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The emergence of a climate change signal in long-term Irish meteorological observations

Conor Murphy [a,*], Amy Coen [b], Ian Clancy [b], Victoria Decristoforo [b], Steven Cathal [b], Kevin Healion [b], Csaba Horvath [a], Christopher Jessop [b], Shane Kennedy [b], Rosalynd Lavery [b], Kevin Leonard [b], Ciara McLoughlin [b], Rory Moore [b], Daire O'Hare-Doherty [b], Ricky Paisley [b], Bipendra Prakash [b], Julie Vatu [b], Peter Thorne [a], Carla Mateus [a], Ciara Ryan [c], Simon Noone [a]

[a] *Irish Climate Analysis and Research UnitS (ICARUS), Department of Geography, Maynooth University, Co. Kildare, Ireland*
[b] *MSc Climate Change Class of 2022, Department of Geography, Maynooth University, Co. Kildare, Ireland*
[c] *Climate Services, Met Éireann, Dublin, Ireland*

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A B S T R A C T

Detecting the emergence of a forced anthropogenic climate change signal from observations is critical for informing adaptation responses. By regressing local variations in climate onto annual Global Mean Surface Temperature (GMST), we track the emergence of an anthropogenic signal in long-term quality assured observations of temperature and precipitation for the island of Ireland, a sentinel location on the western European Atlantic seaboard. Analysis of station based observations, together with island scale composite series is undertaken for annual and seasonal means, together with 16 indices of extremes, with the derived signal-to-noise ratio classified as normal, unusual or unfamiliar relative to early industrial climate. More than half of indices show the emergence of at least unusual conditions relative to early industrial climate. The increase in annual mean temperature has led to the emergence of unfamiliar climate at six of eleven stations. Warming at the island scale is estimated at 0.88 °C per degree warming in GMST. While many stations show the emergence of unusual climate for spring, summer and autumn mean temperature, no forced signal of change is found for winter mean temperature. Changes in cool/warm days and nights are unfamiliar relative to early industrial climate. However, no anthropogenic signal is found for the hottest day annually or in summer – an extreme often associated with climate change in public consciousness. Increases in annual precipitation totals have emerged as unusual for western stations with large increases in winter totals per degree warming in GMST (e.g., 25.2% and 19.7% at Malin Head and Markree, respectively), indicating heightened flood risk with continued warming. By contrast, summer precipitation shows no significant relationship with GMST. Increases in rainfall intensity have emerged as unusual for 30% of stations, with increases consistent with the Clausius-Clapeyron relationship. Our analysis shows that an emerging climate change signal is discernible for Ireland, a location strongly influenced by climate variability.

1. Introduction

Discerning a forced anthropogenic climate change signal in observations is important for public communication and for identifying impacts that require adaptation, especially where the magnitude of change exceeds the local amplitude of climate variability to which society may be adapted (Sutton et al., 2015; Hawkins et al., 2020). Detection and attribution of a climate change signal in observations been the focus of numerous international studies, often at large regional scales to maximise the signal-to-noise ratio. For instance, Mahlstein et al. (2011, 2012) demonstrated the emergence of a climate change signal from temperature observations most notable in the tropics during boreal summer, while Lehner et al. (2017) highlighted the emergence of observed temperature change from the noise of background variability in winter and summer in the northern extratropics. For precipitation, Min et al. (2011) showed that the signal of change in extreme precipitation was detectable and attributable to human activity over large parts of the northern hemisphere.

* Corresponding author.
E-mail address: conor.murphy@mu.ie (C. Murphy).

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More recently, Hawkins et al. (2020) demonstrated that significant changes in temperature and precipitation observations are evident over many parts of the world compared to the magnitude of past variations, highlighting that many regions are already experiencing a climate which would be unknown by late 19th century standards. In addition to evaluating global datasets, Hawkins et al. (2020) employed long-term observations of station-based temperature series (for Oxford) and gridded precipitation data (for the UK). By regressing these local datasets onto global mean surface temperature (GMST), they quantified the signal of anthropogenic climate change (as represented by GMST) and the noise, or local variations, not explained by variations in GMST to quantify where in the UK the signal of change has emerged from the noise of background variability. Using the language of Frame et al. (2017) to describe how climate has changed from being familiar to unusual or unknown relative to lived experience, Hawkins et al. (2020) show that temperatures in Oxford have become unknown relative to early industrial conditions, while for precipitation clear shifts towards increased annual totals in northern and western UK, together with increases in extreme rainfall are emerging from background variability. Ossó et al. (2022) used the same framework to examine the emergence of new climate extremes over Europe relative to a recent baseline of 1951–1983, representative of 'living memory', for societally relevant impact metrics.

