Climate Change and Hydrology: From Observations to Projections

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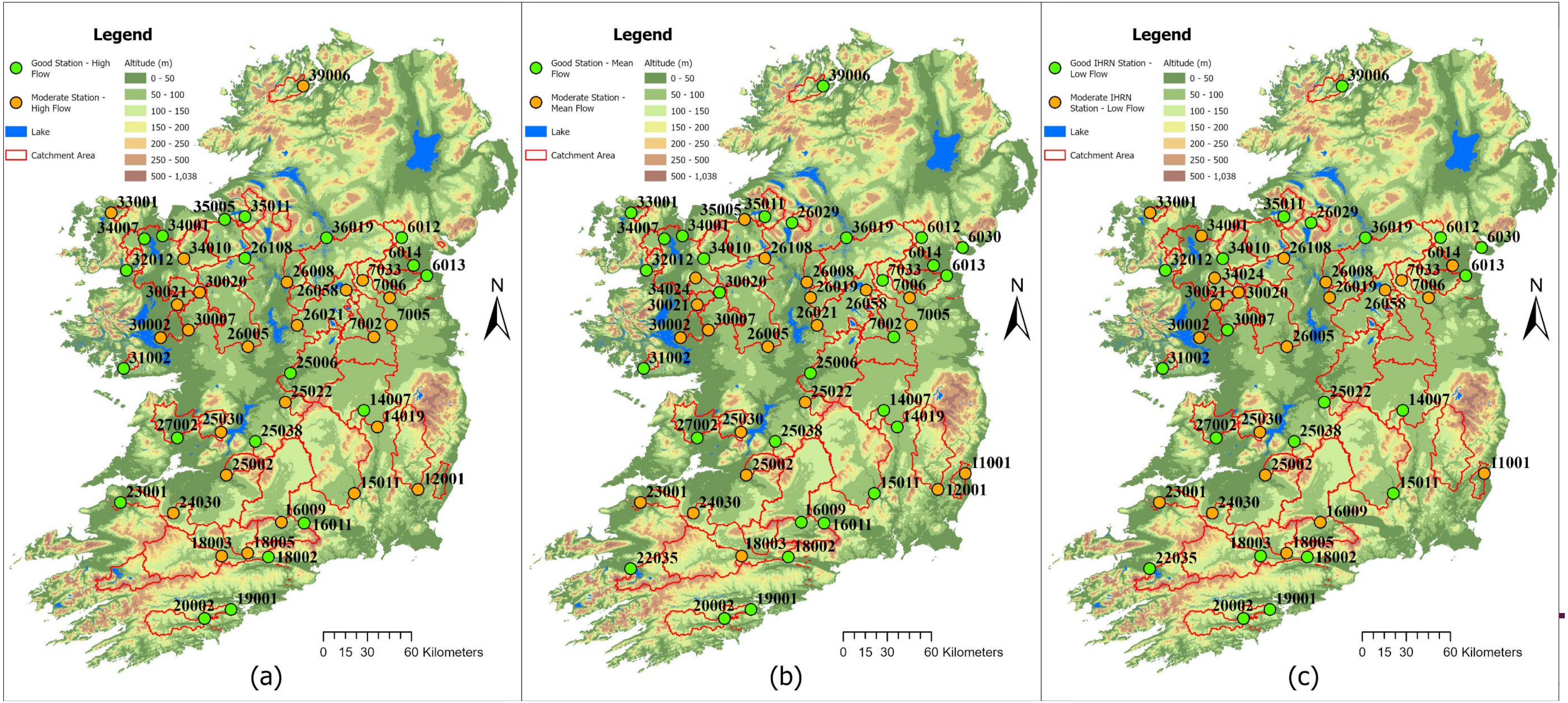
Met Éireann

Content from Recent and Ongoing Projects

- Part 1: Observations
  - Datasets, detection and attribution
  - Irish Hydrometric Reference Network V2 (IHRN) Project
  - HydroDARE: Detection and Attribution of Change in Hydrological Series
- Part 2: Projections
  - CMIP6 and Cordex simulations
  - HydroPredict Project
  - WaterFutures Project
- Acknowledge the researchers employed on these project and collaborators

Irish Hydrometric Reference Network

- Maps of IHRN stations suitable for flow assessment at high (a), mean (b), and low (c) flows.

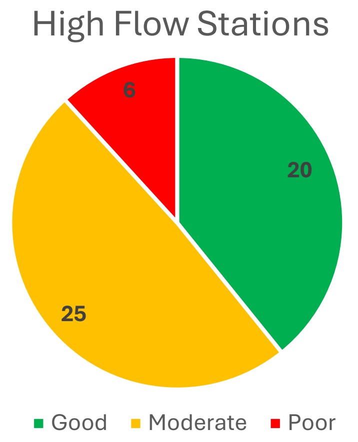


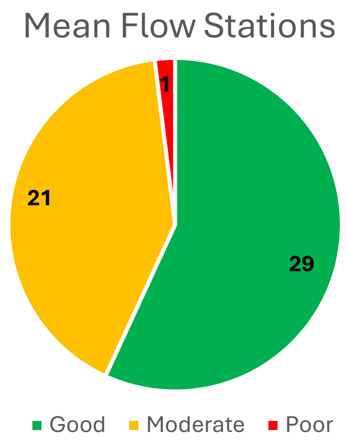
IHRN V2: Final Numbers

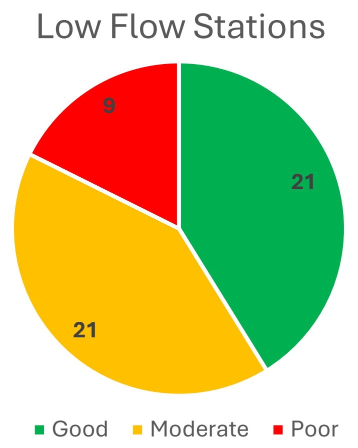
1. A total of 51 IHRN stations identified.
2. Station performances ranked at high, mean, and low flows as good = 1, moderate = 2 or poor = 3.
3. Stations noted as performing poor (red) are not employed in the IHRN for the given flow regime.

A	EK	EL	EM	EN	EO	EP	EQ
Stations	Latitude	Longitude	Nested	Nested Within	High_cat	Mean_cat	Low_cat
6012	54.093	-6.66514	No	0	1	1	1
6013	53.856	-6.41305	No	0	1	1	1
6014	53.921	-6.54864	No	0	1	1	1
6030	54.026	-6.2433	No	0	3	1	1
7002	53.488	-6.9699	Yes	7005	2	1	3
7005	53.556	-6.79095	No	0	2	2	2
7006	53.726	-6.80198	No	0	2	2	2
7033	53.834	-7.07771	Yes	7006	2	1	2
11001	52.643	-6.26984	No	0	3	2	2
12001	52.548	-6.5493	No	0	2	2	
14007	53.039	-7.08418	Yes	14019	1	1	1
14019	52.935	-6.94893	No	0	2	1	3
15005	52.847	-7.39717	Yes	15011	2	2	
15011	52.531	-7.18847	No	0	2	1	1
16009	52.357	-7.9222	Yes	16011	1	1	2
16011	52.351	-7.69383	No	0	1	1	1
16051	52.716	-7.79101	Yes	16011	2	3	2
18002	52.144	-8.05123	No	0	1	1	1
18003	52.149	-8.51473	Yes	18002	2	2	1
18005	52.168	-8.25827	Yes	18002	2	3	2
19001	51.822	-8.42089	No	0	1	1	1
20002	51.765	-8.68203	No	0	1	1	1
21002	51.738	-9.45103	No	0		1	2
22035	52.061	-9.61657	No	0	2	1	1
23001	52.468	-9.53386	No	0	1	1	1
24008	52.543	-8.76678	No	0	2		2

Final_River_Stations_List







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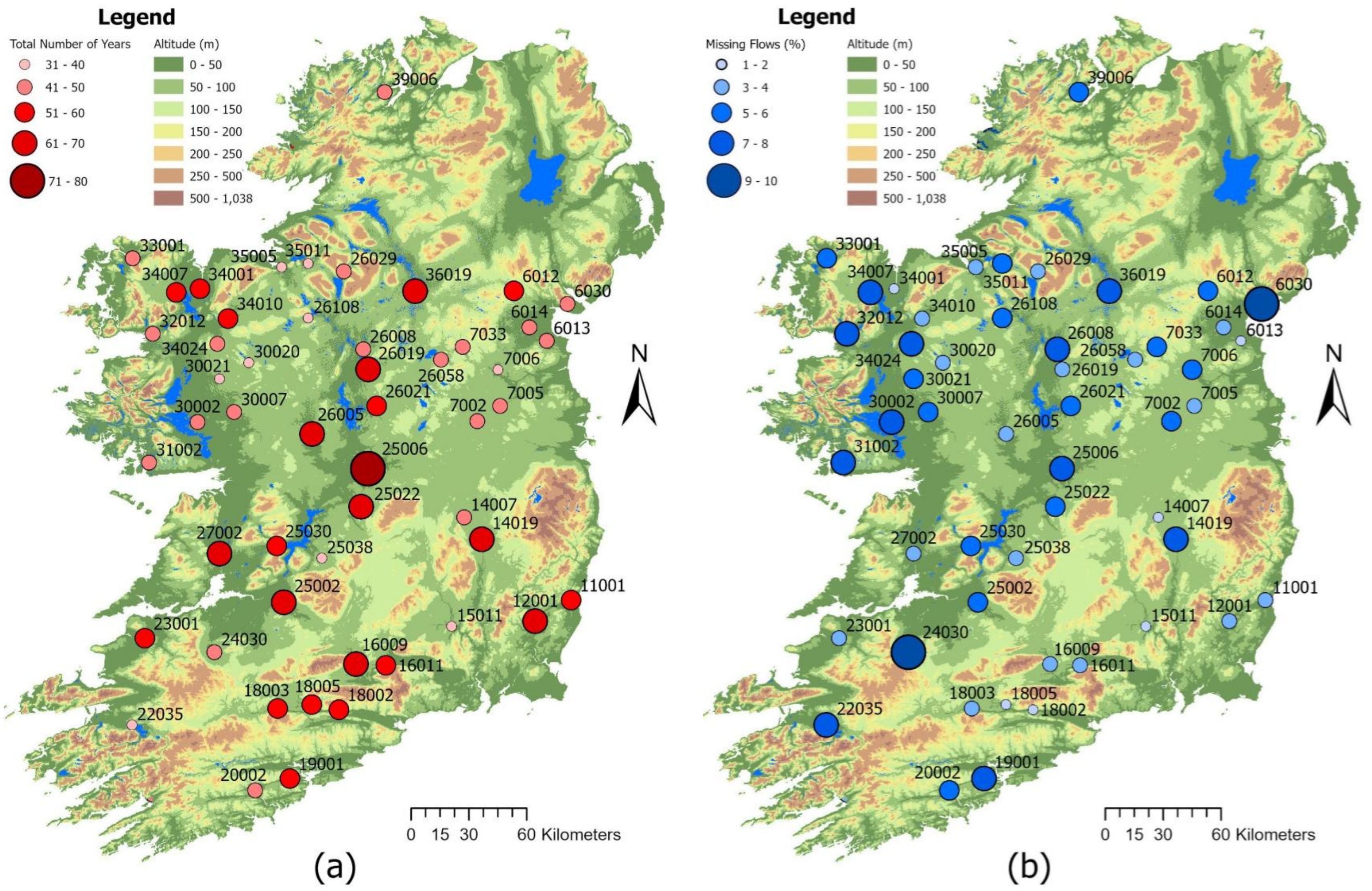
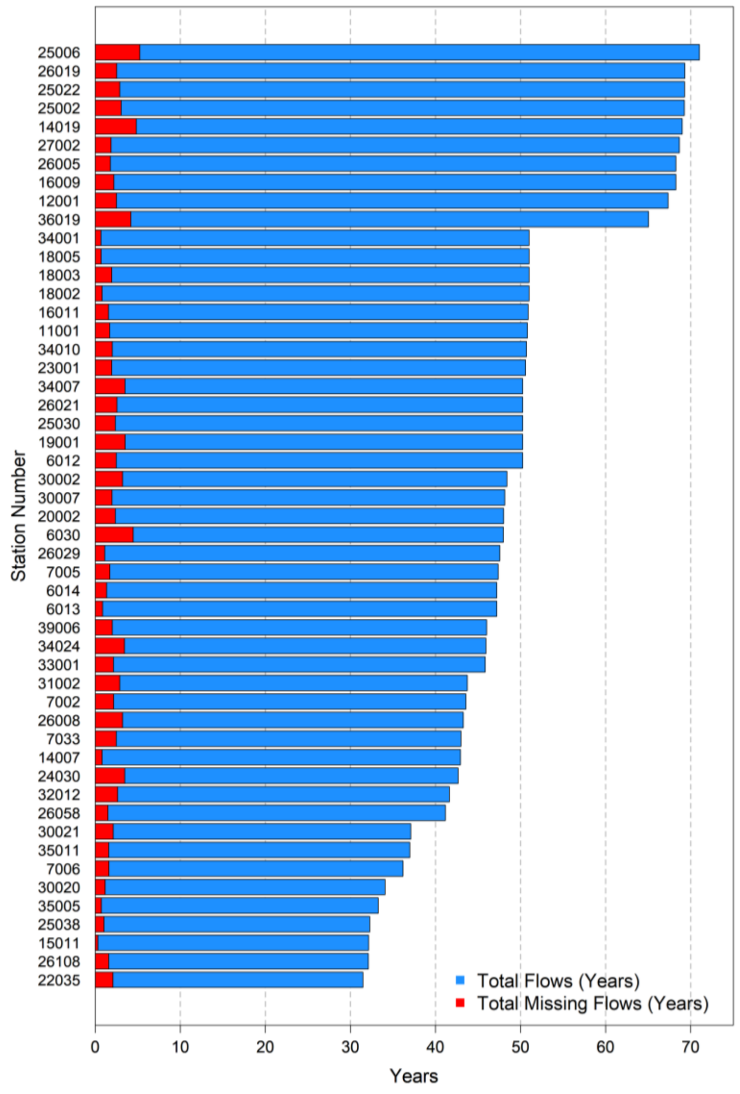
Missing Data

- Average record length – 49.2 years [31 to 71 years]; average missing data - 4.5 % [0.9 % to 9.3 %]



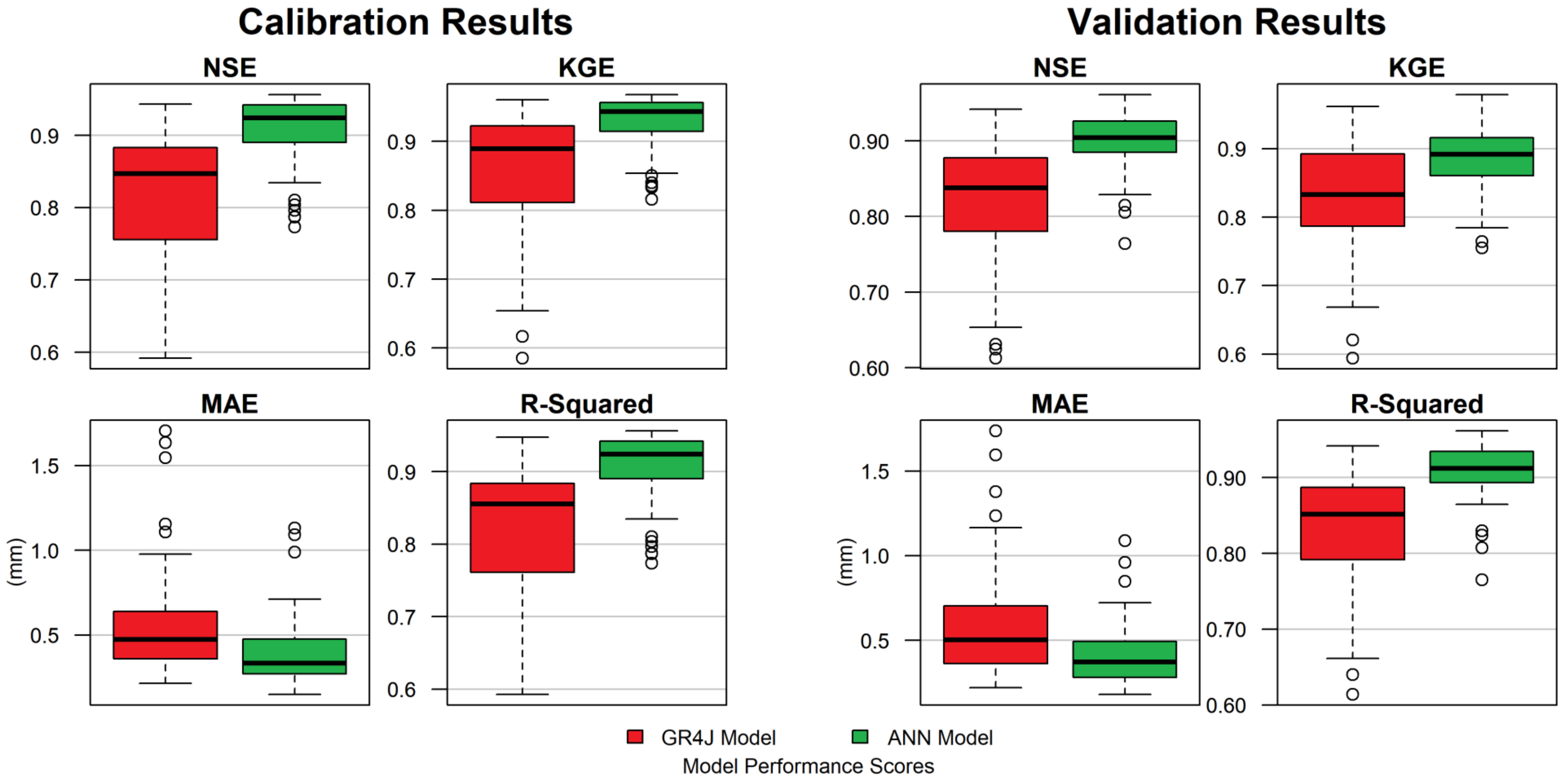


Infilling Missing Flows

1. Missing data modelled for all 51 IHRN stations from start of record till 2022.
2. Observations from Met Éireann 1km x 1km gridded dataset; ERA5 temperature data bias corrected (Q-mapping); Oudin's formula - PET.
3. GR4J (4 parameter lumped rainfall-runoff model) – generated daily flows from precipitation and PET inputs.
4. ANN (backpropagation neural network) – inputs included lagged GR4J flow, temperature, precipitation, precipitation lagged by one to four days.
5. Kling Gupta (KGE) and Nash Sutcliffe (NSE) objective functions used to identify best combination of parameter sets (GR4J) and neurons (ANN).

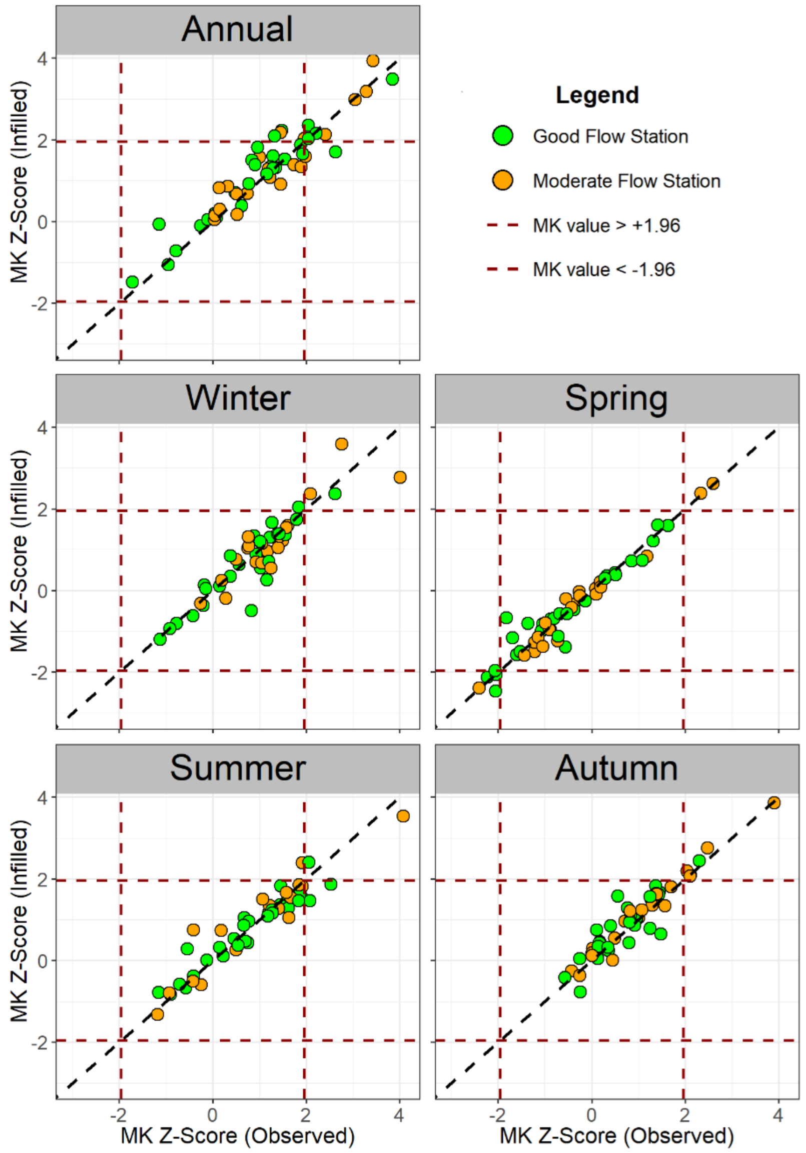
Hydrological Model Performances

- NSE, KGE, Mean Absolute Error (MAE) and R-squared values used to assess performance for the calibration (start year - 1999) and validation (2000-2022) periods.



