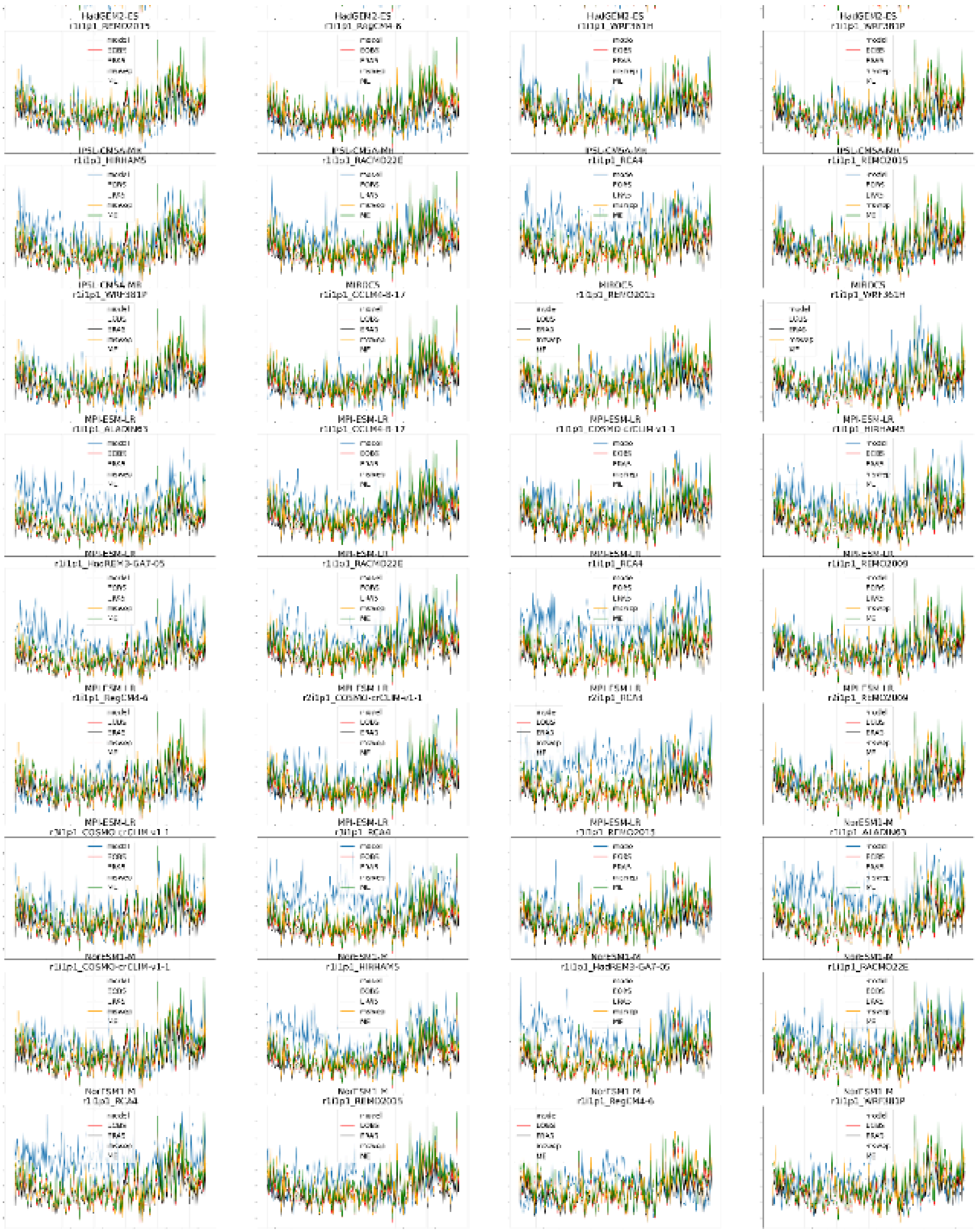
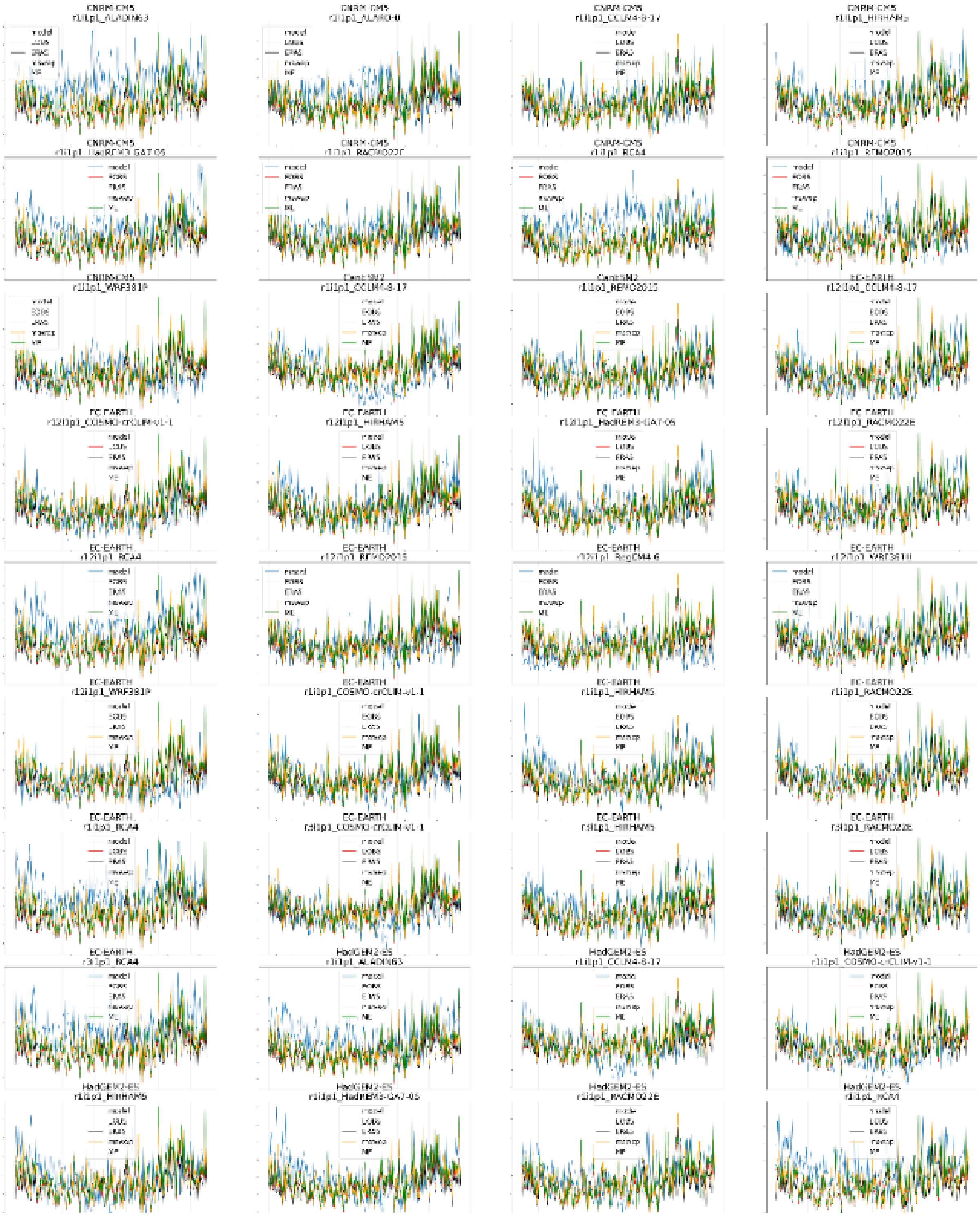


Figure A.3: Seasonal cycles of 2-day precipitation in observations, EOBS shown in red, ERA5 shown in black, MSWEP in yellow, Met Éireann in green, and CORDEX models, shown in blue.


CNRM-CM5 r1i1p1_ALADIN63
CNRM-CM5 r1i1p1_ALARO-0
CNRM-CM5 r1i1p1_CCLM4-8-17
CNRM-CM5 r1i1p1_HIRHAM5
CNRM-CM5 r1i1p1_HadREM3-GA7-05
CNRM-CM5 r1i1p1_RACMO22E
CNRM-CM5 r1i1p1_RCA4
CNRM-CM5 r1i1p1_REMO2015
CNRM-CM5 r1i1p1_WRF381P