Numerous Irish studies have developed, quality-assured and evaluated variability and change in long-term records of temperature and precipitation. Noone et al. (2016) developed an Island of Ireland precipitation network of monthly precipitation stations dating back to 1850, finding increases in winter and decreases in summer precipitation totals. Ryan et al. (2021) presented a network of 30 daily precipitation stations across Ireland extending to a common start date of 1910, finding evidence for increases in precipitation intensity in the east and south-east, and an increasing contribution of heavy and extreme precipitation events to annual totals. Mateus and Potito (2021, 2022) quality assured and assessed trends from a network of daily maximum and minimum temperature observations for 11 stations across Ireland dating back to 1885. While each of these studies detected trends and one relates changes to key modes of climate variability (Mateus and Potito, 2022), none go beyond the evaluation of consistency with climate model simulations as a means of attributing detected change (Merz et al., 2012). Here, we employ these long-term datasets, together with the methods developed by Hawkins et al. (2020), to examine the emergence of forced climate change signals in Irish meteorological observations. Ireland, located on the Atlantic margins of western Europe, offers a stern test for detecting emerging climate change signals given the large variability of climate in this sentinel location. The remainder of the paper is organised as follows: section 2 presents the data and methods employed, before the results are presented in section 3. Findings are discussed in section 4 before key conclusions are distilled in section 5.

2. Data and methods

Following Hawkins et al. (2020), we produce estimates of the signal-to-noise ratio $\left(\frac{S}{N}\right)$ for changes in observed climate indices by linearly regressing local variations in climate onto annual Global Mean Surface Temperature (GMST) change

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

where $L(t)$ is the local change in temperature and precipitation indices (see below) over time, $G(t)$ is a smoothed version of GMST anomalies over the same period, $\propto$ is the linear scaling between L and G, and β is a constant. Significance of $\propto$ is evaluated at the 0.10 level. To calculate $G(t)$, we derive annual anomalies in GMST relative to 1850–1900 (representative of the early industrial era (see Hawkins et al., 2017; Hawkins et al., 2020)) from the Berkely Earth temperature dataset for 1850–2018 (Rohde et al., 2013) combined with HadSST4 from Kennedy et al. (2019). Data were downloaded from the KNMI Climate Explorer (https://climexp.knmi.nl/getindices.cgi?WMO=BerkeleyData/t2m_land_ocean_best&STATION=Berkeley_land_ocean_temperature&TYPE=i&id=someone@somewhere) and smoothed using a Loess filter with a span of 0.25. The signal of global temperature change is defined as the value of the smoothed GMST in 2018 ($G_{2018} = 1.24$ K), the signal of local climate change described by GMST is $\propto G$ and the noise component is defined as the standard deviation of the residuals ($L - \propto G$). We apply the terminology of Frame et al. (2017) to describe how climate has changed from being normal or familiar ($\left|\frac{S}{N}\right| < 1$), to being unusual ($\left|\frac{S}{N}\right| > 1 < 2$)), unfamiliar ($\left|\frac{S}{N}\right| > 2 < 3$), and unknown ($\left|\frac{S}{N}\right| > 3$), relative to the early industrial period.

The analysis is performed for indices representing seasonal and annual means and extremes from available, quality-assured and homogenised long-term temperature and precipitation data for stations across the island of Ireland. While all series contain in excess of 100 years of record, they commence at different times (e.g., 1885 for annual and seasonal mean and daily extreme temperature indices, 1851 for annual and seasonal total precipitation indices, and 1910 for daily extreme precipitation indices). In all cases, smoothed GMST (1851–2018) is used as G, with regression performed only over the period for which local temperature and precipitation data are available. Following Hawkins et al. (2020), the signal relative to the early industrial era can still be calculated assuming that the estimated regression parameter alpha ($\propto$) is representative of the whole period and that the signal is always $\propto G_{2018}$, irrespective of the period used to calculate $\propto$. We use 2018, given that this is the common end year of available temperature and precipitation data (see sections 2.1 and 2.2). We only provide a central estimate of results in the text, but results for all indices and stations analysed, including $\propto$, its standard error, and the signal-to-noise ratio $\frac{S}{N}$ (henceforth SNR) are provided in Supplementary Information. In addition, we present results for all derived models and, where appropriate, highlight where no significant relationship with GMST is found, with p-values for all models reported in Supplementary Information.