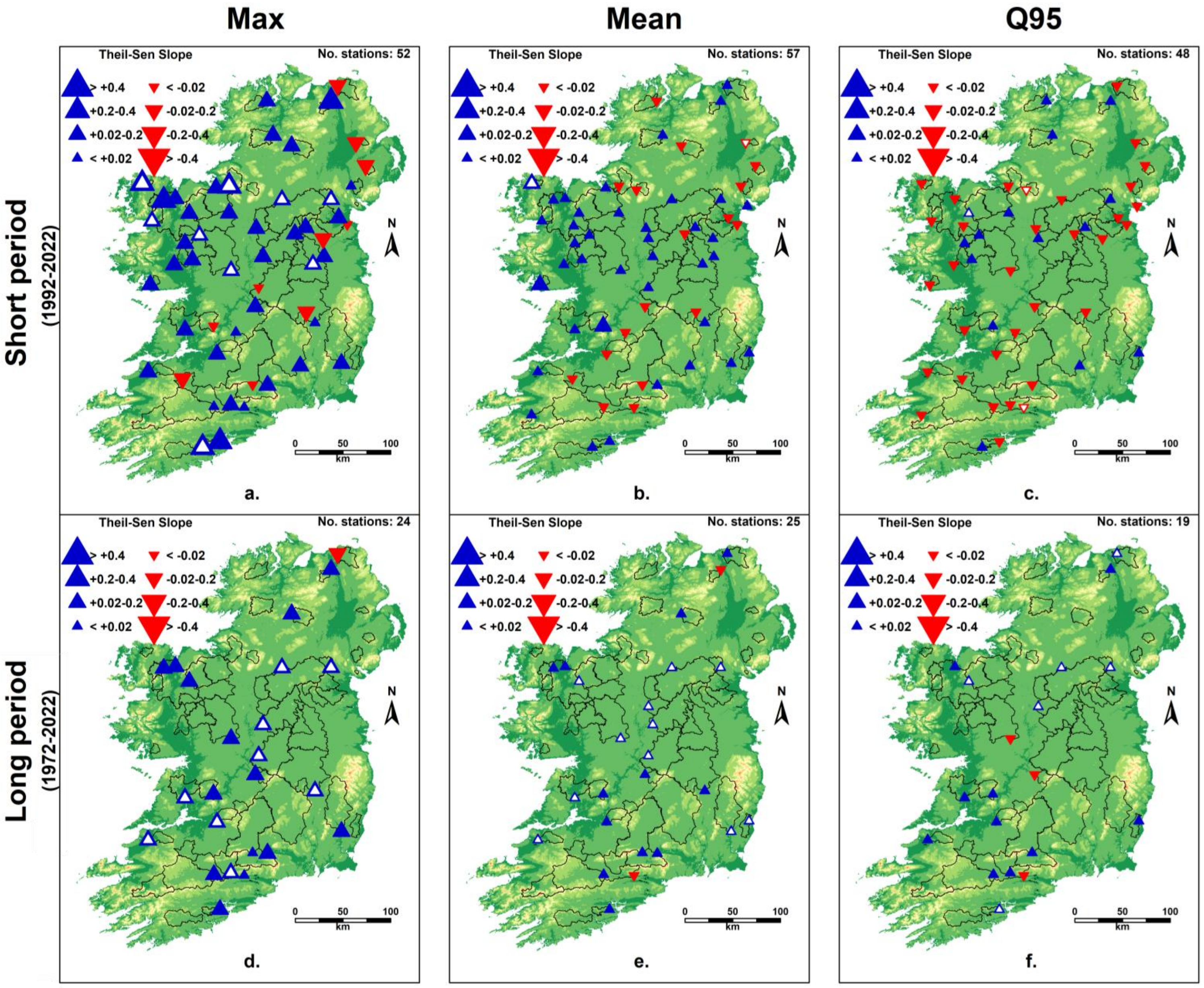
Infilled versus Observed Trends

- Trends determined using Mann Kendall (MK)
- Z statistic scores above (below) 1.96 (-1.96) represent significant increasing (decreasing) trends.
- MK scores initially derived for infilled and observed flows for full period for each station.
- Annual and seasonal values extracted and plotted.
- Trends showing good agreement in general - close to 1:1 reference line.

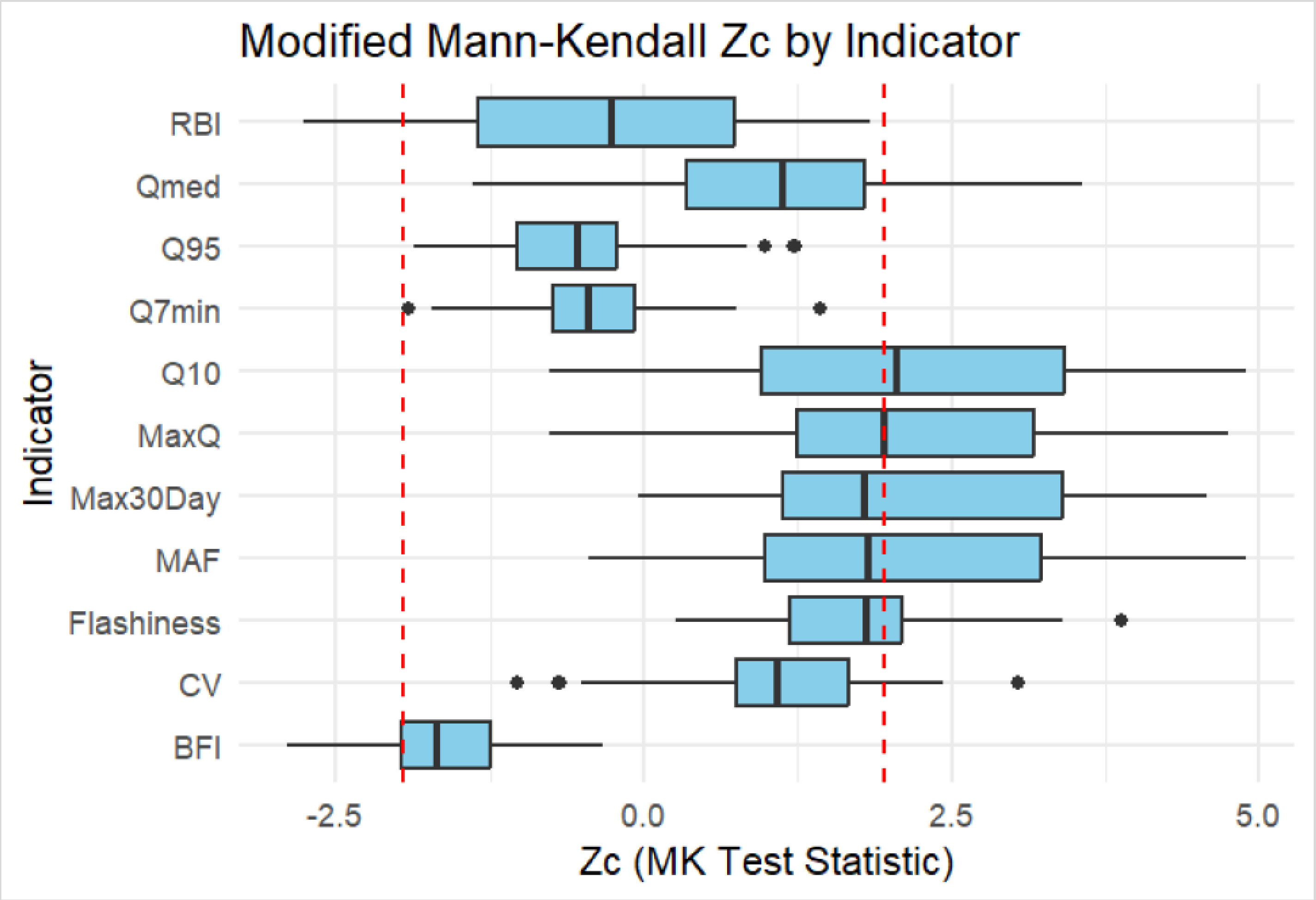


Annual Trend Magnitudes

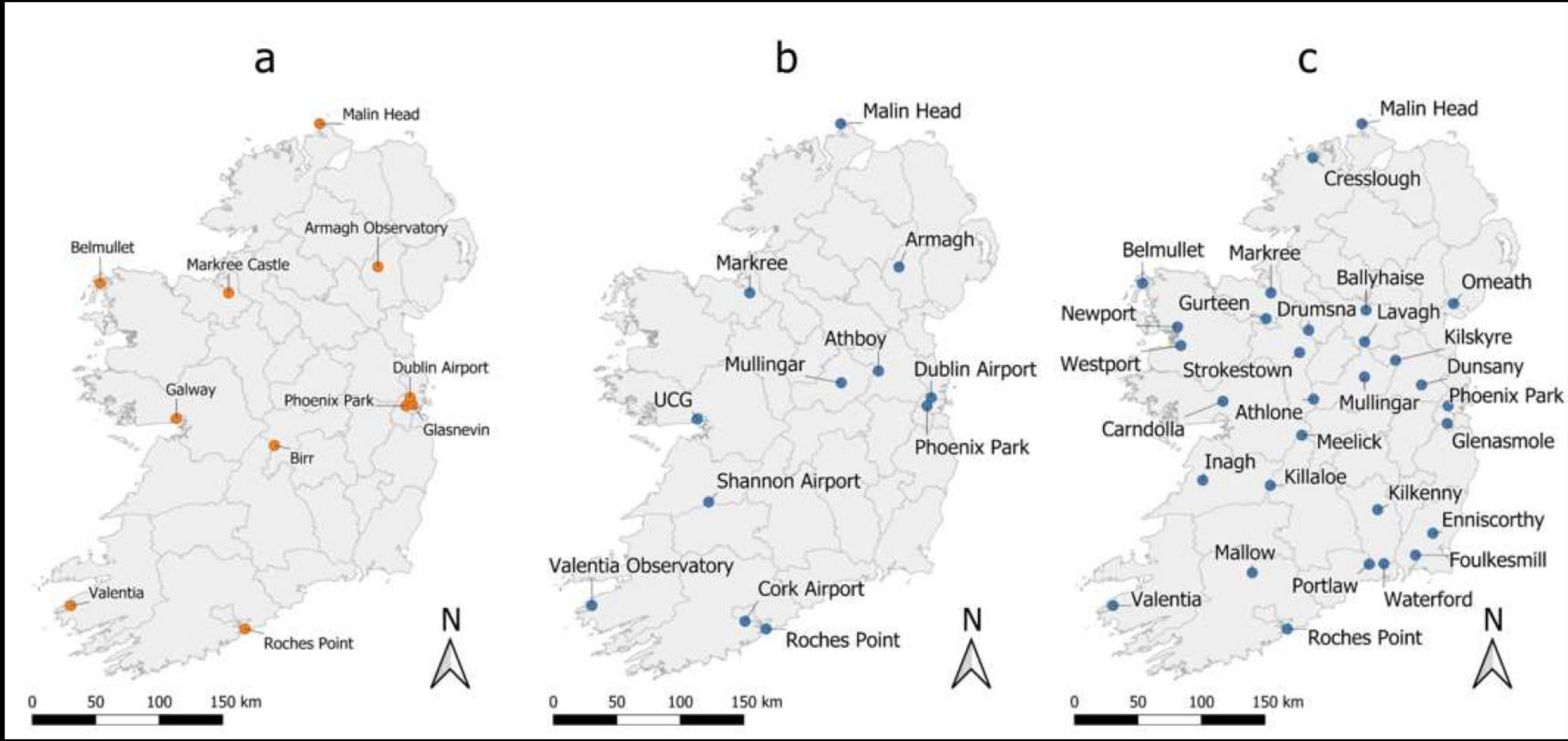
- Theil Sen's slope identified for annual infilled flows.
- This test identifies magnitude of change.
- White arrows are significant trends.
- Assessment of Long (1972-2022) versus Short (1992-2022) trends highlights importance of chosen period.
- Longer period identifies more statistically significant trends.



Trends in hydro indices from reconstructions 1941-2022



Emergence of a climate change signal: Leveraging long records in Ireland



Location of stations, updated to 2018, used for mean temperature (a), annual and seasonal precipitation totals (b) and extreme precipitation indices (c).

Table 1 Details of the ETCCDI temperature indices evaluated for each station. Tick marks indicate which indices were assessed for annual (Ann), winter (W), spring (Sp), summer (S) and autumn (A) series. TX refers to daily maximum air temperature, TN to daily minimum air temperature, TM to daily mean air temperature, SCN to standard climate normal period 1961-1990.

Name	Acronym	Units	Definition	Type	Ann	W	Sp	S	A
Cold spell duration	CSDI	Days	Annual count of days with at least 6 consecutive days when TN < 10th percentile of SCN	Duration	√				
Warm spell duration	WSDI	Days	Annual count of days with at least 6 consecutive days when TX > 90th percentile of SCN	Duration	√				
Frost days	FD	Days	Annual Count when TN < 0°C	Threshold	√	√	√		√
Growing season length	GSL	Days	Annual Count between the first span of at least 6 days with TM > 5°Cand first span after july 1st of 6 days with TM < 5°C	Duration	√				
Diurnal temperature range	DTR	°C	Monthly mean difference between TX and TN	Absolute	√	√	√	√	√
Ice days	ID	Days	Annual count TX < 0 °C	Threshold		√			
Coldest night	TNn	°C	Monthly minimum value of TN	Absolute	√	√	√	√	√
Hottest night	TNx	°C	Monthly maximum value of TN	Absolute	√	√	√	√	√
Hottest day	TXx	°C	Monthly maximum value of TX	Absolute	√	√	√	√	√
Coldest day	TXn	°C	Monthly minimum value of TX	Absolute	√	√	√	√	√
Cool days	TX10p	Days	% of days when TX < 10th percentile of SCN	Percentile	√	√	√	√	√
Cool nights	TN10p	Days	% of days when TN < 10th percentile of SCN	Percentile	√	√	√	√	√
Warm nights	TN90p	Days	% of days when TN > 90th percentile of SCN	Percentile	√	√	√	√	√
Warm days	TX90p	Days	% of days where TX > 90th percentile of SCN	Percentile	√	√	√	√	√

Table 2 Definitions of the five ETCCDI precipitation indices analysed.

Name	Acronym	Units	Definition
Maximum 1-day precipitation amount	RX1day	mm	Annual maximum 1-day precipitation
Maximum 5-day precipitation amount	RX5day	mm	Annual maximum consecutive 5-day precipitation
Simple daily intensity index	SDII	mm/day^{-1}	Ratio of annual total precipitation to number of wet days (≥1 mm)
Very wet days	R95pTOT	mm	Annual sum of precipitation on days when precipitation exceeds the 95th percentile of daily precipitation in the base period (1961-1990)
Extremely wet days	R99pTOT	mm	Annual sum of precipitation on days when precipitation exceeds the 99th percentile of daily precipitation in the base period (1961-1990)

Indicators analysed and method

- Large number of temperature and precipitation extremes, together with annual and seasonal mean temperature and precipitation

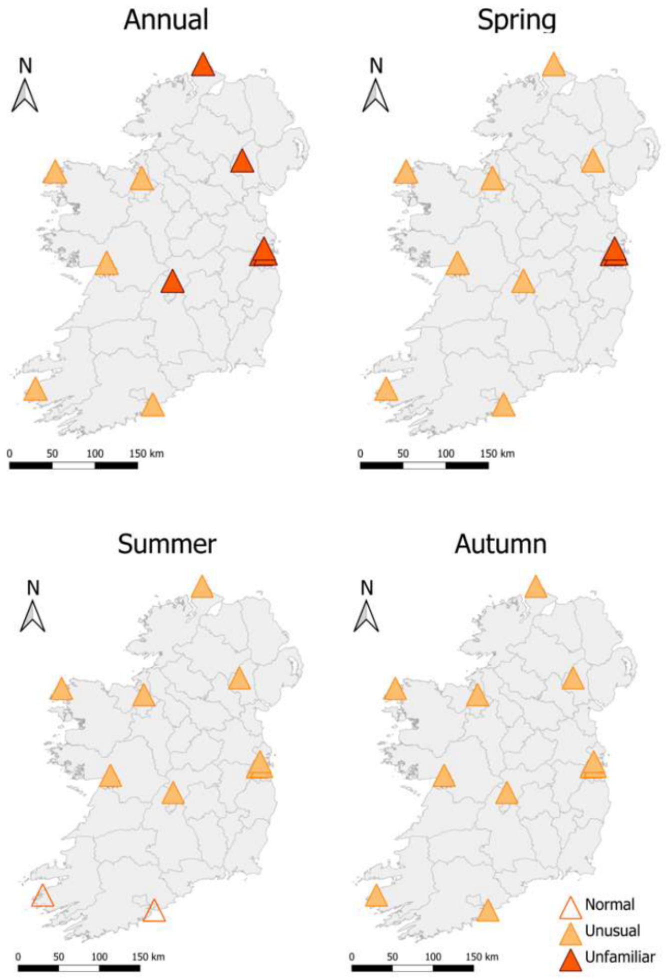
- We produce estimates of the signal to noise ratio (S/N) for changes in observed climate indices by linearly regressing local variations in climate onto annual Global Mean Surface Temperature (GMST) change.

$$L(t) = \propto G(t) + \beta$$

- $L(t)$ is the local change in temperature and precipitation indices; $G(t)$ is a smoothed version of GMST anomalies; ∝ is the linear scaling between L and G; β is a constant. Significance evaluated at the 0.10 level

- We apply the terminology of Frame et al. (2017) to describe how climate has changed from being normal or familiar ($SN <|1|$), to being unusual ($SN >|1|< |2|$)), unfamiliar ($S/N >|2|<|3|$), and unknown ($SN >|3|$), relative to the early industrial period.

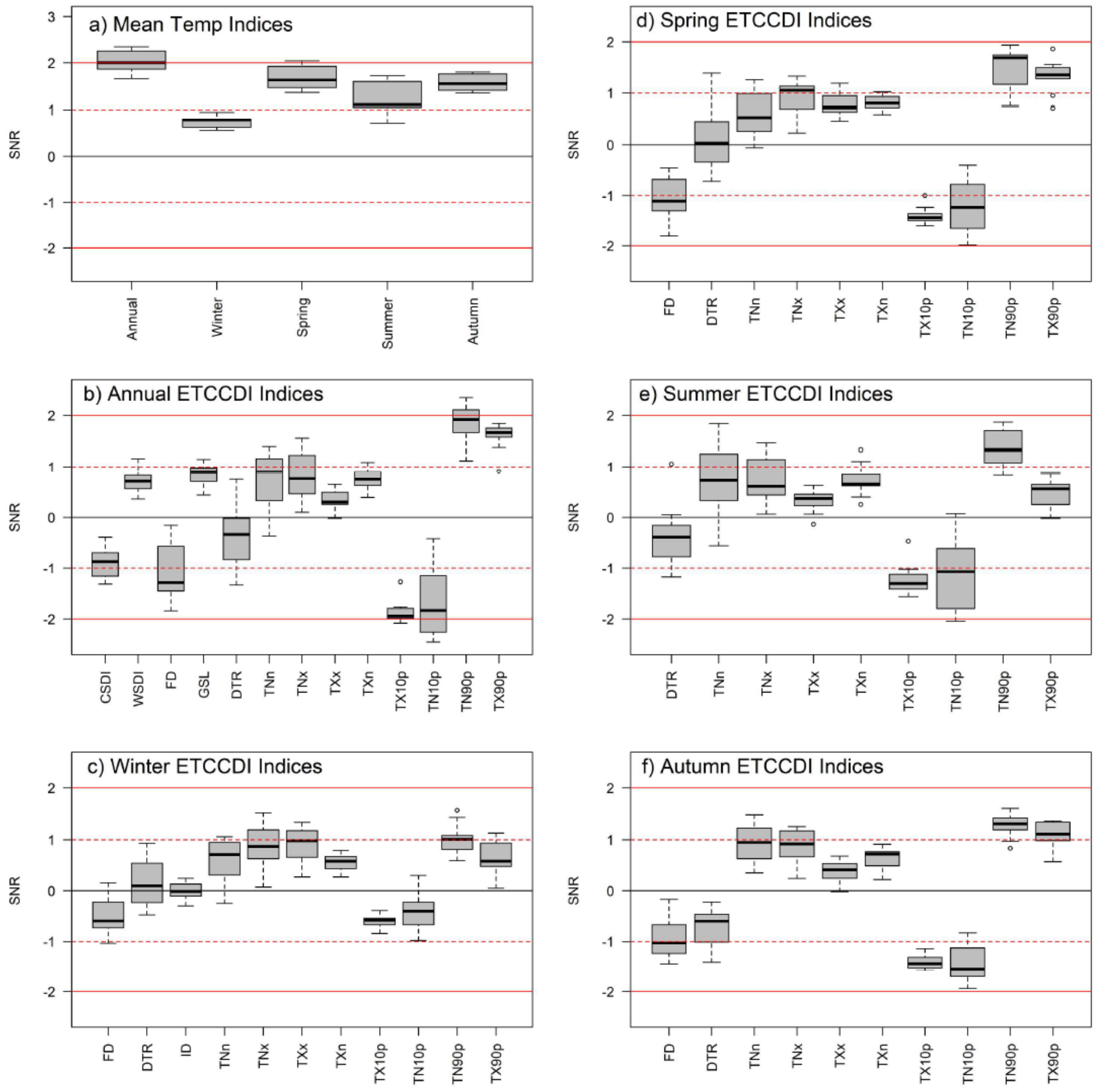
Annual and Seasonal Temperature (note winter missing)



Annual Mean Temp	alpha (ºC)	p-value	SNR
Phoenix Park	1.14	0.00	2.34
Glasnevin	1.11	0.00	2.34
Dublin	1.05	0.00	2.23
Armagh	1.05	0.00	2.27
Birr	1.05	0.00	2.22
Roches Point	0.63	0.00	1.66
Malin Head	0.77	0.00	2.00
Markree	0.72	0.00	1.81
Galway	0.71	0.00	1.83
Valentia	0.72	0.00	1.94
Belmullet	0.74	0.00	1.89
Island of Ireland	0.88	0.00	2.14