CanESM2 r1i1p1_CCLM4-8-17
CanESM2 r1i1p1_REMO2015
EC-EARTH r12i1p1_CCLM4-8-17
EC-EARTH r12i1p1_COSMO-crCLIM-v1-1
EC-EARTH r12i1p1_HIRHAM5
EC-EARTH r12i1p1_HadREM3-GA7-05
EC-EARTH r12i1p1_RACMO22E
EC-EARTH r12i1p1_RCA4
EC-EARTH r12i1p1_REMO2015
EC-EARTH r12i1p1_RegCM4-6
EC-EARTH r12i1p1_WRF361H
EC-EARTH r12i1p1_WRF381P
EC-EARTH r1i1p1_COSMO-crCLIM-v1-1
EC-EARTH r1i1p1_HIRHAM5
EC-EARTH r1i1p1_RACMO22E
EC-EARTH r1i1p1_RCA4
EC-EARTH r3i1p1_COSMO-crCLIM-v1-1
EC-EARTH r3i1p1_HIRHAM5
EC-EARTH r3i1p1_RACMO22E
EC-EARTH r3i1p1_RCA4
HadGEM2-ES r1i1p1_ALADIN63
HadGEM2-ES r1i1p1_CCLM4-8-17
HadGEM2-ES r1i1p1_COSMO-crCLIM-v1-1
HadGEM2-ES r1i1p1_HIRHAM5
HadGEM2-ES r1i1p1_HadREM3-GA7-05
HadGEM2-ES r1i1p1_RACMO22E
HadGEM2-ES r1i1p1_RCA4
model
EOBS
ERA5
mswep
ML

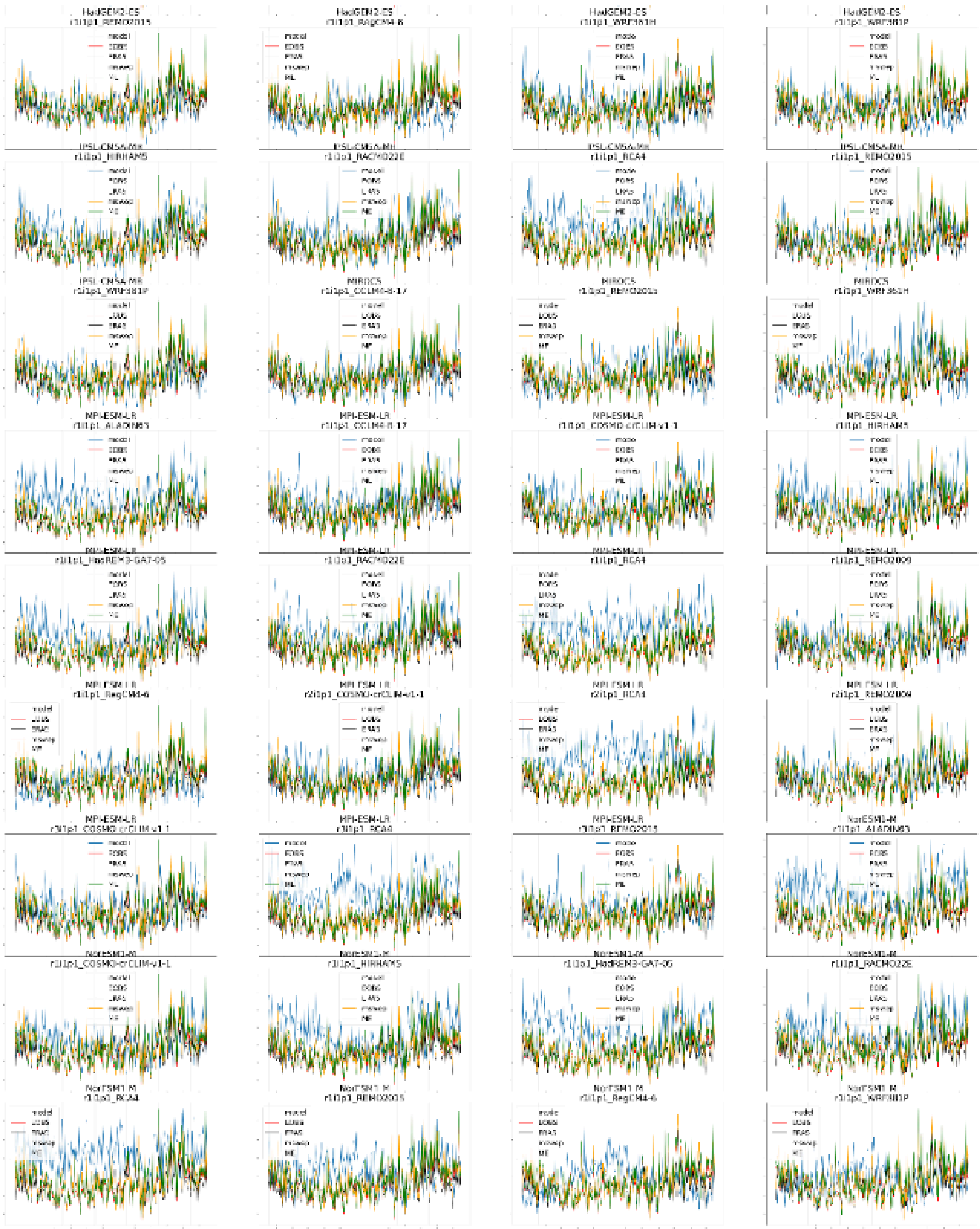


Figure A.5: Seasonal cycles of 30-day precipitation in observations, EOBS shown in red, ERA5 shown in black, MSWEP in yellow, Met Éireann in green, and CORDEX models, shown in blue.