2.1. Temperature data and indices

Mateus and Potito (2022) provide annual and seasonal daily extreme air temperature indices for 11 stations for the period 1885 to 2018. Historical daily maximum and minimum air temperature data were rescued from multiple sources, including manuscripts, newspapers, proceedings and monographs (Mateus et al., 2020, 2021) and quality-assured using a semi-automatic procedure comprising inter- and intra-station consistency checks, evaluation of step changes and persistence tests (Mateus and Potito, 2021). Suspected outliers were manually examined through inspection of metadata and documentary sources, with quality-controlled series for the period 1885 to 1960 merged with pre-existing digital series from 1961 onwards (Mateus and Potito, 2021). Data were further quality-controlled and homogenised using MASHv3.03 software (Szentimrey, 2017; Mateus and Potito, 2022). Mateus and Potito (2022) used these data to extract 16 indices as defined by the Expert Team on Climate Change Detection and Indices (ETCCDI; climdex.org) for evaluation of changes in the frequency, duration and intensity of daily extreme air temperatures for 11 stations. Table 1 provides an overview of the resultant annual and seasonal ETCCDI temperature indices evaluated as part of this study, while Fig. 1a shows the distribution of the 11 stations. We also evaluate changes in annual and seasonal mean temperature, with seasons and their constituent months defined as winter [DJF], spring [MAM], summer [JJA] and autumn [SON]. Finally, for all indices, we derive an island of Ireland series by taking the mean of all indices across the 11 stations.

2.2. Precipitation data and indices

Precipitation data comes from two sources. First, monthly

Table 1
Details of the ETCCDI temperature indices evaluated for each station. Tick marks indicate which indices were assessed for the 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 °C and the 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	✓	✓	✓	✓	✓

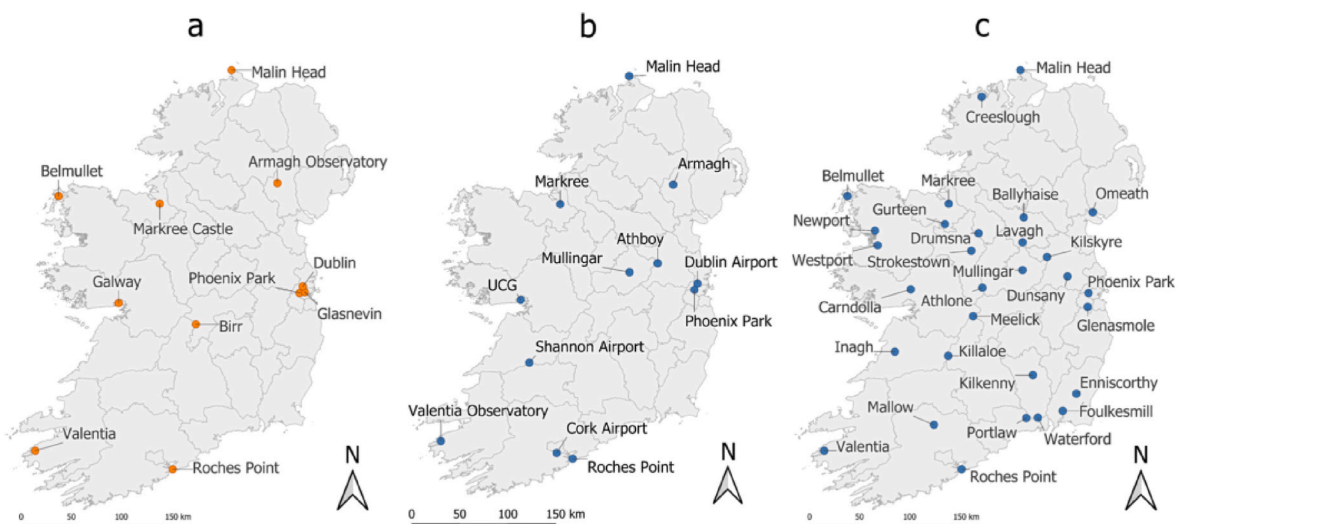

Fig. 1. Location of stations used for mean and extreme temperature indices (a), annual and seasonal precipitation totals (b) and extreme precipitation indices (c).