Alpha: Scaling of change to GMST

Overview of all temperature indices

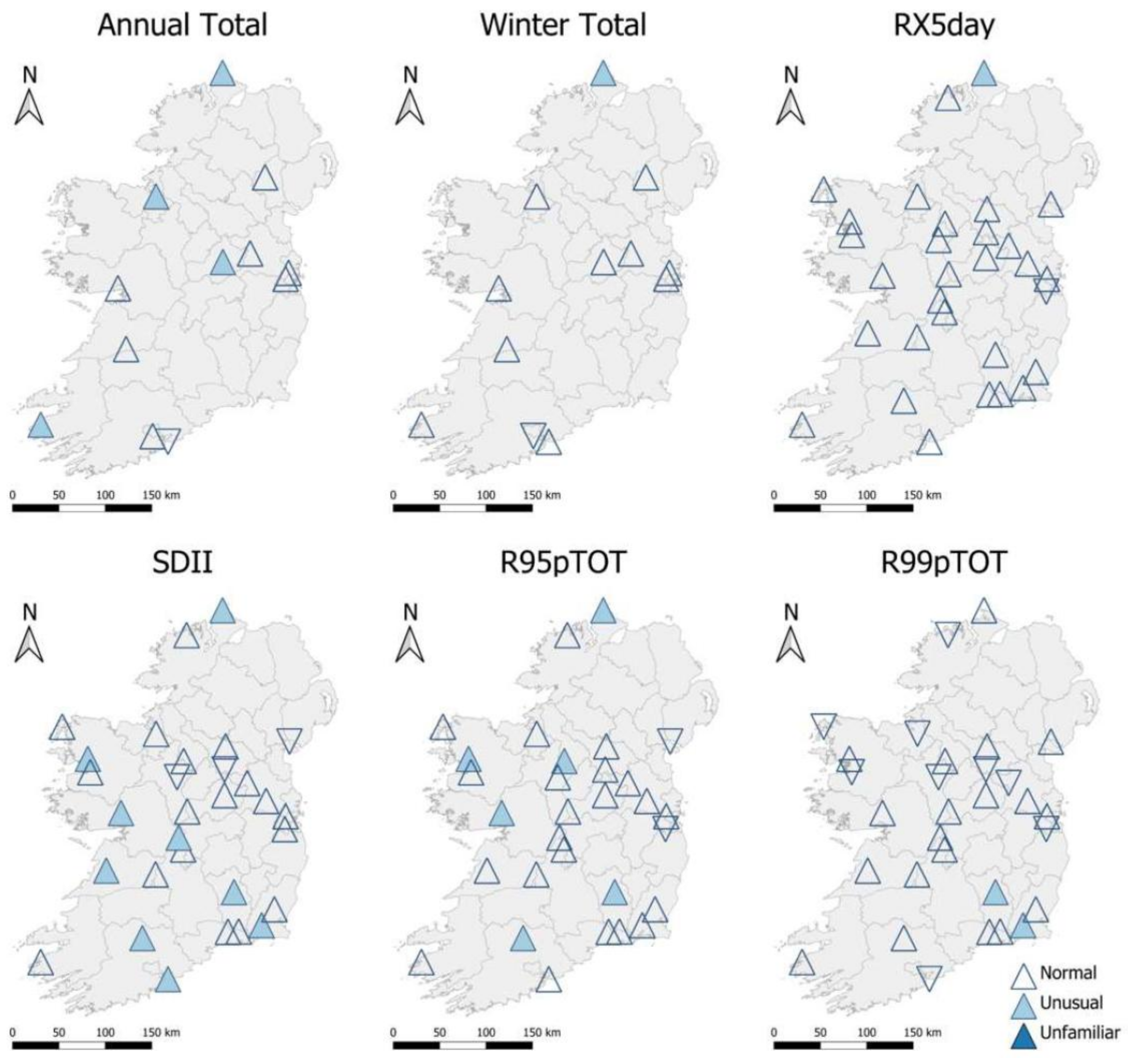


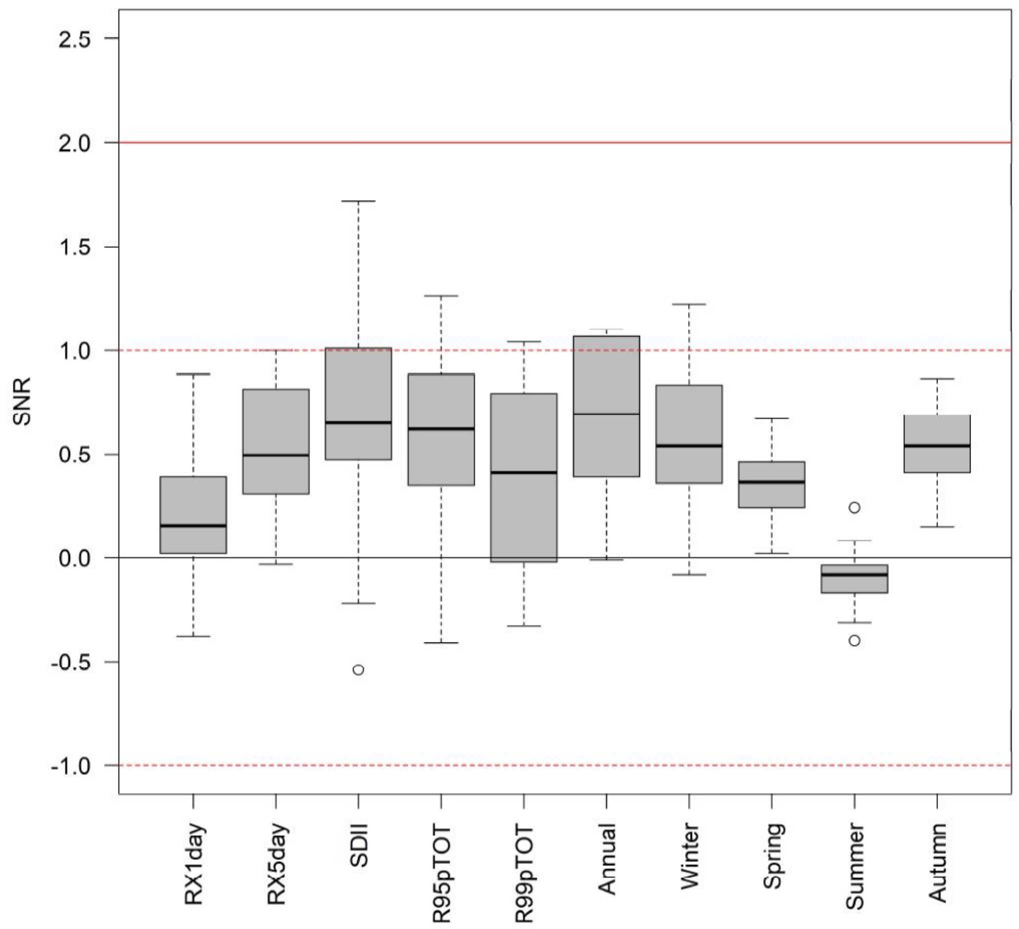
For the ETCCDI temperature indices cool days (TX10p), cool nights (TN10p), warms days (TX90p) and warm nights (TN90p) show the largest SNR of all indices annually and seasonally

Seasonally, spring shows the greatest proportion of stations/ETCCDI indices where the warming signal emerges as at least unusual relative to early industrial, with notable decreases in frost days (FD) apparent.

While hot days are often associated with climate change in the public imagination, we find few significant relationships between the hottest day (TXx) and GMST across stations and seasons, with no evidence for the emergence of a climate change signal in this indicator.

Precipitation indices



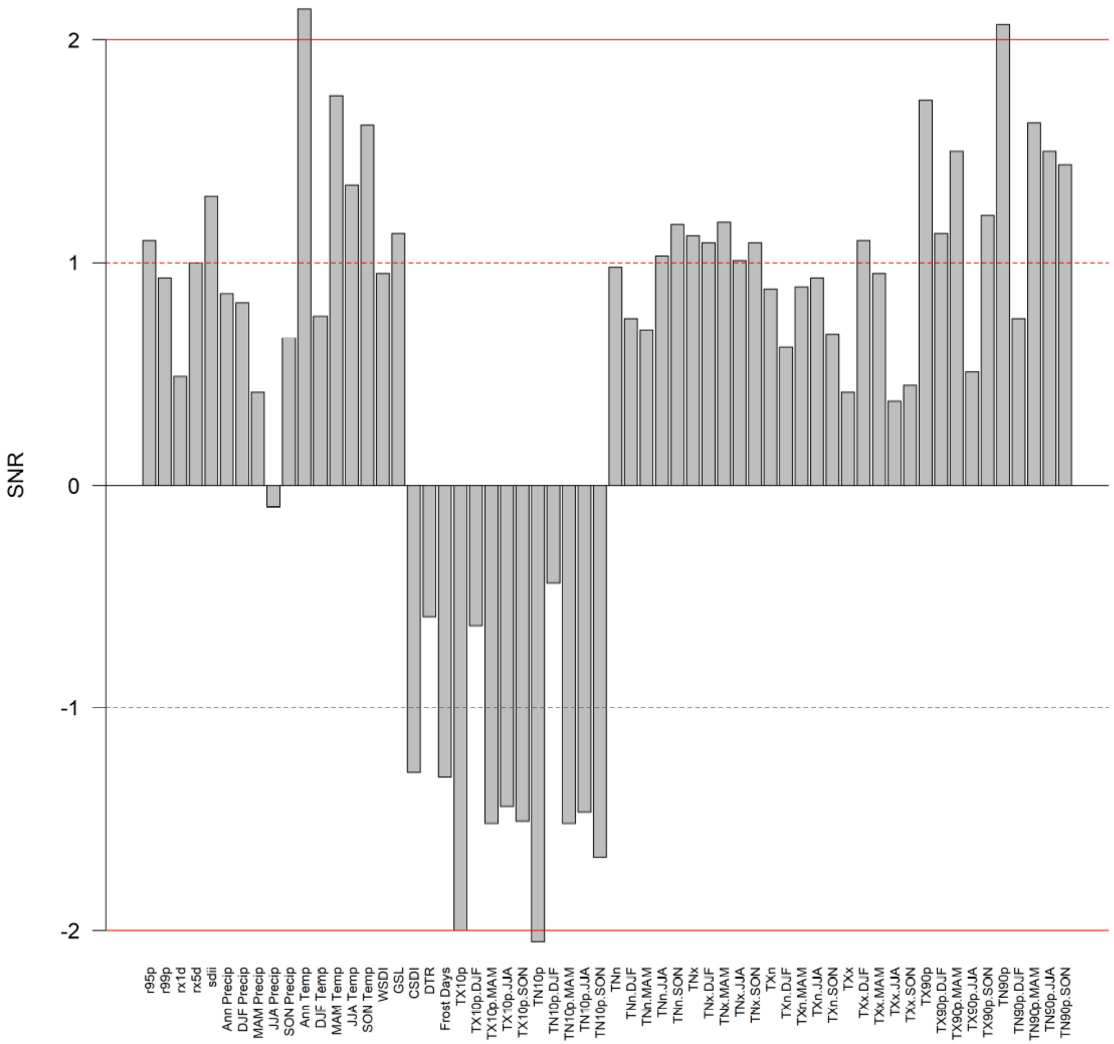


Note: summer precipitation shows no significant relationship (0.1 level) with GMST at any station

Scaling of SDII to GMST: Consistent with CC relationship

Simple daily intensity index (SDII)	alpha (%)	p-value	alpha.se	avg obs	signal	noise	SNR
Foulkesmills (s108)	8.00	0.00	0.18	6.94	0.69	0.68	1.01
Inagh (Mt. Callan s417)	7.66	0.00	0.19	8.08	0.77	0.72	1.07
Mallow (Hazelwood s706)	9.60	0.00	0.14	5.84	0.69	0.55	1.25
Mullingar (s875)	6.37	0.00	0.12	5.56	0.44	0.46	0.96
Cresslough (s944)	5.42	0.05	0.18	6.47	0.43	0.66	0.66
Roches Point (s1075)	7.58	0.00	0.16	6.20	0.58	0.58	1.00
Newport (s1175)	13.77	0.00	0.17	6.90	1.18	0.69	1.71
Dunsany (s1375)	6.28	0.00	0.11	5.37	0.42	0.42	0.98
Meelick (Victoria Lock s1519)	9.57	0.00	0.15	5.32	0.63	0.56	1.12
Malin Head (s1575)	9.99	0.00	0.14	5.54	0.69	0.54	1.28
Carndolla (s2227)	13.85	0.00	0.15	5.72	0.98	0.62	1.59
Enniscorthy (s4015)	7.03	0.01	0.18	6.42	0.56	0.66	0.85
Kilkenny (s4513)	13.65	0.00	0.13	5.47	0.92	0.54	1.72
Kilaloe Dock (s6019)	6.39	0.01	0.16	6.97	0.55	0.61	0.91
Portlaw (Mayfield s8212)	7.44	0.02	0.22	7.15	0.66	0.80	0.83
Island of Ireland	5.64	0.00	0.09	6.13	0.43	0.33	1.30

Island of Ireland Scale



Four indices show the emergence of unfamiliar climate (SNR > 2)

Annually the number of cool days (TX10p) and cool nights (TN10p) have decreased to unfamiliar levels with a SNR of -2.00 and -2.05, respectively.

Largest increases are evident for warm nights (TN90p) and annual mean temperature, which show a SNR of 2.07 and 2.14, respectively. TN90p has increased 6.84 percent per degree warming in GMST

Largest SNR was found for annual mean temperature with warming for the island of Ireland composite series estimated at 0.88oC per degree increase in GMST

Trends in seasonal rainfall extremes

Winter

- ➢Strong west–east gradient: significant increases in the west, decreases or weak trends in the east.

- ➢PRCPTOT and Rx5day show the most robust increases (up to ~19% in the west).

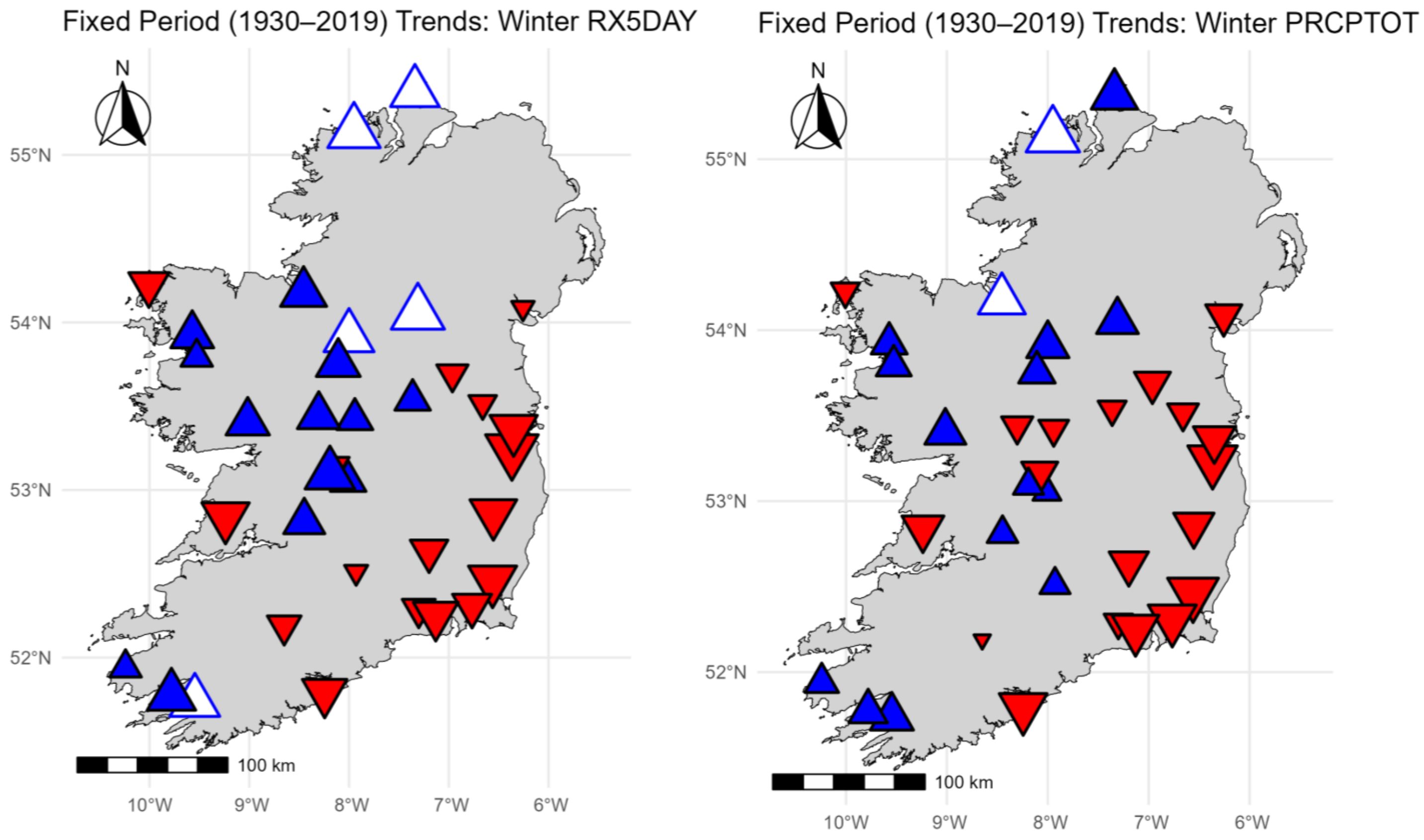


Figure: Magnitude and direction of trends fixed period for winter Rx5day and PRCPTOT. Blue triangles represent increasing trends and red decreasing trends, with magnitude proportional to size. Significant trends (0.05 level) shown by white triangles and derived from MKZs values.

Trends in seasonal rainfall extremes

Spring

- Widespread increases across all indicators, especially in the west.
- PRCPTOT shows the strongest increases (up to ~27% in the west).
- Short-duration extremes (Rx1day, Rx3day, Rx5day) also increasing significantly.

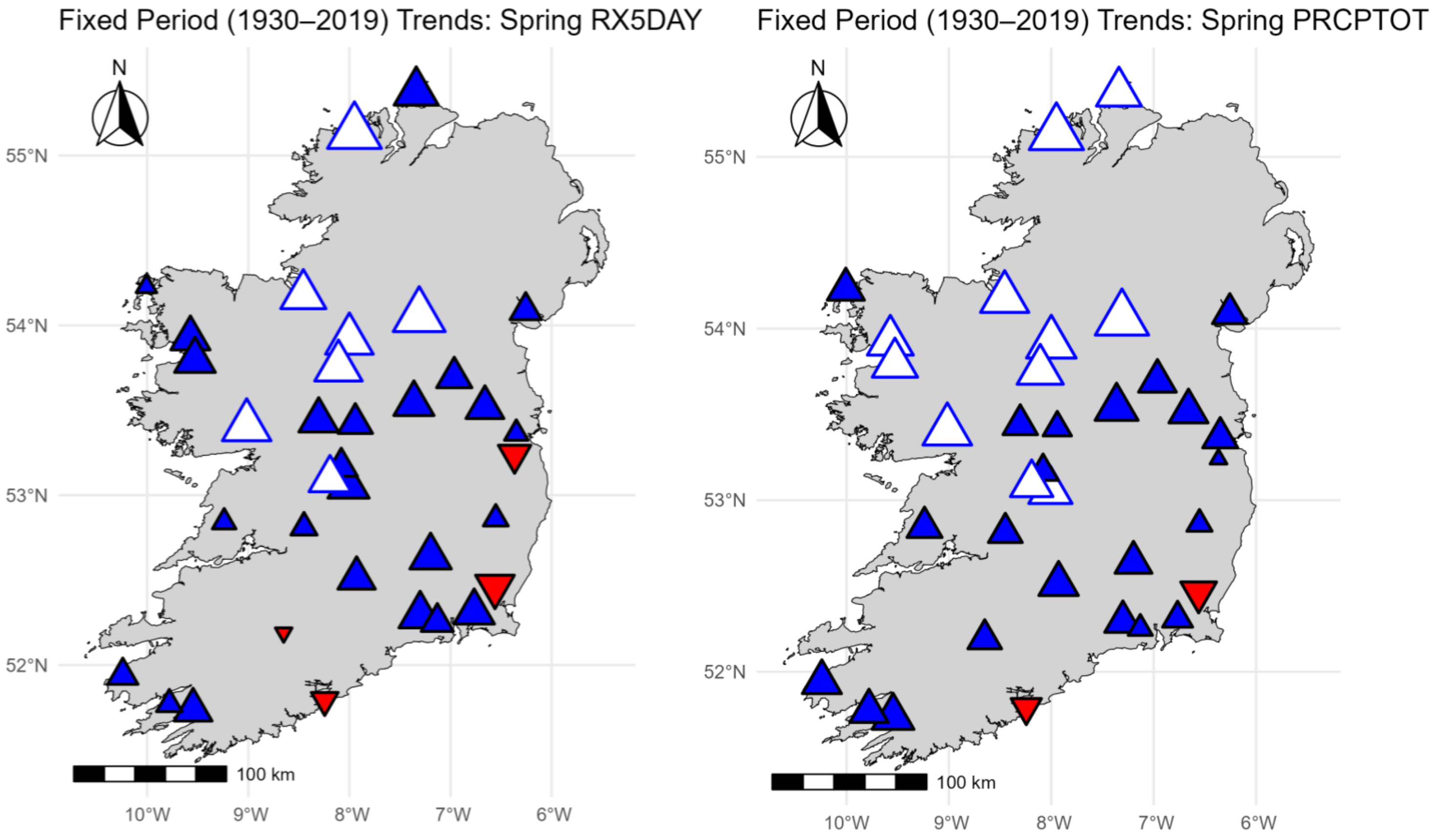


Figure: Magnitude and direction of trends fixed period for spring Rx5day and PRCPTOT. Blue triangles represent increasing trends and red decreasing trends, with magnitude proportional to size. Significant trends (0.05 level) shown by white triangles and derived from MKZs values.

Trends in seasonal rainfall extremes

Summer

- Regional divergence: decreasing trends in the west, increasing intensity in the southeast.
- WD shows significant declines in the southeast (up to –25%).
- SDII increases in the southeast suggest fewer but more intense events.