precipitation data is taken from Noone et al. (2016), who developed long-term (1850–2016) quality-assured and homogenised series for 25 statons across the island of Ireland. Following the transcription of paper-based records and bridging with available digital series, Noone et al. (2016) applied the HOMogenisation softwarE in R (HOMER) tool to detect and correct breaks (Mestre et al., 2013). Here, we employ 12 stations for which data were readily available from Met Éireann to update the series to 2018. Fig. 1b shows the location of each of the 12 stations. These long-term monthly precipitation series are used to derive annual and seasonal precipitation totals, while an island of Ireland composite series is derived as the mean across all 12 stations.

The second precipitation data source comprises daily precipitation series for 30 sites across Ireland for the period 1910–2018, produced by Ryan et al. (2021). The spatial distribution of stations is shown in Fig. 1c. These data are the outcome of data rescue efforts to digitise pre-1940 daily precipitation series (Ryan et al., 2018, 2020). Quality-control of rescued data was carried out before the creation of the long-term series by joining with available post-1940 series from Met Éireann's database. Homogeneity testing was then carried out using RHtests software (Ryan et al., 2021; Wang and Feng, 2013). For each series, 5 ETCCDI indices for annual precipitation extremes, representing changes in intensity and frequency, were extracted and analysed (Table 2). We do not include

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)

duration indices, given that Ryan et al. (2021) find no evidence of significant trends in consecutive dry or wet days at any station. In deriving indices, a wet day is defined as a day with ≥1 mm precipitation, while the common 30-year base period used to define thresholds for percentile-based indices is 1961–1990. We also derive an island of Ireland composite series for each indicator.

3. Results

3.1. Temperature indices

3.1.1. Annual and seasonal mean temperature

Fig. 2 maps the SNR (derived using the methods described in 2.1) for each station for annual and seasonal mean temperature, while Fig. 3 shows the SNR range across each station. Annual mean temperature shows the emergence of unfamiliar climate relative to early industrial for six stations, with the remaining five showing the emergence of unusual climate. The largest changes are evident for Phoenix Park, Glasnevin, Dublin, Roches Point, Malin Head and Galway. Dublin-based stations show the largest signal of change with an increase of 1.14 °C in annual mean temperature per degree warming in annual GMST (See SI). For winter mean temperature, while increasing trends predominate, no station shows the emergence of unusual climate (i.e., SNR < 1). Spring mean temperature shows the emergence of unfamiliar conditions for Phoenix Park, Glasnevin and Dublin (SNR > 2), with all other stations showing the emergence of unusual conditions relative to early industrial. For spring, Dublin and inland stations tend to show warming of >1 °C per degree warming in annual GMST, while coastal stations show warming of <1 °C per degree warming in annual GMST. All but two stations show the emergence of unusual climate in summer mean temperatures, with Armagh and Birr classed as normal, despite increasing trends. No station shows the emergence of unfamiliar climate in summer. For all stations the rate of warming in summer is less than 1 °C per degree warming in annual GMST. Finally, for autumn mean temperature, all stations show the emergence of unusual climate relative to early industrial. Phoenix Park, Glasnevin, Dublin, Armagh and Birr each show a rate of warming of ~1.2 °C per degree warming in annual GMST.

3.1.2. Annual ETCCDI temperature indices

Fig. 3 shows boxplots of the SNR range across stations and indicators, while Fig. 4 maps the SNR for each. Annual temperature extremes show large variation in the emergence of a climate change signal. Cold Spell Duration (CSDI) shows decreasing trends for all stations, with five showing the emergence of unusual conditions relative to early industrial (Dublin-based stations, Birr and Armagh). Warm Spell Duration (WSDI) shows increasing trends at all stations, but only Malin Head shows the emergence of unusual conditions. In relation to Frost Days (FD), no significant relationship is found with annual GMST at Belmullet, but all other stations show decreasing trends in FD, with six stations showing the emergence of unusual conditions relative to early industrial. Growing Season Length (GSL) is increasing at all stations, though for Valentia, no significant relationship is found with annual GMST. For GSL, the emergence of unusual conditions relative to early industrial are found for Glasnevin, Birr and Armagh. There is large variability in the extension of GSL across stations ranging from 7.8 days (Roches Point) to 29.4 days (Birr) per degree warming in annual GMST (See SI). Changes in the Diurnal Temperature Range (DTR) show no significant relationship with annual GMST at Roches Point, Valentia, Markree and Belmullet, while decreases in DTR at Phoenix Park and Armagh show the emergence of unusual conditions. Other stations remain within the normal range relative to early industrial climate.