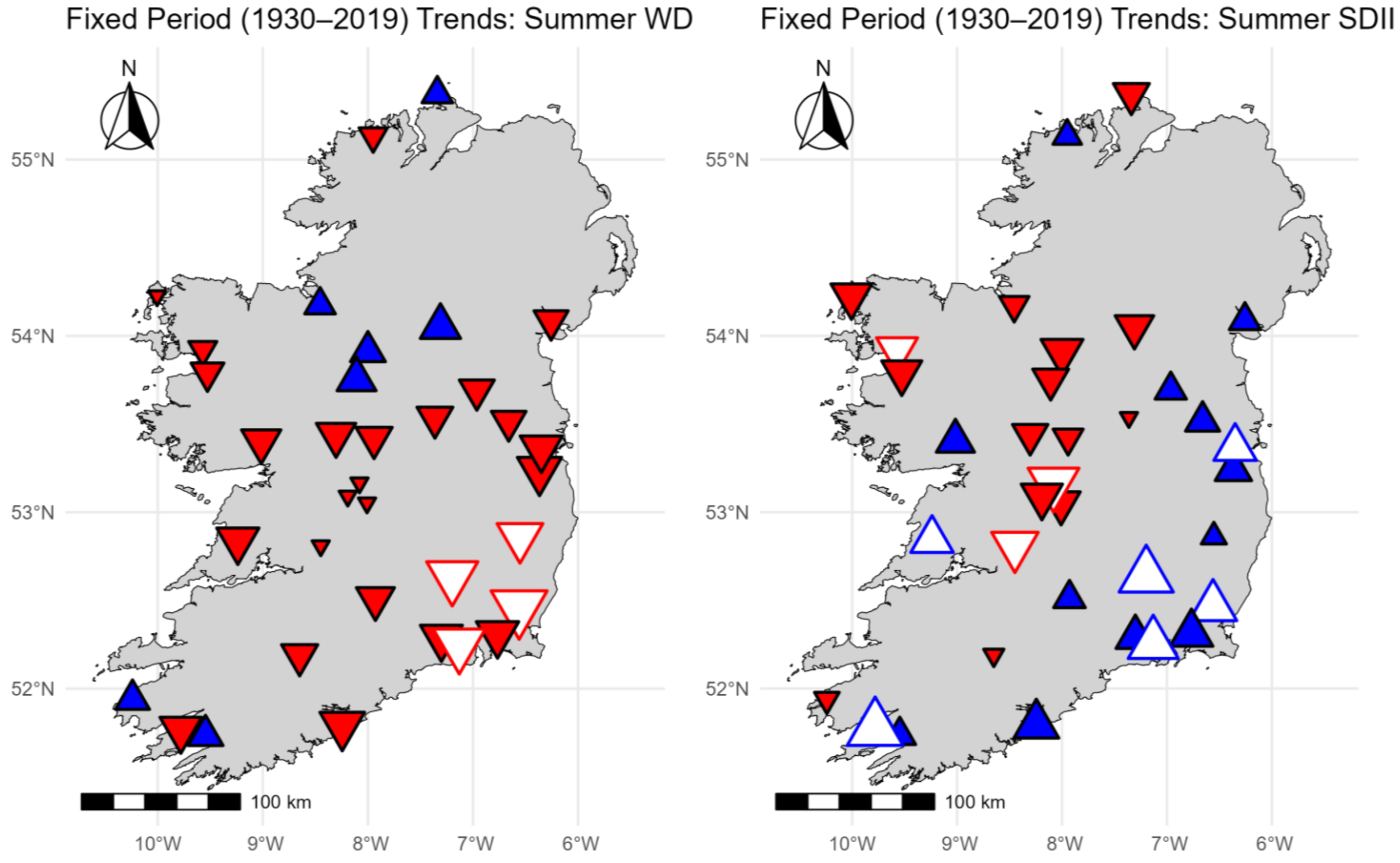


Figure: Magnitude and direction of trends fixed period for summer WD and SDII. Blue triangles represent increasing trends and red decreasing trends, with magnitude proportional to size. Significant trends (0.05 level) shown by white triangles and derived from MKZs values.

Trends in seasonal rainfall extremes

Autumn

- Few significant trends overall across indices.
- Localized increases in SDII and short-duration extremes in the southeast.

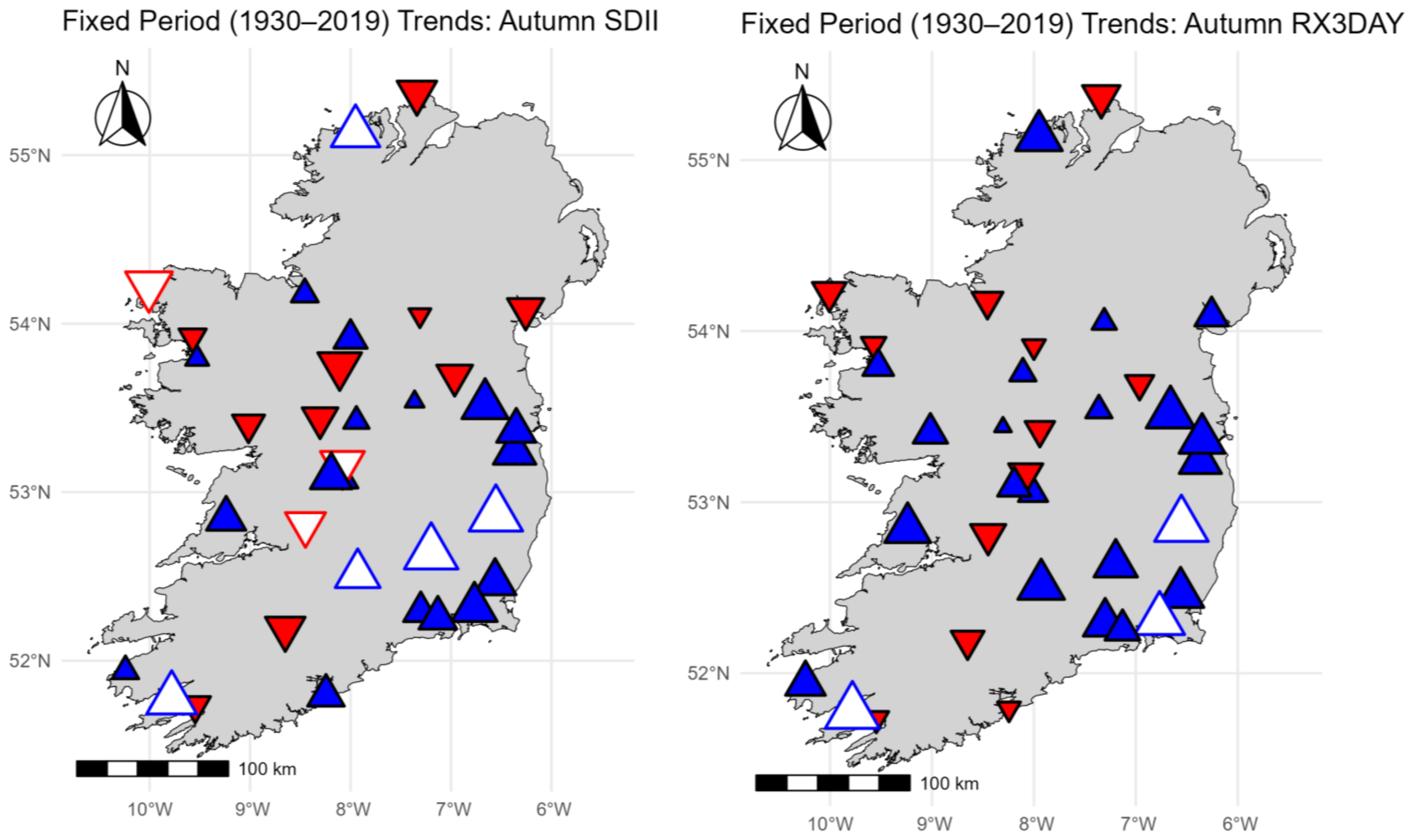


Figure: Magnitude and direction of trends fixed period for autumn SDII and Rx3day. Blue triangles represent increasing trends and red decreasing trends, with magnitude proportional to size. Significant trends (0.05 level) shown by white triangles and derived from MKZs values.

Emerging Climate Change Signals - Winter

- Strong emergence signals are evident in the west, especially for PRCPTOT and Rx5day. This aligns with trend results.
- Up to six stations are now classified as unusual relative to the early industrial baseline
- Relative to the 1950–1980 baseline, emergence is beginning, with many stations nearing the SNR > 1 threshold.

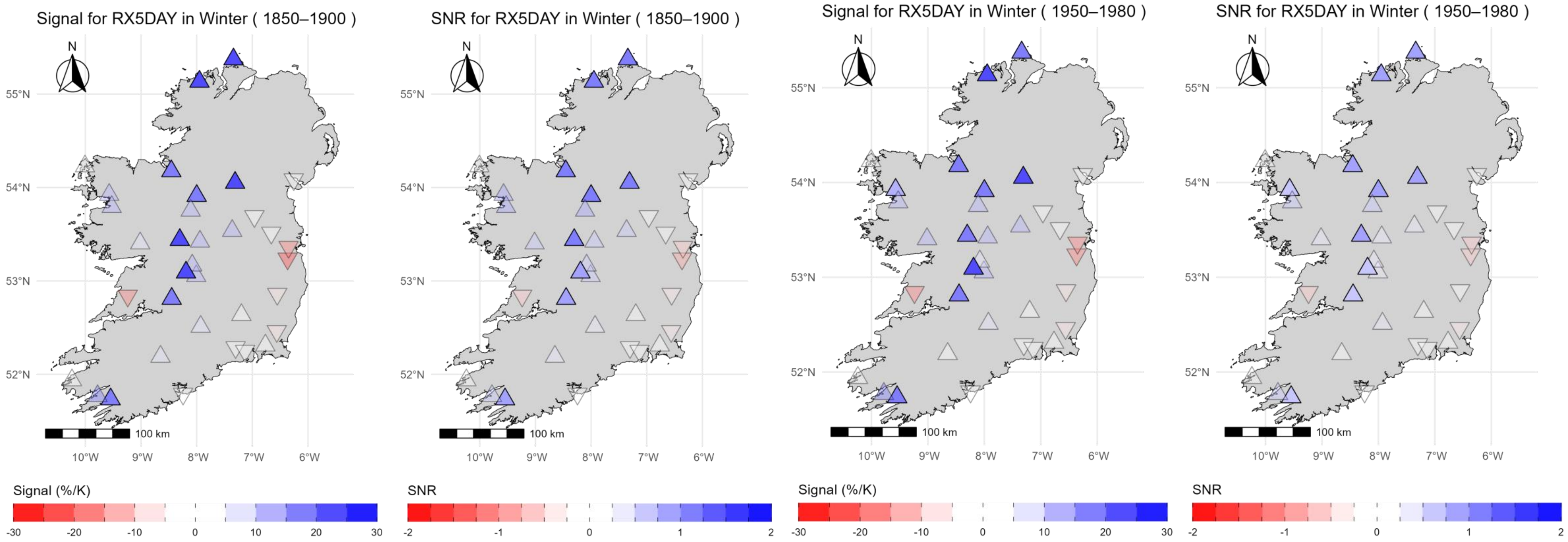


Figure: Signal (% change per degree warming in GMST) and SNR for Winter Rx5day. Left is relative to pre industrial and right is relative to 1950-1980 baseline. Opaque triangles are statistically significant and transparent are non- significant.

Emerging Climate Change Signals - Summer

- SDII is the only indicator with emergence, which is localized to the southeast.
- Four stations exceed the SNR threshold relative to the early industrial baseline
- Relative to the 1950-1980 baseline, one station in the southeast is classified as unusual, with an increase of 24.2%per °C. Several other stations in the region exhibit large increases per °C (15.5–23.4%) but remain within the bounds of natural variability (SNR: 0.66–0.83).

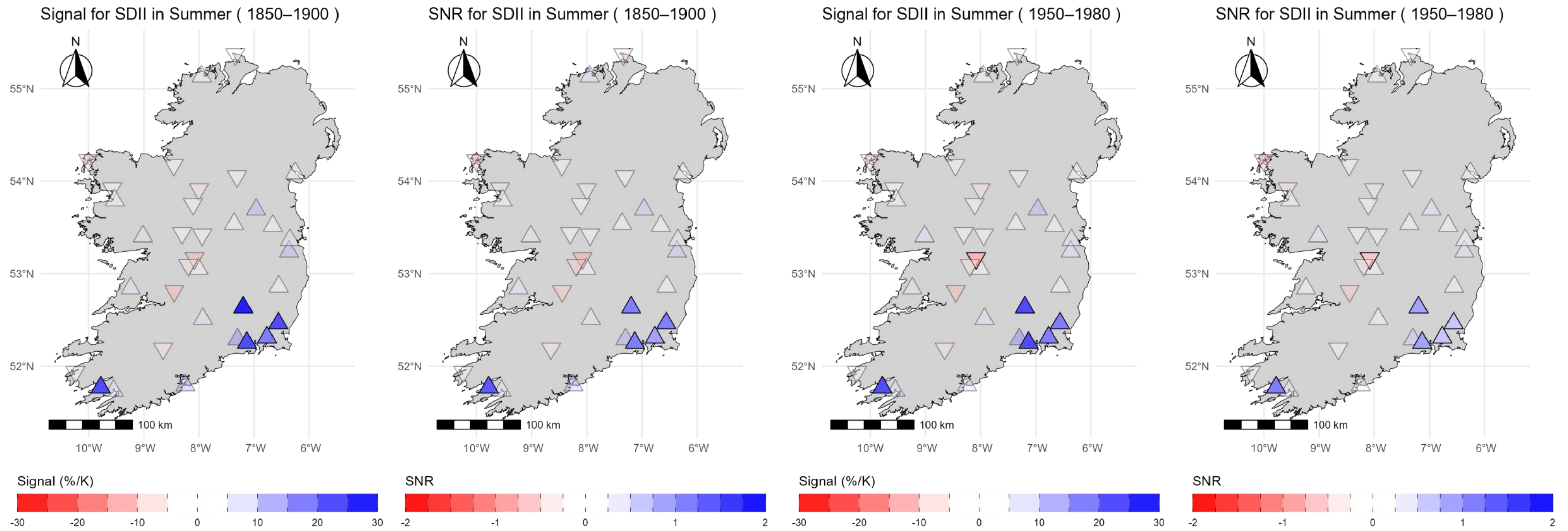


Figure: Signal (% change per degree warming in GMST) and SNR for Summer SDII. Left is relative to pre industrial and right is relative to 1950-1980 baseline. Opaque triangles are statistically significant and transparent are non- significant.

Midleton Floods: First Event Attribution Study for Ireland

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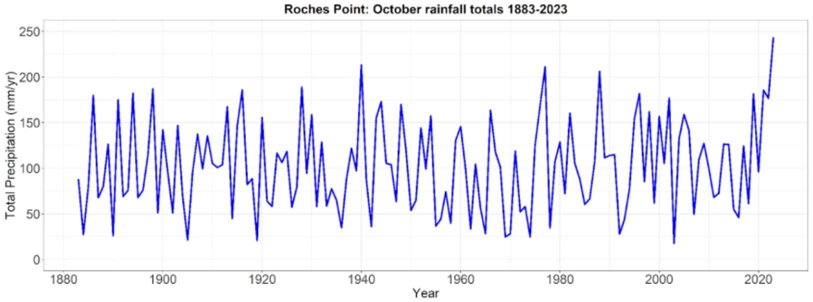
Cost of helping businesses damaged in autumn storm flooding doubles to €11m

Flooding in Midleton, Cork, last year.

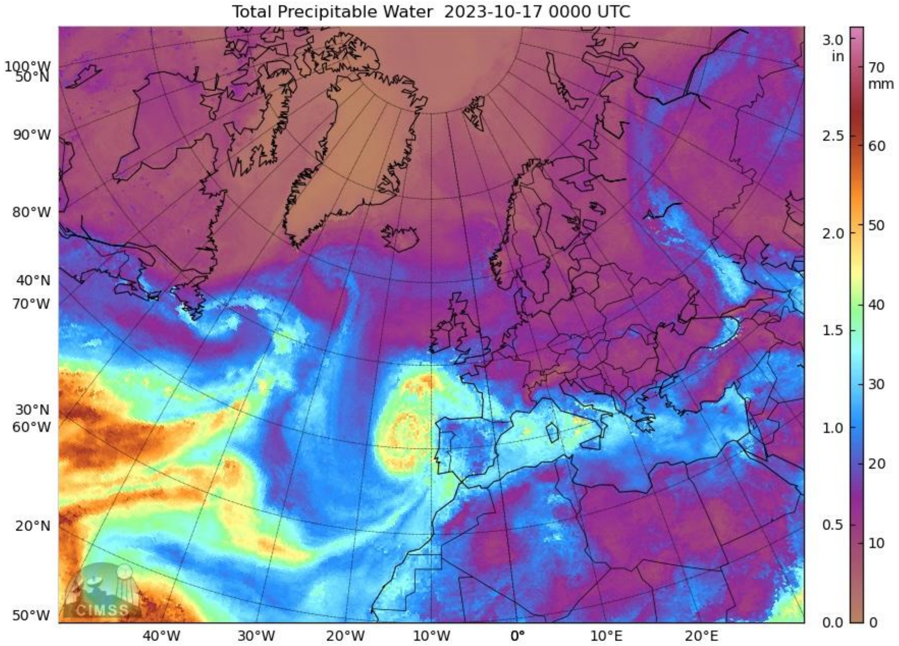
Caroline O'Doherty

Fri 9 Feb 2024 at 14:39



Roches Point October total precipitation since the late 19th Century. 2023 constituted the wettest October on record for this station. Sourced from Met Éireann.

- Collaborative study between MU, Met Éireann, Imperial College London



Total Precipitable Water (TPW) from 00 UTC on 17/10/23. Storm Babet at this point is approaching Ireland from the south and is present as an elevated region of TPW centred to the west of the Iberian peninsula (c.f. Figure 5 second panel). The 6 hourly snapshots of TPW estimates from 00 UTC on 16/10/23 until 18 UTC on 18/10/23 covering the period of the analysis herein and highlighting the evolution of TPW are given in Figure S1. Sourced from the MIMIC-TPW2 product from CIMMS, University of Wisconsin-Madison.

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.

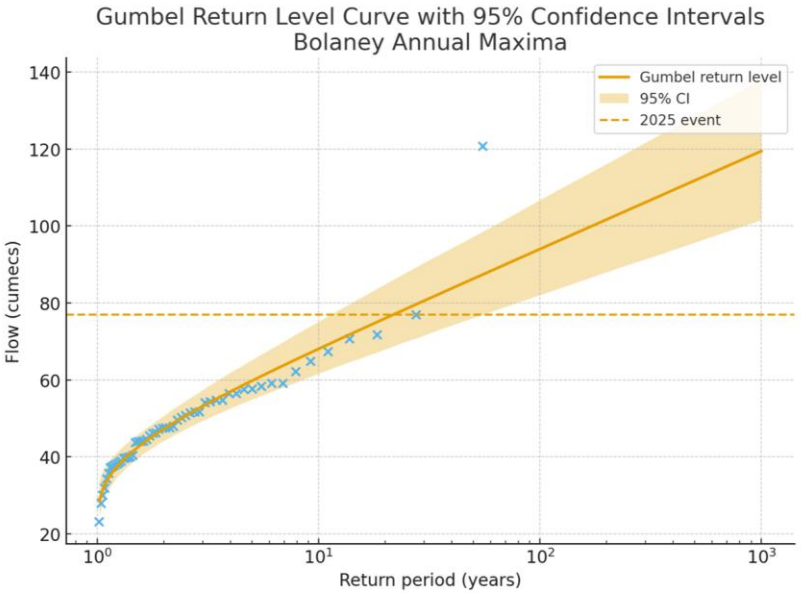
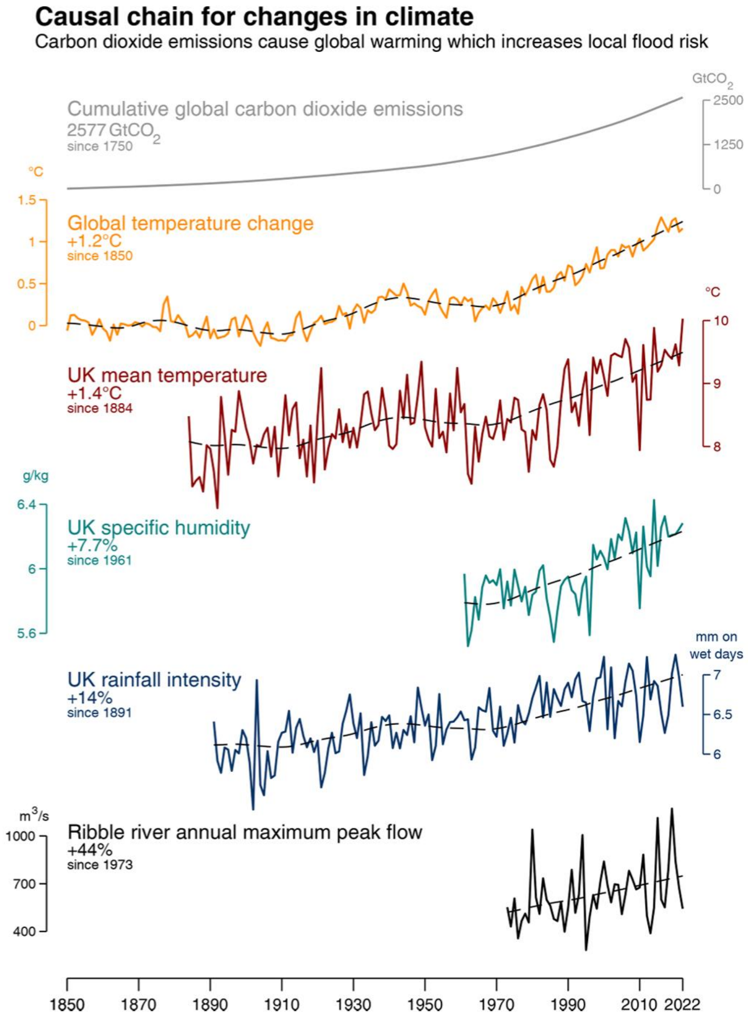


Figure 3.12 Return level plot fitted to the annual maximum series for the Owenavorragh at Bolaney (1972-2025). The blue crosses represent past annual maxima, with the dashed horizontal line indicating the November 2025 flood associated with Storm Claudia. Note that for this analysis this flood is assumed 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).

https://mural.maynoothuniversity.ie/id/eprint/20858/

Attributing and Scaling Climate Change Impacts on Floods Through Causal Chains



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GC Insights: Communicating long-term changes in local climate risk using a physically plausible causal chain

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Aims and Objectives

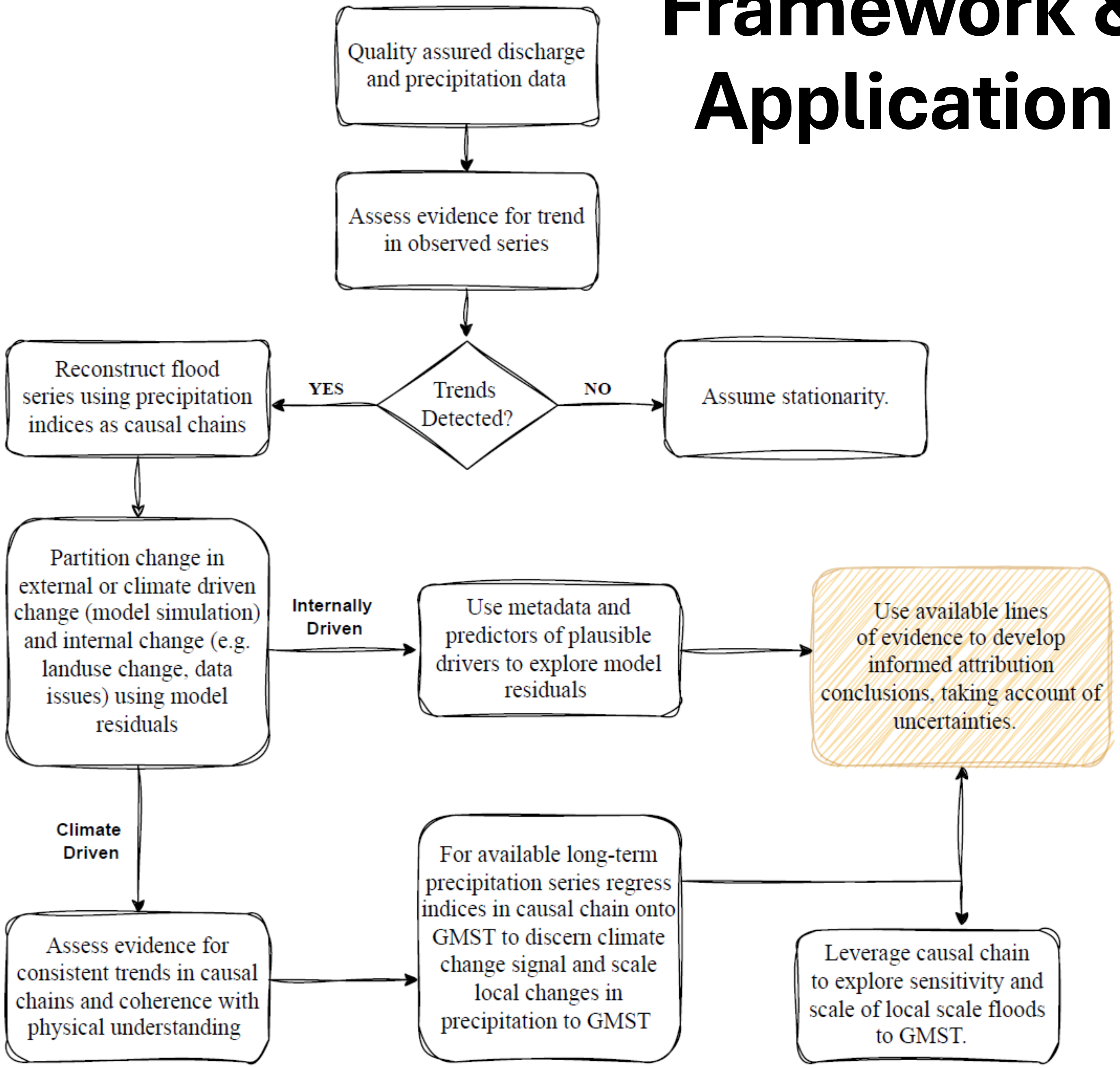
Aim

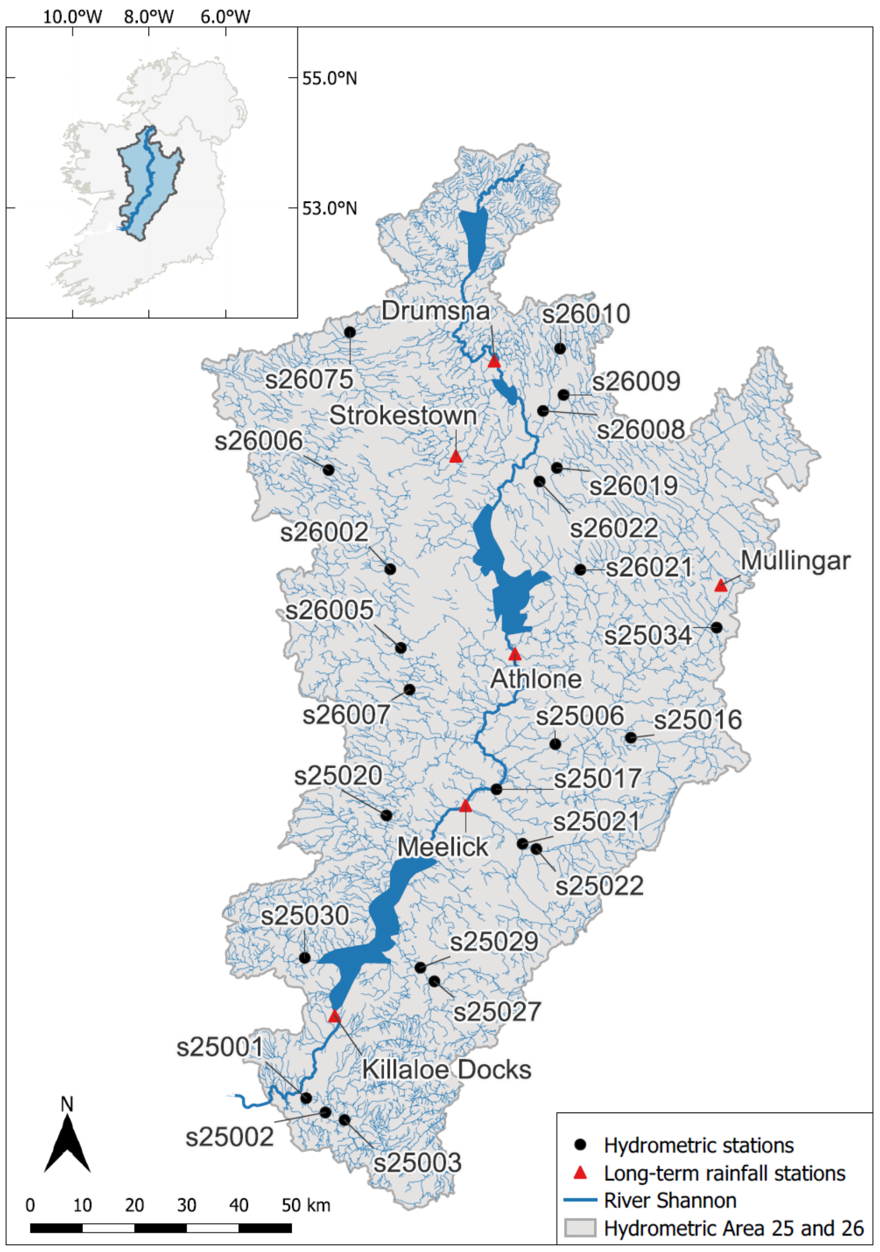
- To develop and apply a robust, observation-based framework for attributing changes in flood risk to anthropogenic climate change, using causal chains that link global temperature rise to local hydrological impacts.

Objectives

- Capture both climate-driven and internal catchment changes influencing flood risk.
- Enable rapid deployment across catchments using consistent methods and existing data (leverages long term records)
- Provide clear, scalable metrics (e.g. % change per °C) to inform communication and decision-making.

Framework & Application





1. Trend Detection

- Non-parametric modified Mann Kendall (Mann, 1945; Kendall, 1975) test which corrects for any autocorrelation in the dataset. Evidence for step changes was evaluated using the non-parametric Pettitt (Pettitt, 1979) test. The non-parametric Sen's slope estimator (Sen, 1968) was used to quantify the magnitude of trends.
- Of the 24 discharge series tested, all but two show increasing trends.
- Ten series returned monotonic and step changes significant at the 0.05 level
- Step changes are distributed throughout the series.

Catchment	MK Zc	P-value	SS	Pettit Year	P-value
s25001	1.01	0.31	0.21	2012	0.57
s25002	1.33	0.18	0.21	2011	0.36
s25003	0.52	0.61	0.06	2012	0.62
s25006	0.26	0.80	0.06	2010	0.55
s25016	1.53	0.13	0.11	1983	**0.01**
s25017	3.43	**0.00**	2.71	2006	0.09
s25020	4.53	**0.00**	1.07	2009	**0.00**
s25021	2.74	**0.01**	0.12	2013	**0.01**
s25022	-0.37	0.71	-0.03	2018	0.61
s25027	1.44	0.15	0.14	1993	0.53
s25029	1.81	0.07	0.32	1985	**0.04**
s25030	0.88	0.38	0.15	2004	0.75
s25034	1.34	0.18	0.01	2006	0.06
s26002	1.39	0.16	0.17	2009	0.20
s26005	1.39	0.16	0.26	2009	0.06
s26006	0.21	0.83	0.02	2016	0.81
s26007	3.31	**0.00**	0.74	2009	**0.01**
s26008	2.03	**0.04**	0.12	2006	0.10
s26009	2.62	**0.01**	0.09	2002	**0.01**
s26010	0.58	0.56	0.02	1985	0.30
s26019	1.61	0.11	0.13	1999	0.31
s26021	1.79	0.07	0.37	1993	0.20
s26022	-1.08	0.28	-0.03	1991	**0.03**
s26075	6.95	**0.00**	0.30	2006	**0.00**

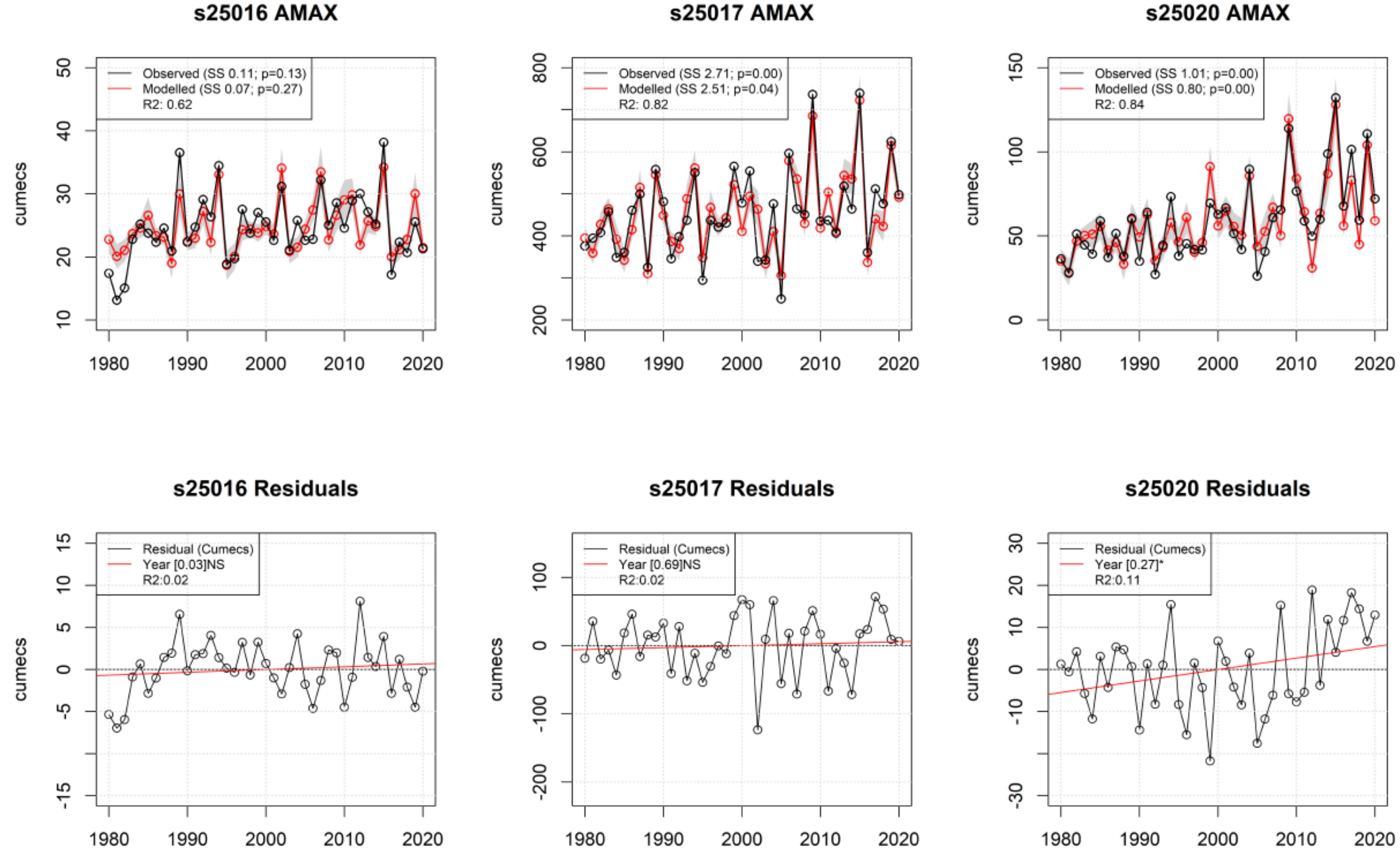
Trend analysis results for monotonic (Mann Kendall test) and step change (Pettit test) from observed IAMAX series for the period 1980-2020. Trend magnitude (cumecs per year) is given by the Sen's slope estimate (SS). Stations returning a significant trend (0.05 level) for either test are highlighted bold.

2. Reconstructing IAMAX using precipitation indices to establish causal chains

Precipitation indices extracted by hydrological year for each catchment and used as potential predictors in reconstructing IAMAX series.

Index Name	Abbreviation	Units	Index Definition	Annual	Seasonal	Monthly
Total wet-day precipitation	PRCPTOT	mm	Total precipitation days >= 1 mm	✔	✔	✔
Consecutive dry days	CDD	days	Maximum number of dry days when precipitation <= 1 mm	✔		
Consecutive wet days	CWD	days	Maximum number of wet days when precipitation >= 1 mm	✔		
Number of heavy precipitation days	R10mm	days	Number of wet days when precipitation >= 10mm	✔	✔	✔
Number of very heavy precipitation days	R20mm	days	Number of wet days when precipitation >= 20mm	✔	✔	✔
Maximum 1-day precipitation amount	RX1Day	mm	Maximum 1-day precipitation total	✔	✔	✔
Maximum 5-day precipitation amount	RX5Day	mm	Maximum 5-day precipitation total	✔	✔	✔
Maximum 30-day precipitation amount	RX30Day	mm	Maximum 30-day precipitation total	✔		
Maximum 50-day precipitation amount	RX50Day	mm	Maximum 50-day precipitation total	✔		
Very wet days	R95PTOT	mm	Precipitation total on days exceeding the 95th percentile of daily precipitation in the base period of 1961-1990	✔		
Extremely wet days	R99PTOT	mm	Precipitation total on days exceeding the 99th percentile of daily precipitation in the base period of 1961-1990	✔		
Simple daily intensity index	SDII	mm/day	Ratio of total precipitation to number of wet days (>=1 mm)	✔	✔	✔

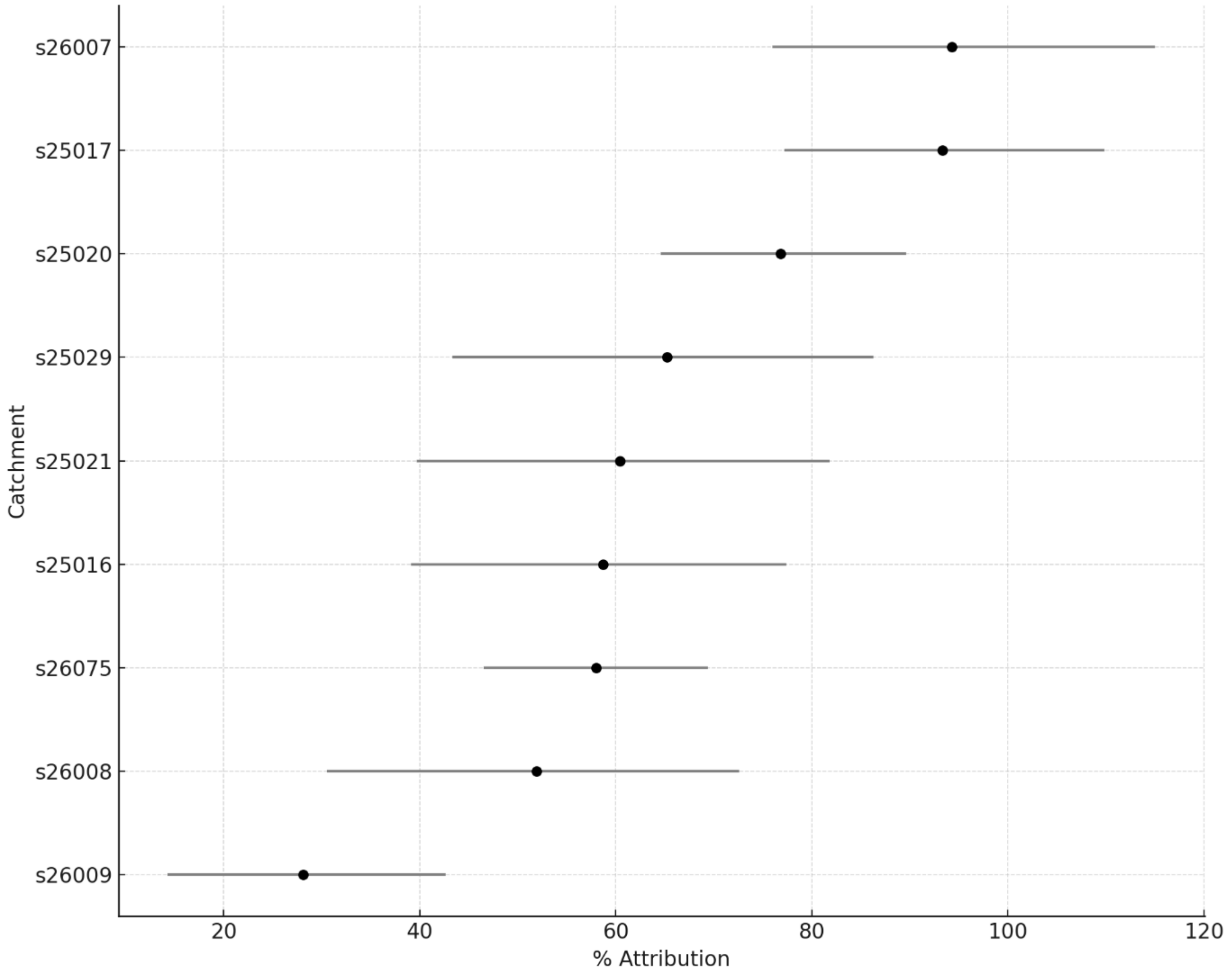
Reconstruction Results and Causal Chains



Catchment	Selected Predictors	R^2	P-value
s25016	rx30day+feb.r20mm+jan.rx1day	0.62	0.00
s25017	rx30day+win.prcptot+jul.r10mm+nov.rx5day	0.82	0.00
s25020	rx30day+win.rx5day+feb.prcptot+nov.r20mm +dec.r20mm+dec.rx5day	0.84	0.00
s25021	ann.cdd+rx30day+feb.r20mm+nov.rx1day	0.61	0.00
s25029	ann.rx1day+rx30day+win.rx5day+jun.r10mm	0.69	0.00
s26007	rx30day+win.r20mm+nov.rx5day	0.85	0.00
s26008	rx30day+sp.r20mm+win.r20mm+nov.rx5day	0.69	0.00
s26009	rx30day+win.r20mm+nov.rx5day	0.52	0.00
s26022	rx30day+win.r20mm+dec.sdii	0.68	0.00
s26075	rx30day+win.rx5day+nov.rx5day	0.80	0.00

Standardised Coefficients revealed importance of these indices as key part of causal chain:
Annual RX30-day
Winter r20mm
Winter RX5-day
November RX5-day

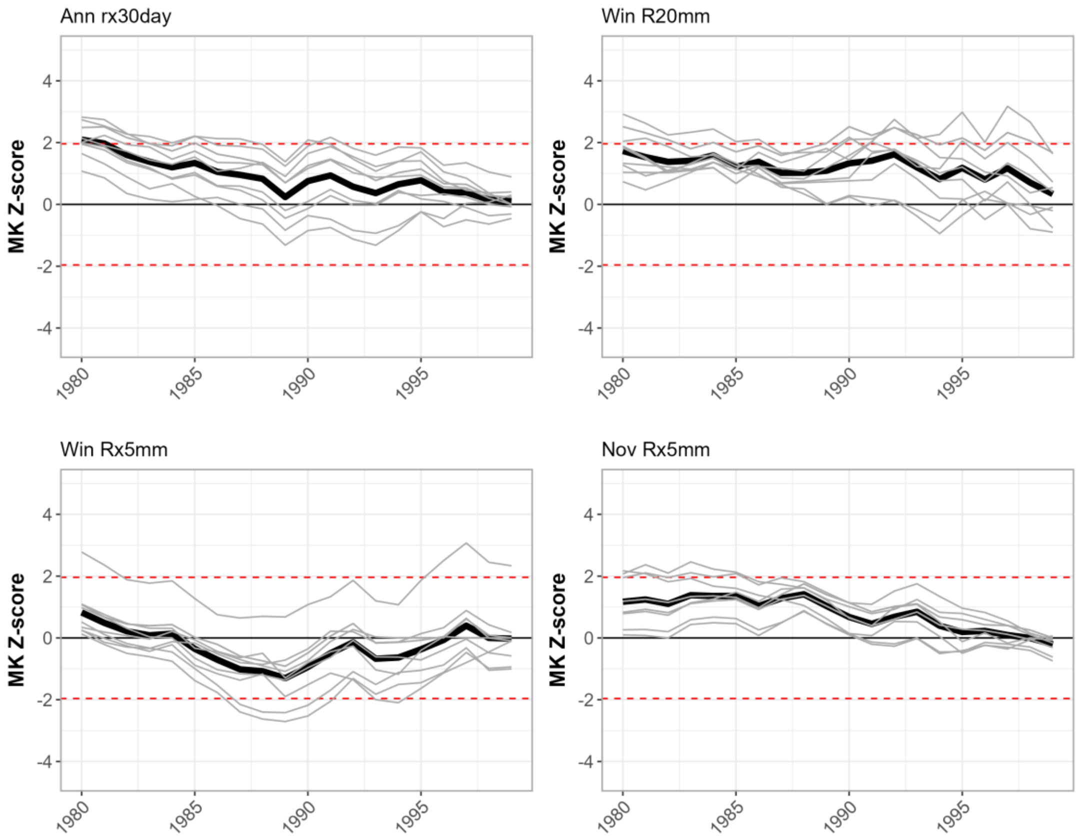
3. Partitioning external and internal change



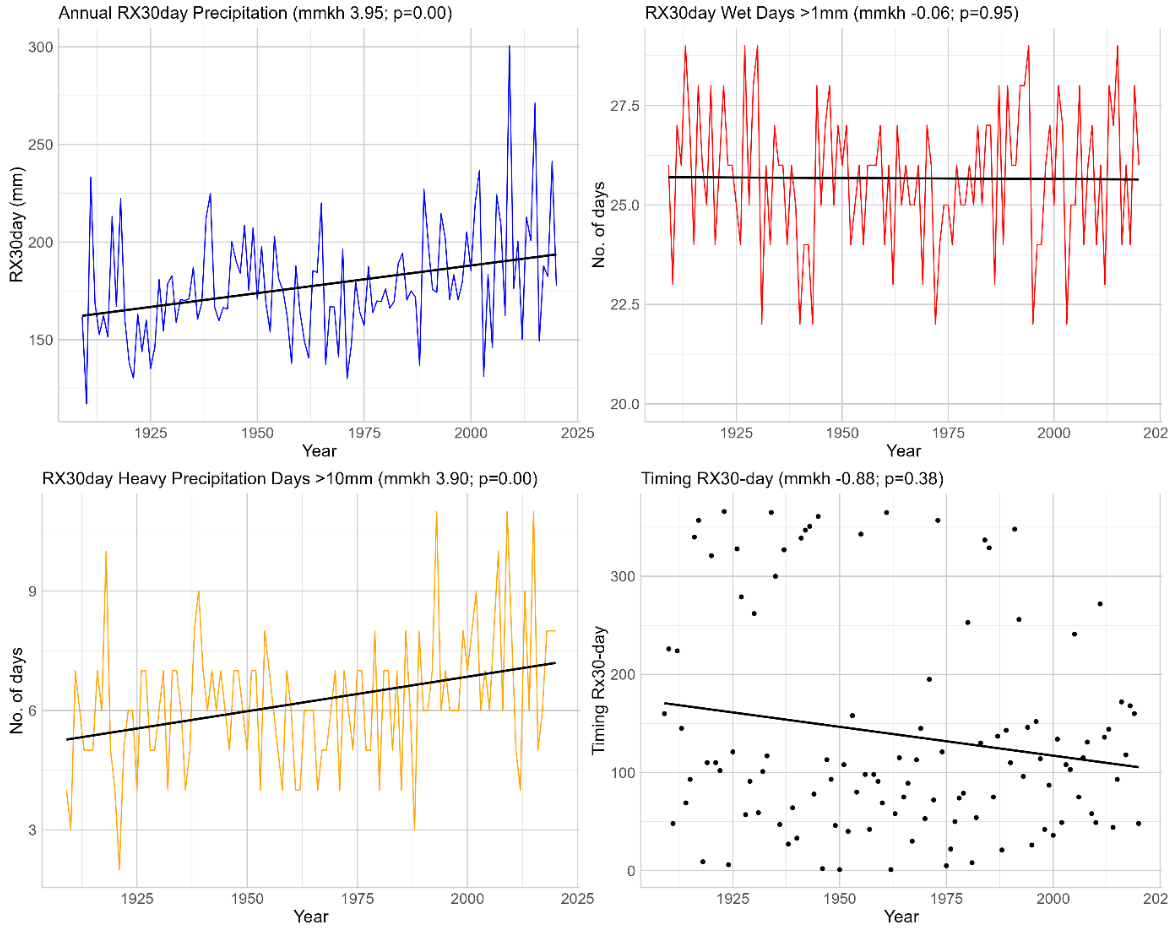
Contribution of precipitation change to observed trends in IAMAX for each catchment over the period 1980-2022.

- Monte Carlo analysis (n = 10k) deployed to quantify the contribution of observed precipitation change to changes in IAMAX, using estimated coefficients and their variance-covariance matrix to account for parameter uncertainty in the derived regression models.
- For each sample an IAMAX series was computed and the associated trend quantified using Sen's slope estimator.
- The ensemble of simulated trend estimates used to estimate the median and 95 percent confidence intervals of the **fractional contribution of precipitation change to observed IAMAX trends.**

4. Check consistency of trends in causal chains



Assessment of trends in four key precipitation variables that formed part of the causal chains established in each catchment. Trend persistence was evaluated by plotting the Mann Kendall Z-score for the full period (1980-2022) of record and then dropping the start year incrementally to a minimum record length of 20 years. The thick black line represents the median trend across catchments for each test period, while the dashed horizontal lines are the thresholds for significance at the 0.05 level (i.e. |1.96|).



Assessment of trends in annual max RX30-day precipitation for the long term (1910-2022) Shannon average series (mean of 6 long-term stations), including the annual RX30-day series (top left), the number of wet days (> 1mm) in each annual 30-day window (top right), the number of heavy precipitation data (> 10mm) in each 30-day window (bottom left) and the timing of occurrence (Julian day per hydrological year) of the max 30-day totals in each year (bottom right). Also provided for each series is the trend magnitude (Mann Kendall score) and the associated p-value for the derived trend.

5. Regress causal chains onto GMST to discern anthropogenic climate change signal

Leverage long term daily rainfall series (1910-2022) previously rescued and quality assured by Ryan et al. (2022).

All predictors in causal chain for each catchment and Shannon Average series examined.

Follow methods of Hawkins et al (2020) and Murphy et al. (2023) for discerning a climate change signal in long term indices:

$$L(t) = \alpha G(t) + \beta$$

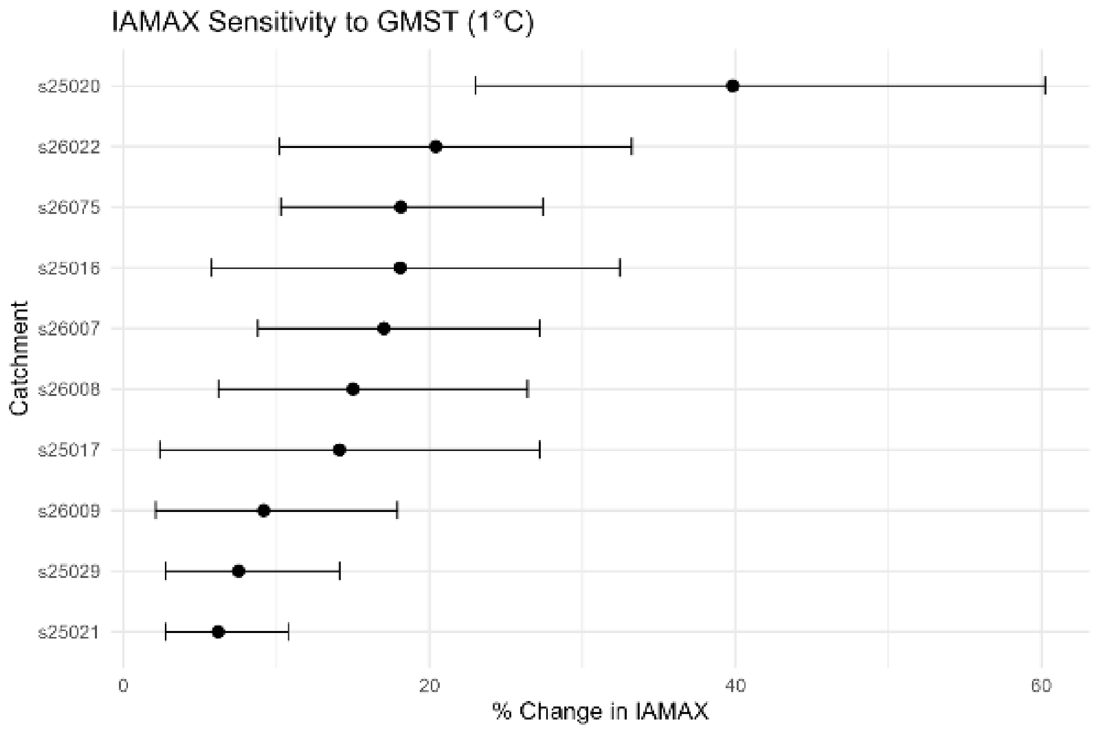
L(t) is the local change in catchment precipitation indices over time, G(t) is a smoothed (Loess filtered, span of 0.25) version of GMST anomalies over the same period, α is the linear scaling between L and G or climate sensitivity, and β is a constant.

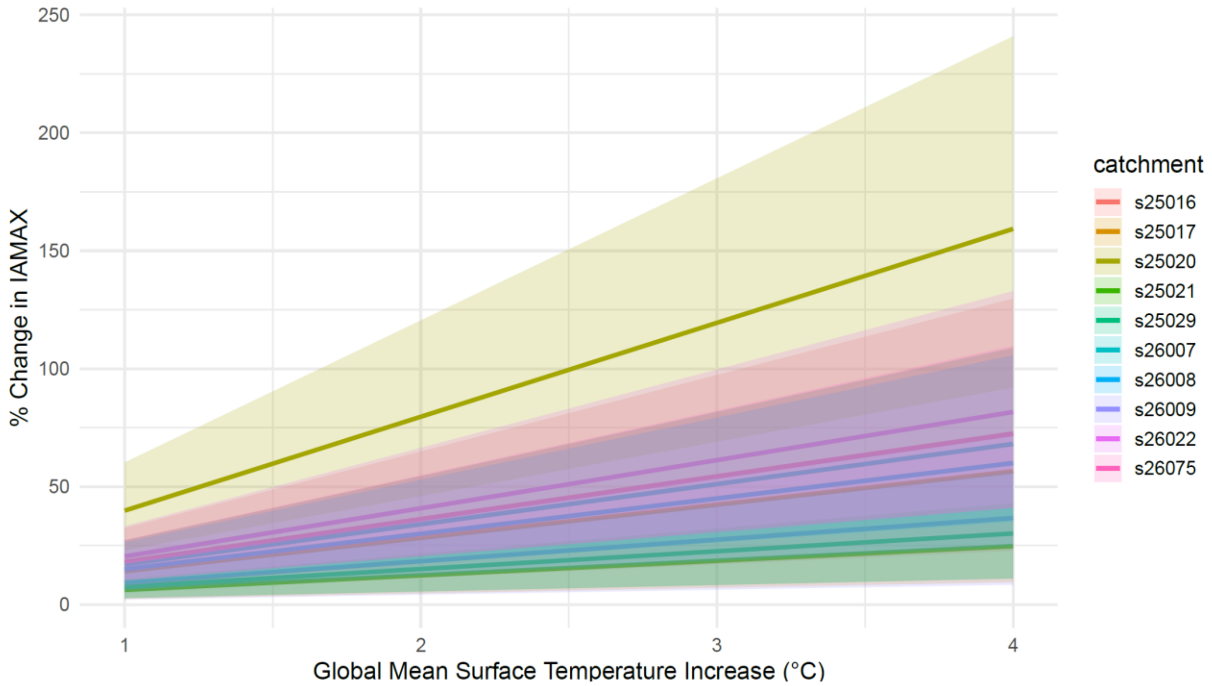
The signal of anthropogenic climate change has emerged from variability (SNR >1) for annual 30-day maximum totals (rx30-day; SNR 1.26), the number of winter days with >20mm precipitation (win_r20mm; SNR 1.08) and the number of spring days with >20mm precipitation (sp_r20mm; SNR 1.08).

Indicator	Unit	alpha	p-value	percent per k
annual_rx30day	mm	29.87	0.00	16.78
feb_r20mm	days	0.28	0.01	194.87
jan_rx1day	mm	2.65	0.06	16.52
dec_r20mm	days	0.31	0.09	100.64
dec_sdii	unitless	0.70	0.04	12.10
winter_prcptot	mm	28.39	0.04	15.74
winter_rx5day	mm	7.61	0.01	17.47
winter_r20mm	days	0.56	0.00	148.67
spring_r20mm	days	0.56	0.00	148.67

Alpha (α) values derived by regressing catchment average precipitation indices onto GMST. Only indices for which a significant (0.10 level) relationship was observed are reported. Also included are the units of each indictor and the percent change per degree increase in GMST, derived relative to the long-term mean of each indicator.

6. Scale IAMAX changes to GMST via causal chain





$$\Delta GMST \rightarrow \Delta Precipitation\ Indicators \rightarrow \Delta IAMAX$$

$$\Delta IAMAX = \frac{\beta \times \alpha}{IAMAX\ mean} \times 100$$

Conclusions

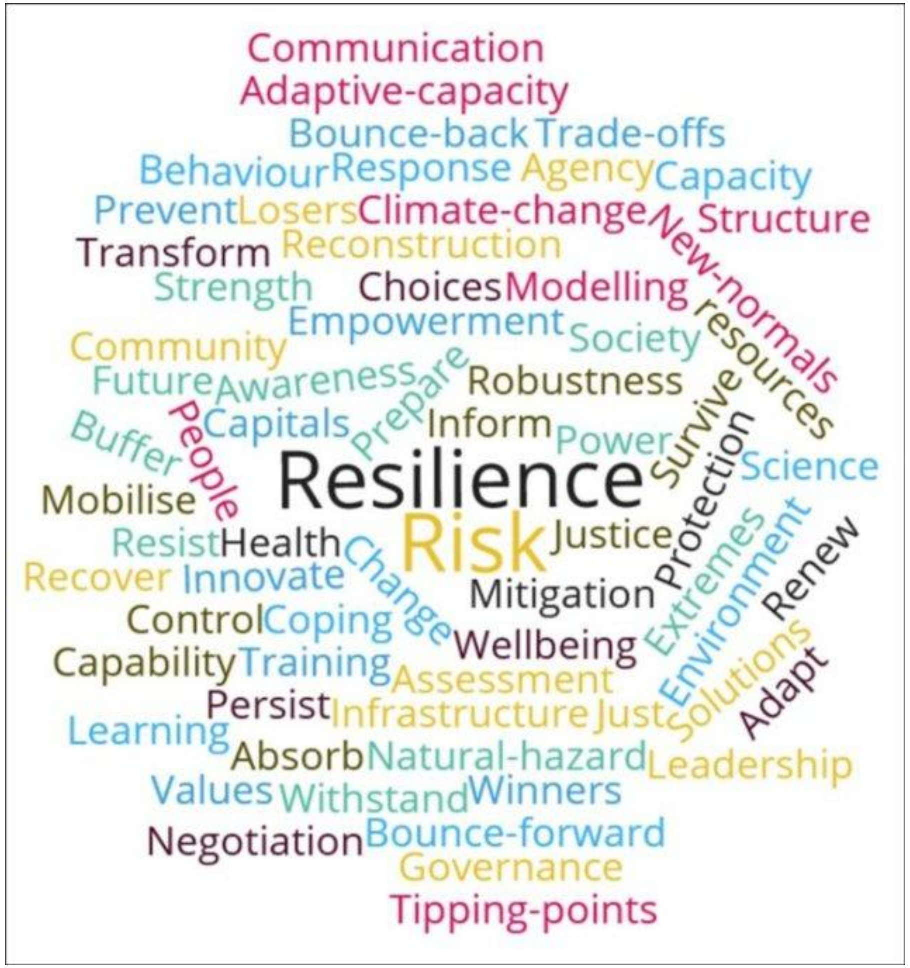
- **Attribution statement:** increasing trends in IAMAX in the Shannon Catchment are predominantly climate driven and show the signal of anthropogenic climate change – based on statistical analysis and physical understanding
- The dominant pathway through which this signal has emerged is via 30-day accumulated totals and winter 5-day totals
- The other (internal) main driver of change in observations is hydrometric and drainage

- **Key contributions**:
  - Novel Framework for attribution and scaling flood risk to climate change that leverages long-term records and data rescue efforts and addresses a key gap internationally
  - Identification of key indices for monitoring and tracking risk in an integrated way
  - Rapidly deployed, updated and extendable to other variables
- **Key limitation**: linear assumptions – future work non-linear models
- **Key strength**: Embedded in causal chains that are empirically tested and physically consistent.
- **Next step** – role of catchment characteristics – highest sensitivity of IAMAX in catchments that have been arterially drained, emergence since more recent baselines?

HydroPredict: Future Projections

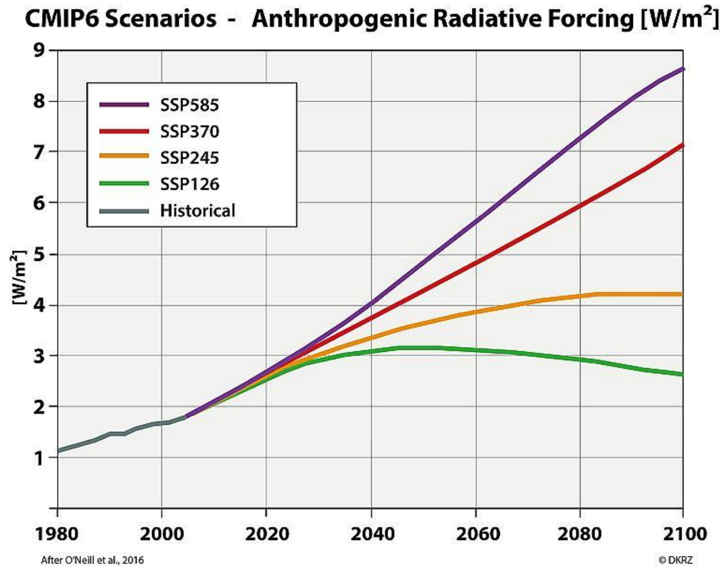
HydroPredict seeks to build capacity for robust adaptation in the water sector in Ireland – a sector that is highly sensitive to changes in climate

- Develop future hydrological simulations for Irish catchments for use in the water sector for climate change adaptation planning
- Incorporate key uncertainties including: global climate models, natural climate variability, downscaling and hydrological model uncertainties.
- Provide guidance on ranges of change likely for key hydrological indicators from across the full flow regime that are of use to water managers.
- Assess the impact of climate change on drought for the island of Ireland and to identify drought hotspots.



Latest CMIP6 ensemble of climate models

Code	Institute	Parent source Id	Institution Id
*CM1	Commonwealth Scientific and Industrial Research Organisation, Australia	ACCESS-CM2	CSIRO
*CM2	Met Office Hadley Centre, UK	UKESM1-0-LL	MOHC
CM3	Beijing Climate Center, China	BCC-CSM2-MR	BCC
CM4	Global Fluid Dynamics Laboratory, USA	GFDL	NOAA-GFDL
CM5	European: EC-EARTH consortium	EC-Earth	EC-EARTH consortium
*CM6	National Center for Atmospheric Research, USA	CESM2	NCAR
*CM7	Met Office Hadley Centre, UK	HadGEM3-GC31-LL	MOHC
CM8	JAMSTEC, AORI, NIES, and R-CCS, Japan	MIROC6	MIROC
CM9	Max Planck Institute for Meteorology, Germany	MPI-ESM1-2-HR	MPI-M
CM10	Meteorological Research Institute, Japan	MRI-ESM2-0	MRI
CM11	NorESM Climate modeling Consortium, Norway	NorESM2-LM	NCC
*CM12	Nanjing University of Information Science and Technology, China	NESM3	NUIST



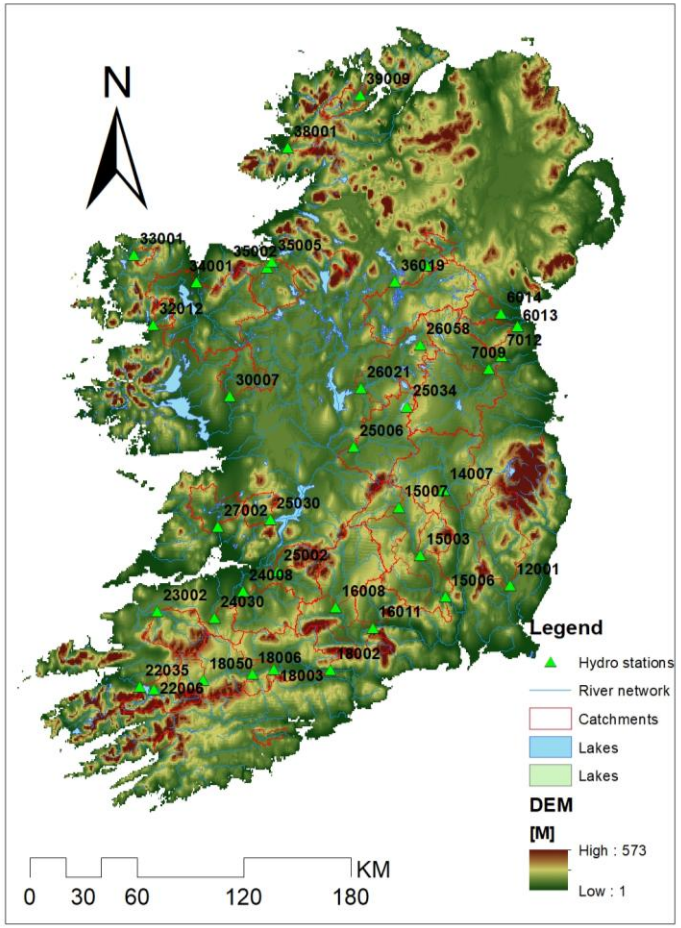
SSP1: Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)

SSP3: Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)

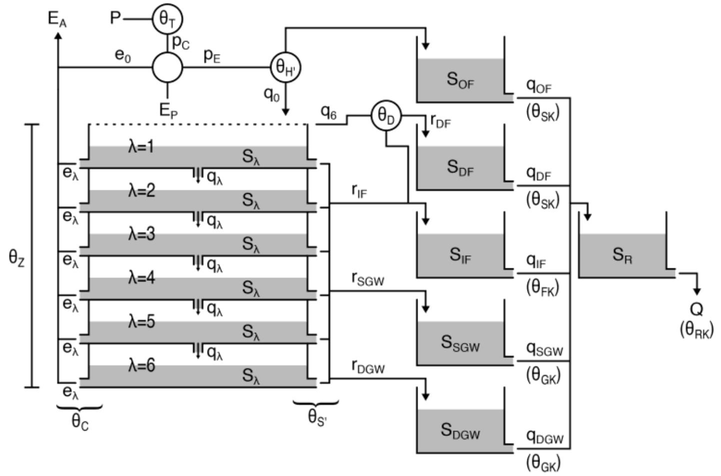
SSP5: Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)

*Models with high climate sensitivity

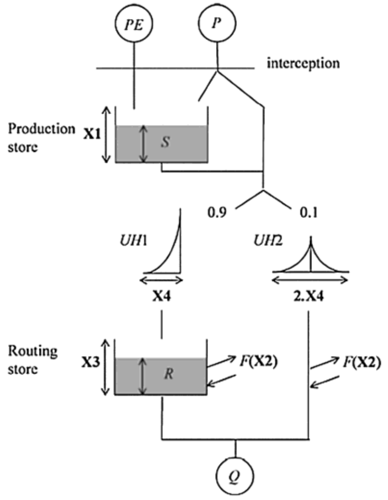
Catchments & Hydrological Models



37 catchments across Ireland



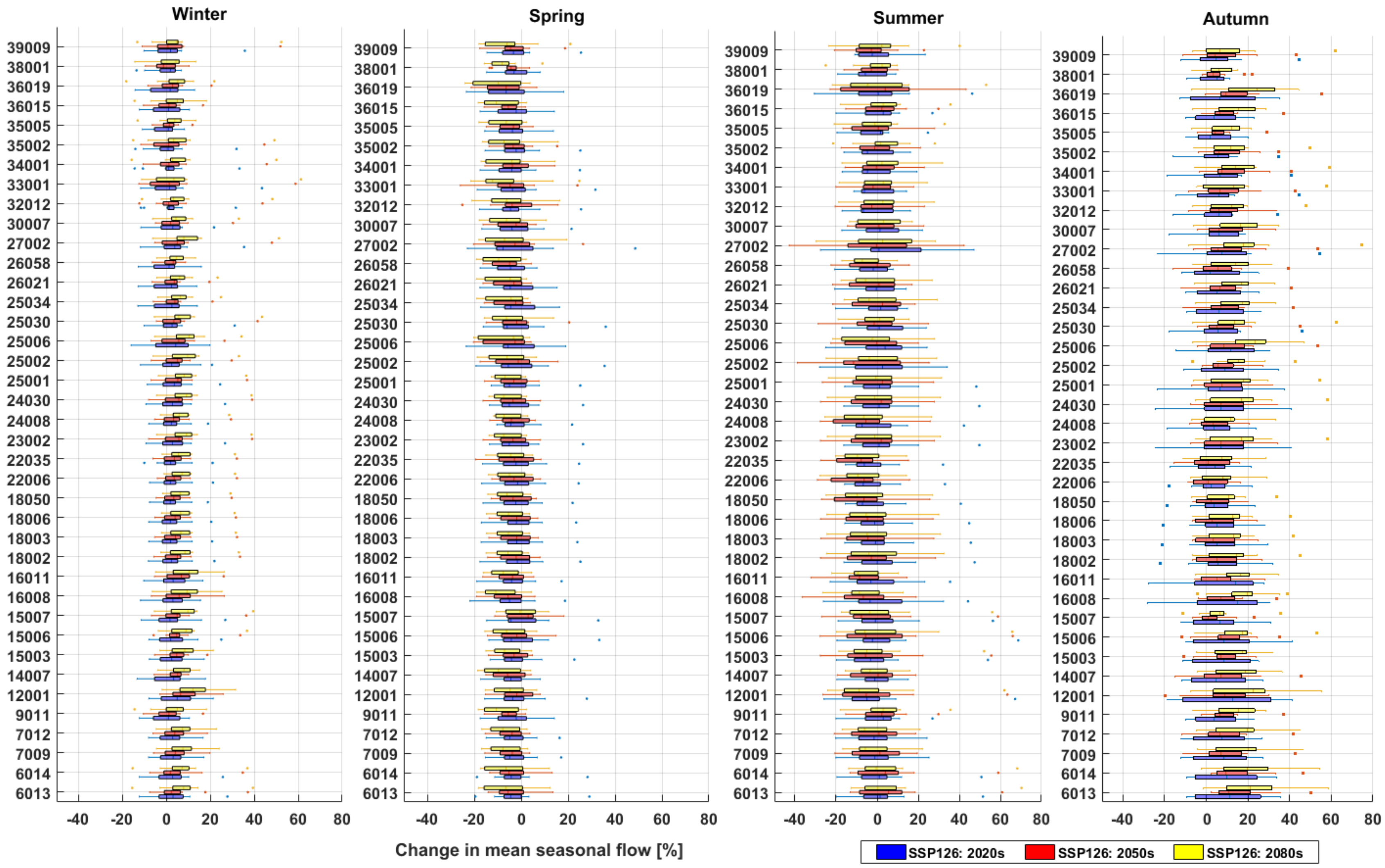
SMART



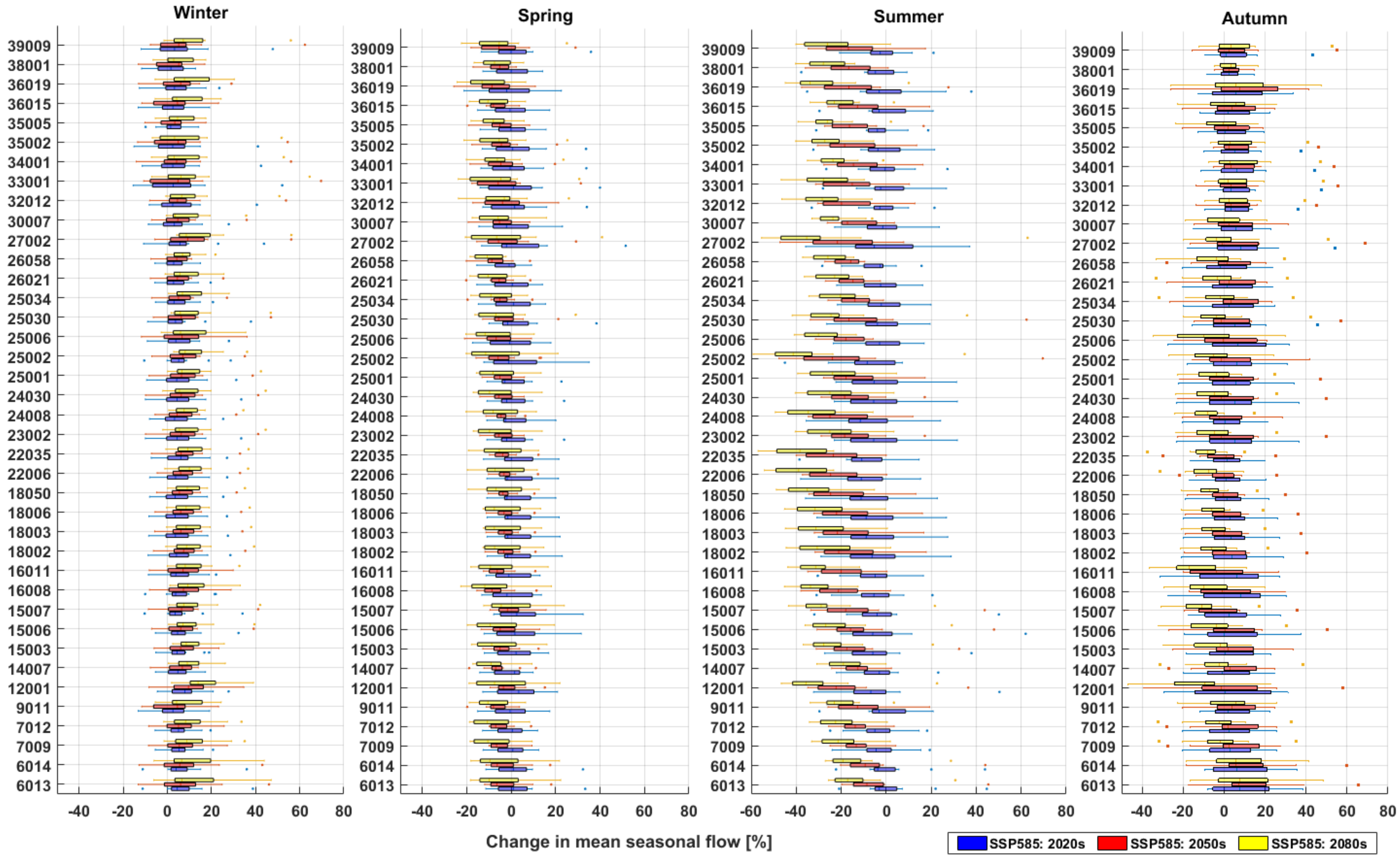
GR4J

Model	Parameter	Description	Lower	Upper	Unit
GR4J	X1	Capacity of the production soil store	2.59	582.75	mm
	X2	Water exchange coefficient	-4.02	4.81	mm/d
	X3	Capacity of the routing store	18.24	500	mm
	X4	Time parameter for unit hydrographs	0.12	5	d
SMART	T	Areal Rainfall Correction coefficient	0.9	1.1	(/)
	C	Evaporation decay parameter	0	1	(/)
	H	Quick runoff coefficient	0	0.3	(/)
	D	Drain flow parameter	0	1	(/)
	S	Soil outflow coefficient	0	0.013	(/)
	Z	Effective soil depth	15	150	mm
	SK	Surface routing parameter	1	240	d
	FK	Interflow routing parameter	48	1440	d
	GK	Groundwater routing parameter	1200	4800	d
	RK	River routing parameter	1	96	d

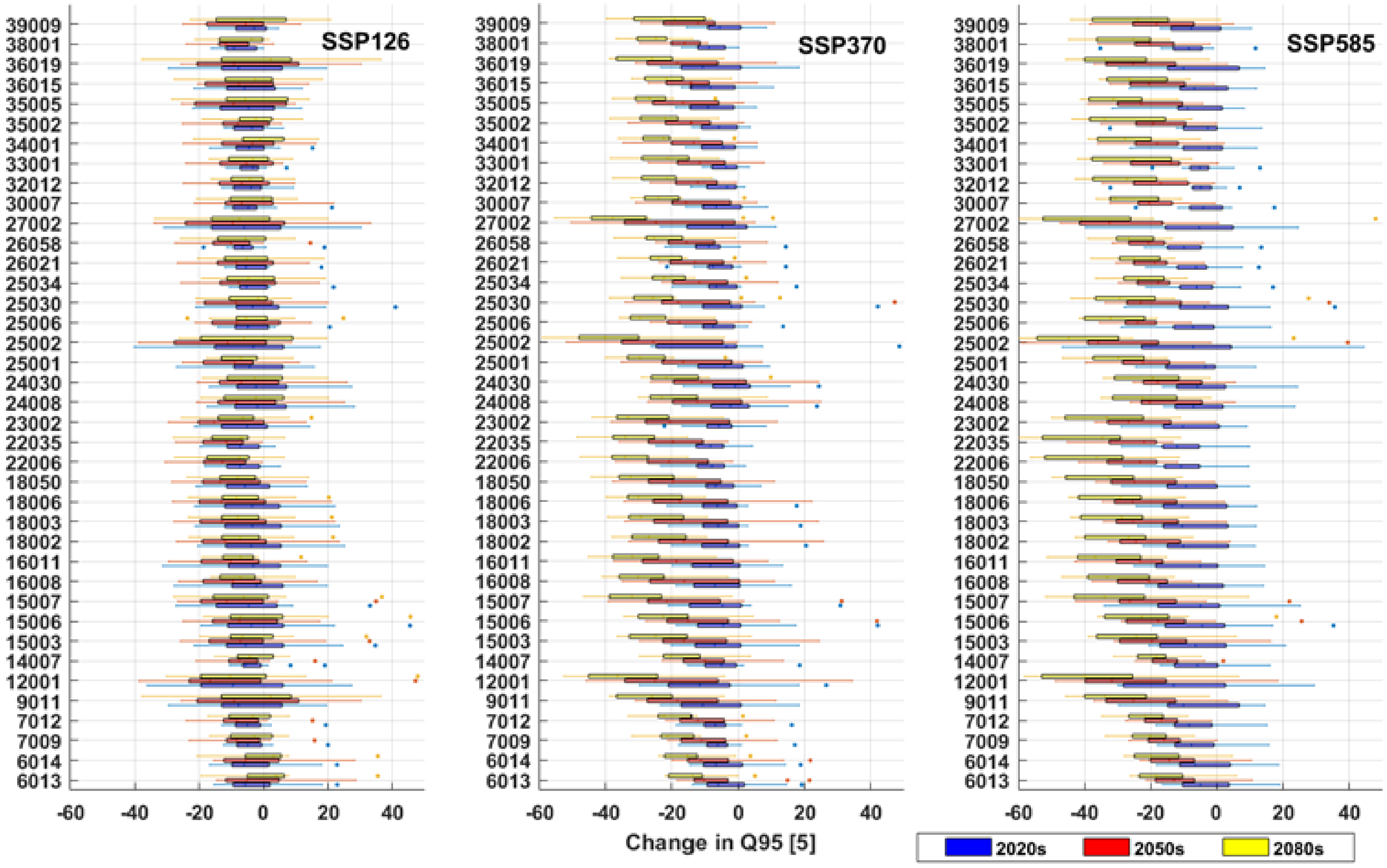
SSP126: Sustainable Future
Changes in seasonal mean flows: GR4J



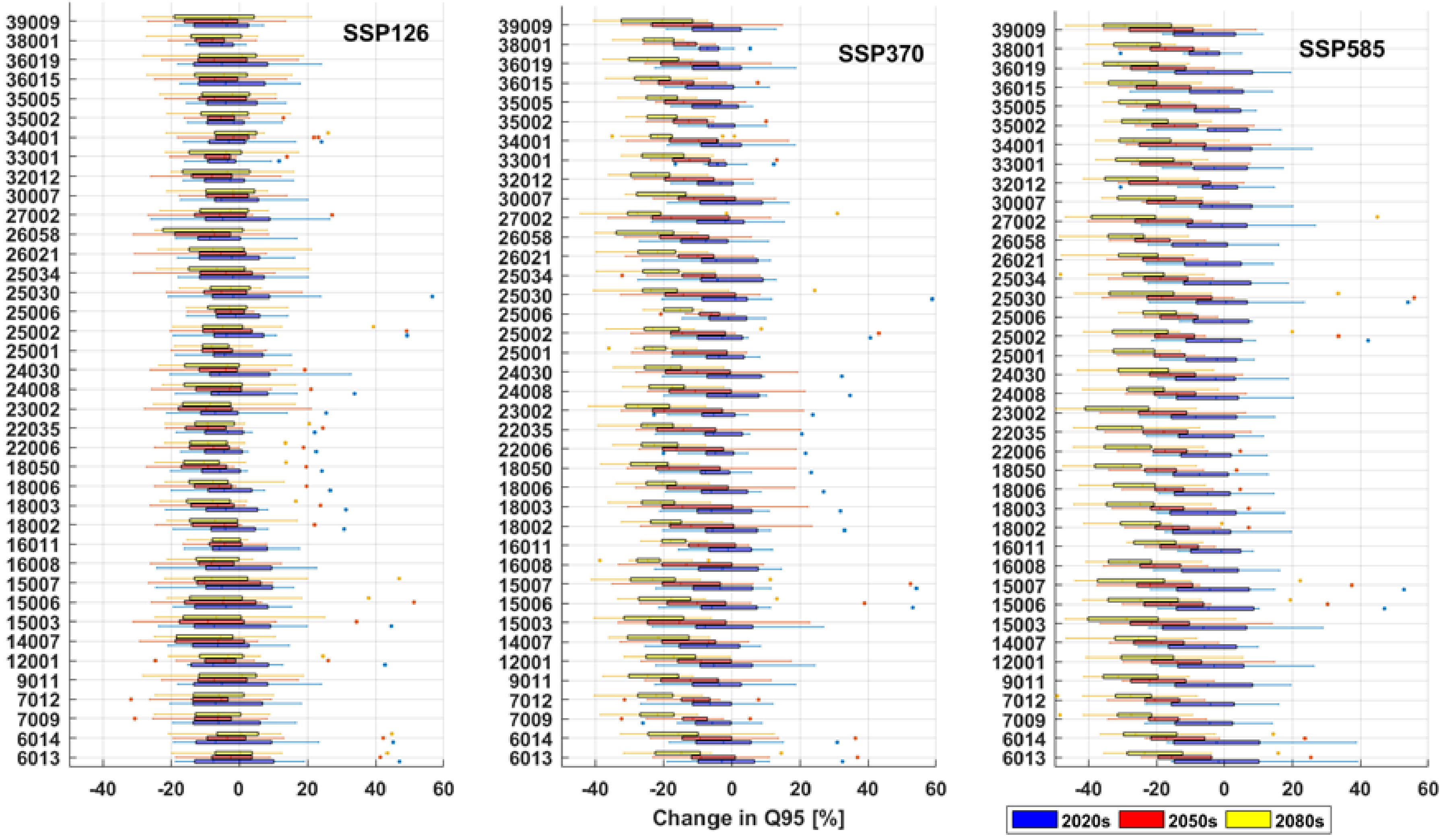
SSP585: Fossil Fuel Intensive
Changes in seasonal mean flows: GR4J



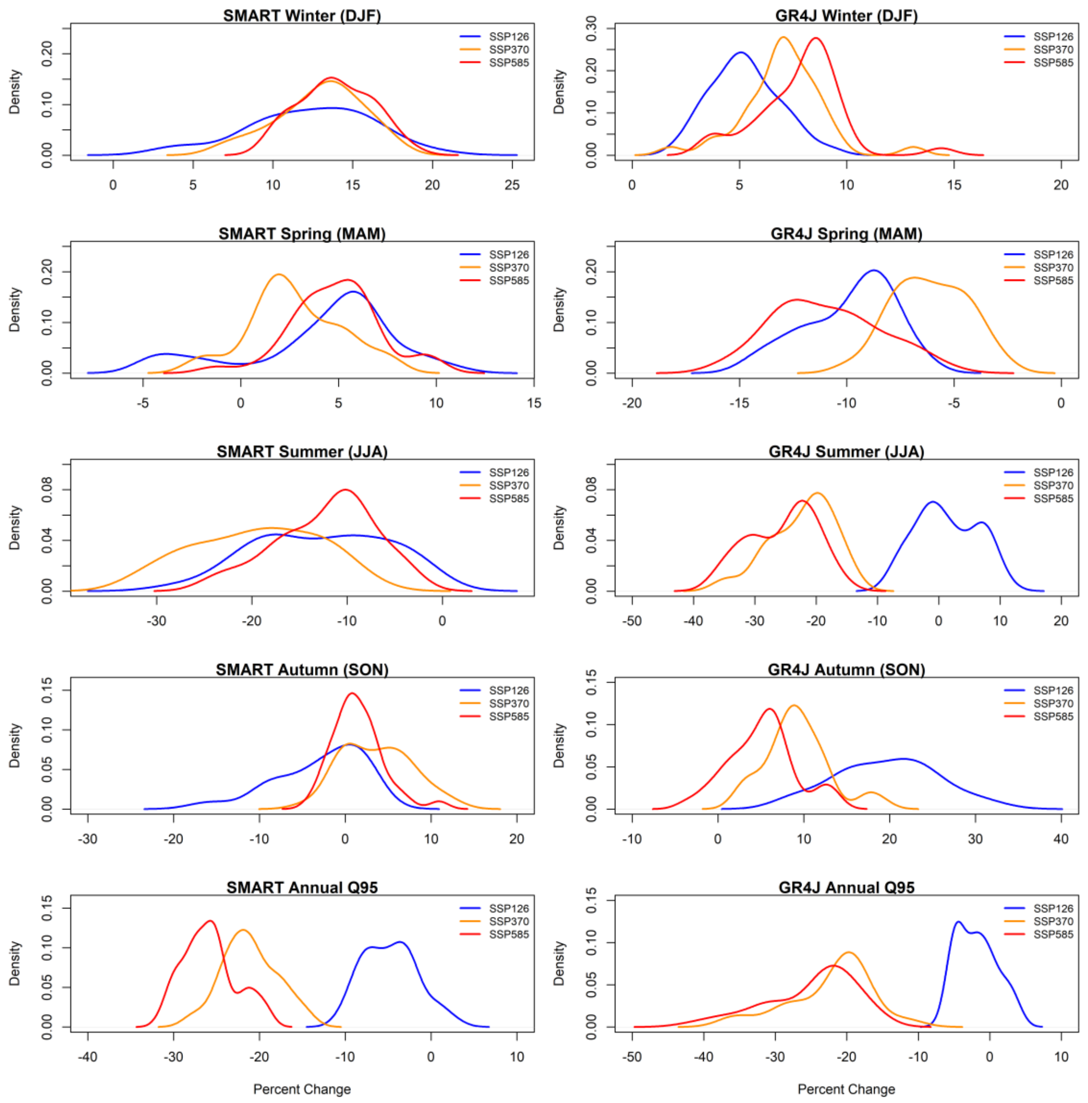
Changes in low flows (Q95): GR4J



Changes in low flows (Q95): SMART

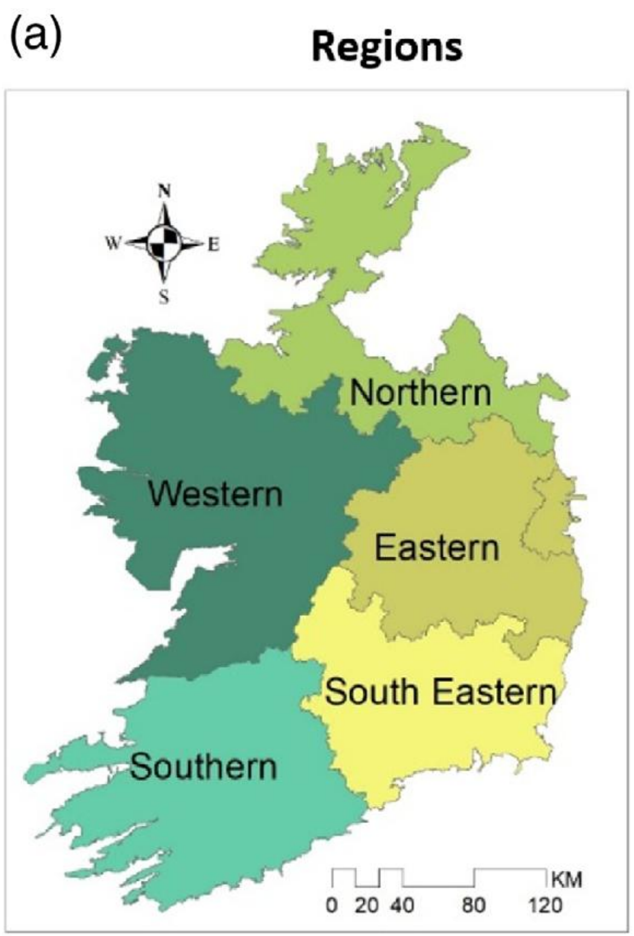


Avoided Impacts through mitigation



- Median changes simulated for seasonal and low flows across the catchment sample for the 2080s, assuming that differences between SSPs are greatest at this time
- **Evident is the importance of mitigation efforts in avoiding the most extreme impacts for low flows**.
- For seasonal mean flows, the differences between outcomes for various SSPs are less clear cut, with results depending on which hydrological model is employed.
- **Highlights the importance of hydrological model structural uncertainty in assessing avoided impacts from mitigation.**

Assessment of Drought from CORDEX



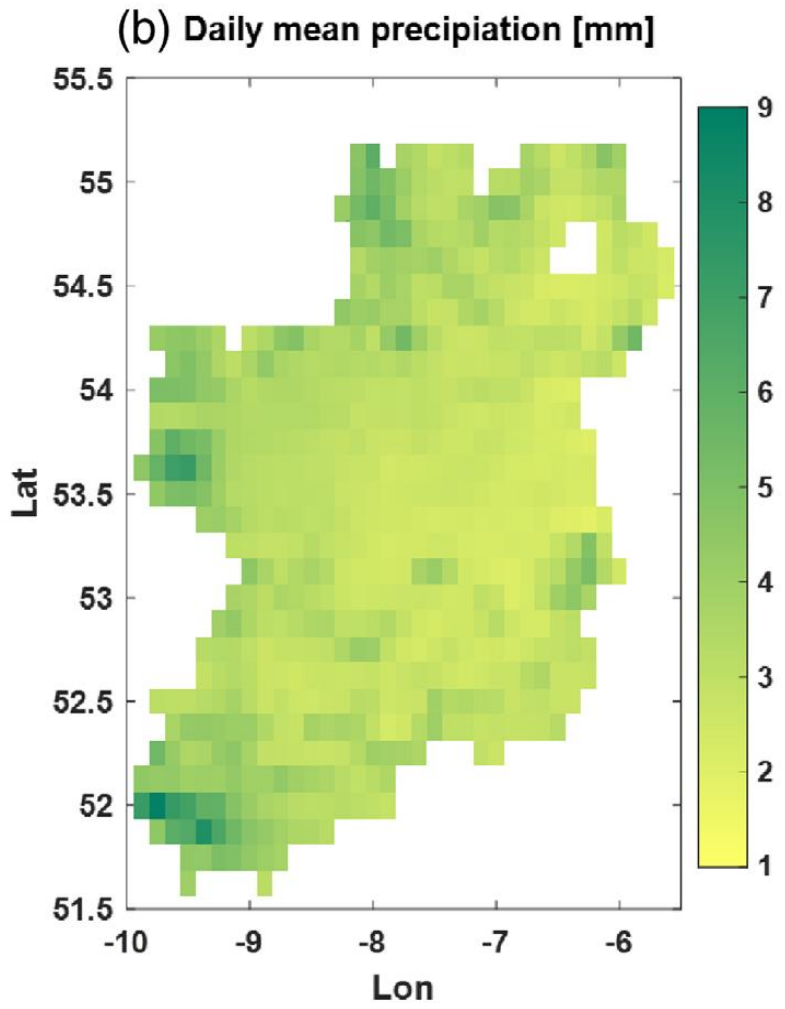
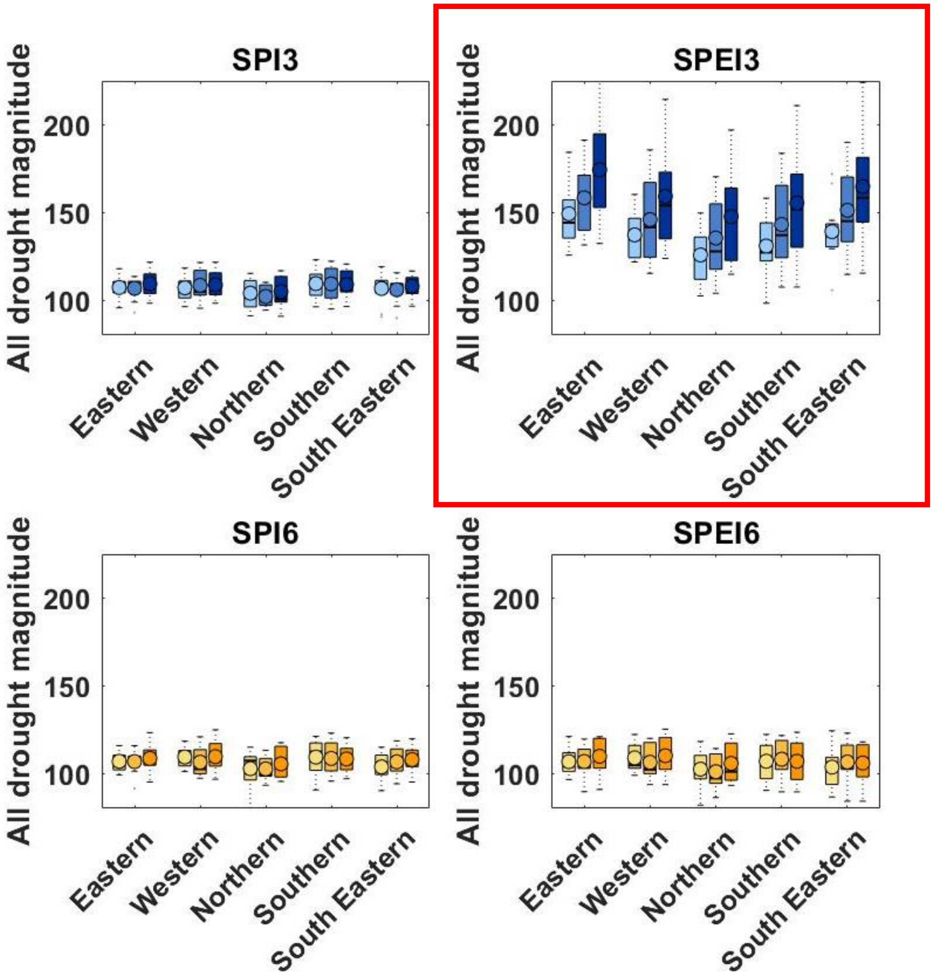


TABLE 1 EURO-CORDEX data including GCMs and RCMs used in this study

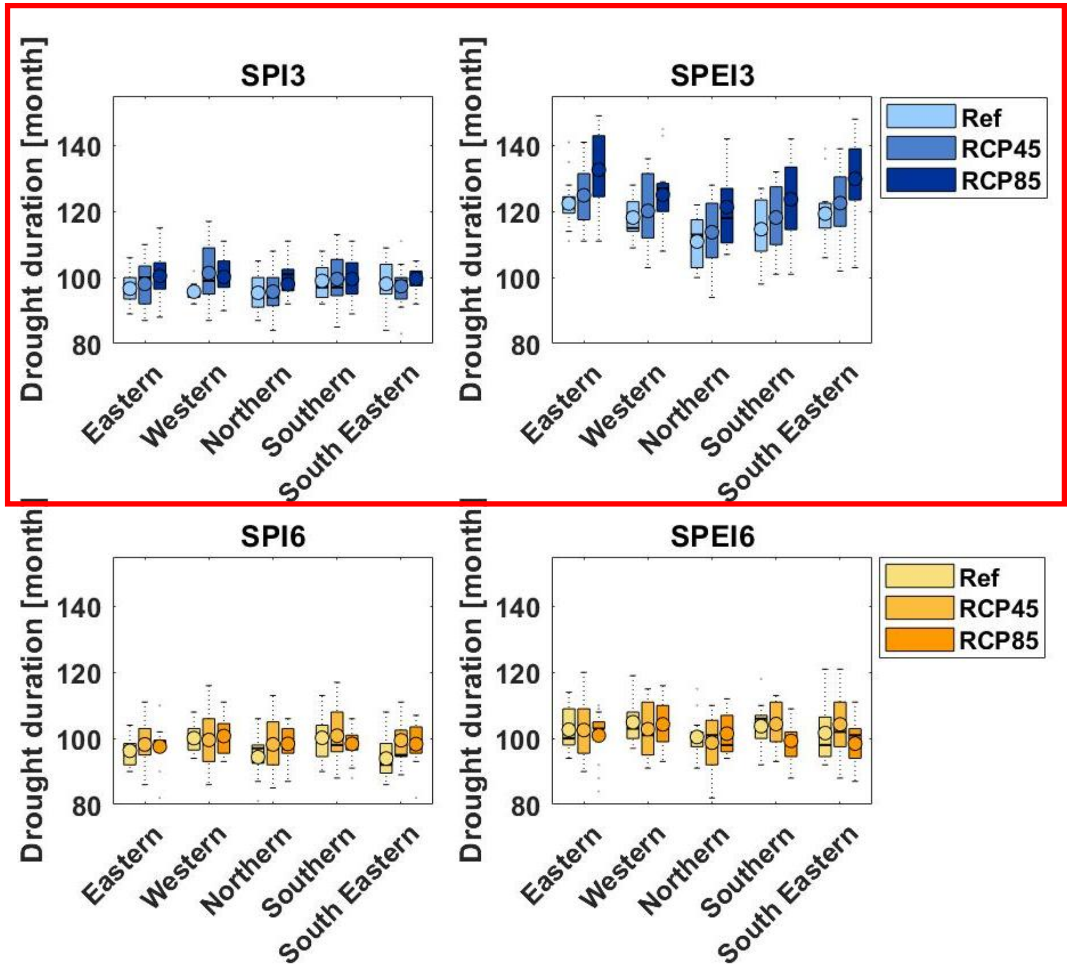
Code	GCM	RCM
CM1	CNRM_CM5	KNMIRACMO22E
CM2	CNRM_CM5	RMIBUGentALARO
CM3	CNRM_CM5	CLMcomCCLM4
CM4	EC_EARTH	KNMIRACMO22E
CM5	HadGEM2_ES	KNMIRACMO22E
CM6	HadGEM2_ES	CLMcomCCLM4
CM7	HadGEM2_ES	DMIHIRHAM5
CM8	MPI_ESM_LR	MPICSCREMO2009
CM9	MPI_ESM_LR	CLMcomCCLM4
CM10	NorESM1_M	DMIHIRHAM5
CM11	GFDL_ESM2G	GERICSREMO2015

RCP4.5 – Middle of the Road
RCP8.5 – Late Action Scenario

Changes in drought magnitude and duration



Drought Magnitude



Drought Duration

Changes in seasonal drought magnitude: SPI

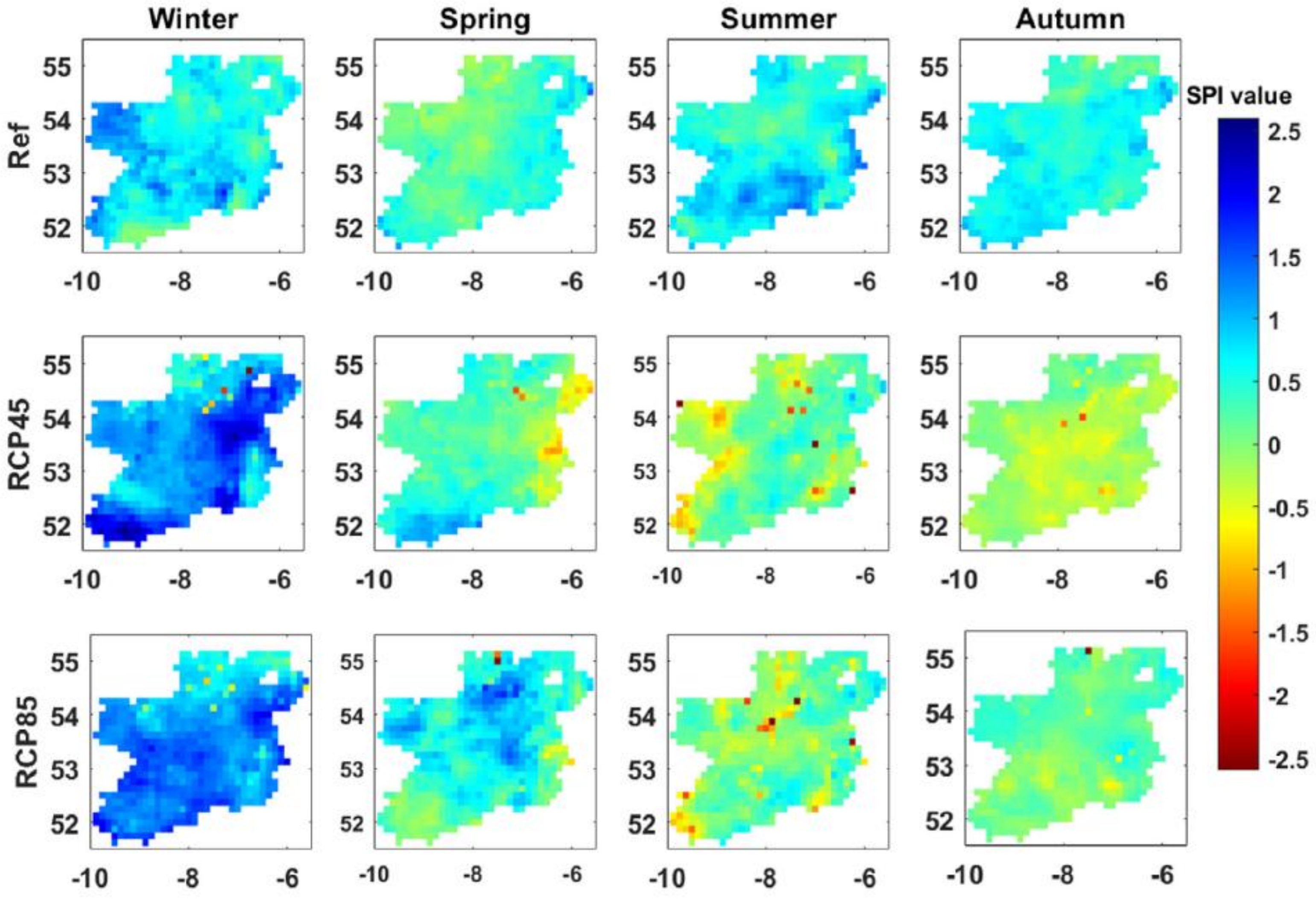


FIGURE 8 Ensemble mean projected changes in seasonal average SPI values for the reference period and far future (2080s) under RCP4.5 and RCP8.5. Each season is represented by SPI-3 for the last month of the season (i.e., summer is August SPI-3)

Changes in seasonal drought magnitude: SPEI

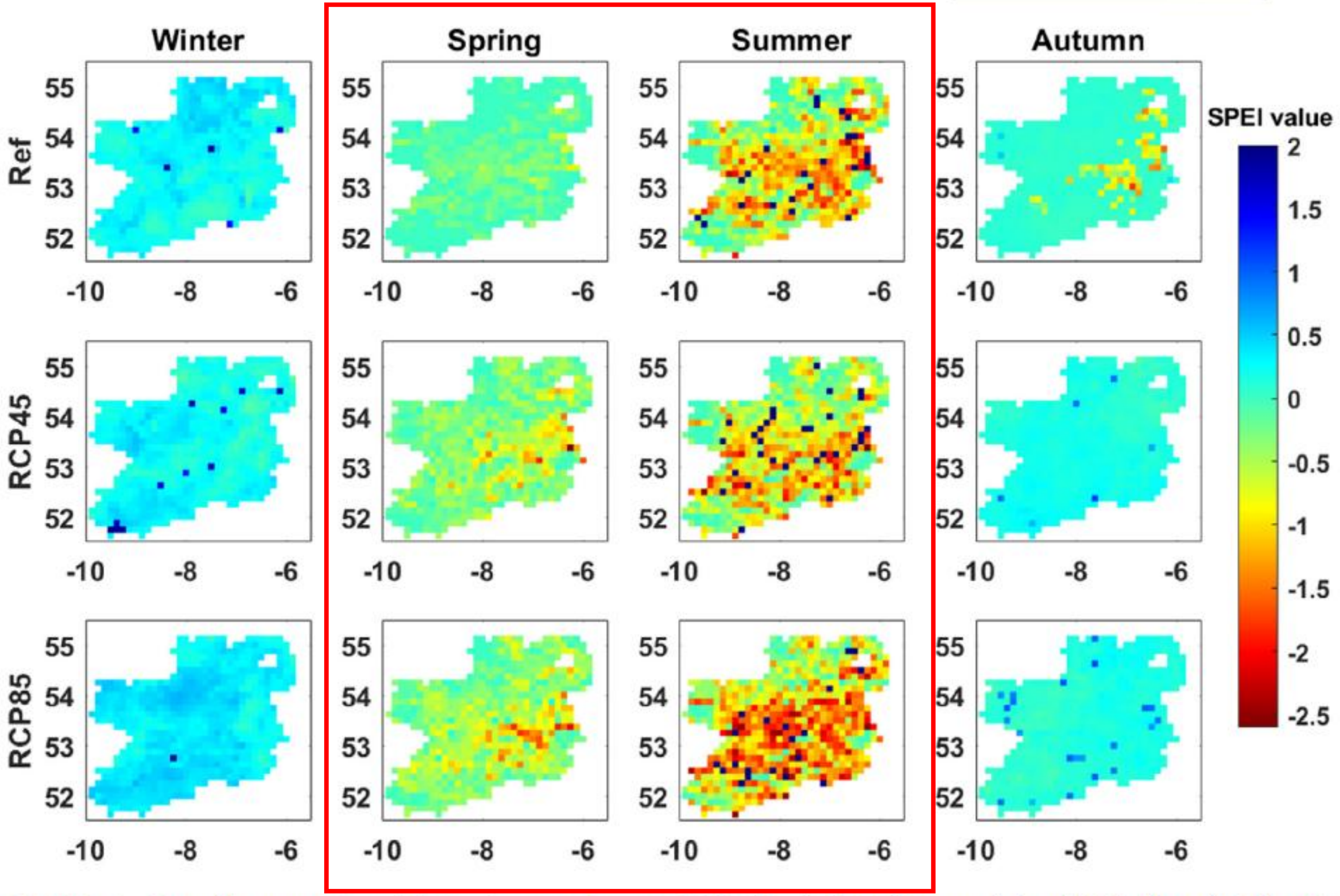


FIGURE 9 Ensemble mean projected changes in seasonal average SPEI values for the reference period and 423 far future (2080s) under RCP4.5 and RCP8.5. Each season is represented by SPEI-3 for the last month of 424 the season (i.e., summer is August SPEI-3)

4 take home messages

1. Projected changes in seasonal and mean flows show a wide range of plausible changes. However, the overall distribution of changes derived suggest increases in winter flows and decreases in summer flows.

2. Substantial reductions in low flows (annual Q95) are also projected for the 2050s and 2080s across catchments, which would also prove problematic for a range of sectors. Reduced greenhouse gas emissions result in more modest impacts on summer flows and low flows, whereby reductions under SSP126 by the 2080s are more modest in comparison to more fossil fuel intensive scenarios.

3. We find increased drought magnitude, frequency and duration, especially using SPEI relative to SPI and for the high emissions pathway (RCP8.5) relative to the more moderate RCP4.5. Results highlight the importance of temperature and associated increases in potential evaporation, and greenhouse gas emissions to future drought risk. Greatest risks are in the east and midlands where increases in SPEI droughts extend from spring to summer.

4. We are already seeing the signal of climate change emerge in observations. The projected changes would have significant implications and require substantial efforts at adaptation. Increases in winter flows and decreases in summer flows, together with increased drought could prove problematic for water resources management, freshwater ecosystems and water quality.