Coldest night time temperatures (TNn) are dominated by increasing trends across the station sample, with the emergence of unusual conditions at the three Dublin stations and Markree. No significant relationship with annual GMST is found for Malin Head, Galway and Valentia. Phoenix Park, Glasnevin and Markree show the largest ∝ with warming of >2 °C at these stations per degree increase in annual GMST. Hottest night time temperatures (TNx) are also dominated by increases across stations. The emergence of unusual conditions relative to early industrial is evident for Phoenix Park, Dublin, Birr, Armagh and Belmullet. Large variations in ∝ are found ranging from 1.4 °C at Birr to 0.4 °C at Roches Point per degree increase in annual GMST. No significant relationship with GMST is found for Markree, Galway or Malin Head.

The coldest day (TXn) shows increases across all stations, but no significant relationship with GMST at Armagh. Two stations (Glasnevin and Dublin) show the emergence of unusual climate relative to early industrial. For the hottest day (TXx), increasing trends predominate, but only Roches Point, Armagh and Belmullet show a significant relationship with GMST. No station shows the emergence of unusual conditions for TXx. Cool days (TX10p) show decreases and a significant relationship with GMST at all stations. Both Malin Head and Birr show the emergence of unfamilar climate relative to early industrial, with all other stations showing the emergence of unusual climate. Simiarly, cool nights (TN10p) show decreases at all stations, but a non-significant relationship with GMST at Belmullet. The three Dublin stations and Birr show the emergence of unfamiliar conditions, while Roches Point, Valentia, Markree and Armagh show the emergence of unusual conditions. Western and northwestern stations show normal conditions. Decreases in cool days and nights show among the largest SNR of all annual ETCCDI indices analysed (Fig. 3).

Warm nights (TN90p) show increases and a significant relationship

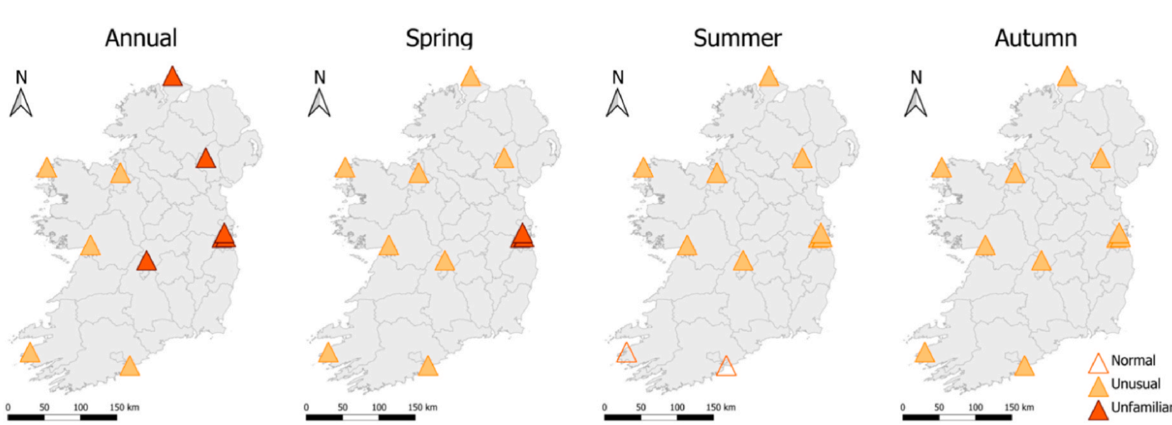

Fig. 2. Signal to Noise Ratio (SNR) for annual and seasonal mean temperature for each station. SNR values are categorised as 0 = Normal, 1 = Unusual, 2 = Unfamiliar, with darker triangles indicating unusual and unfamiliar. The direction of the triangle reflects the direction of the long-term trend. Only indices showing the emergence of unusual climate for at least one station are plotted.

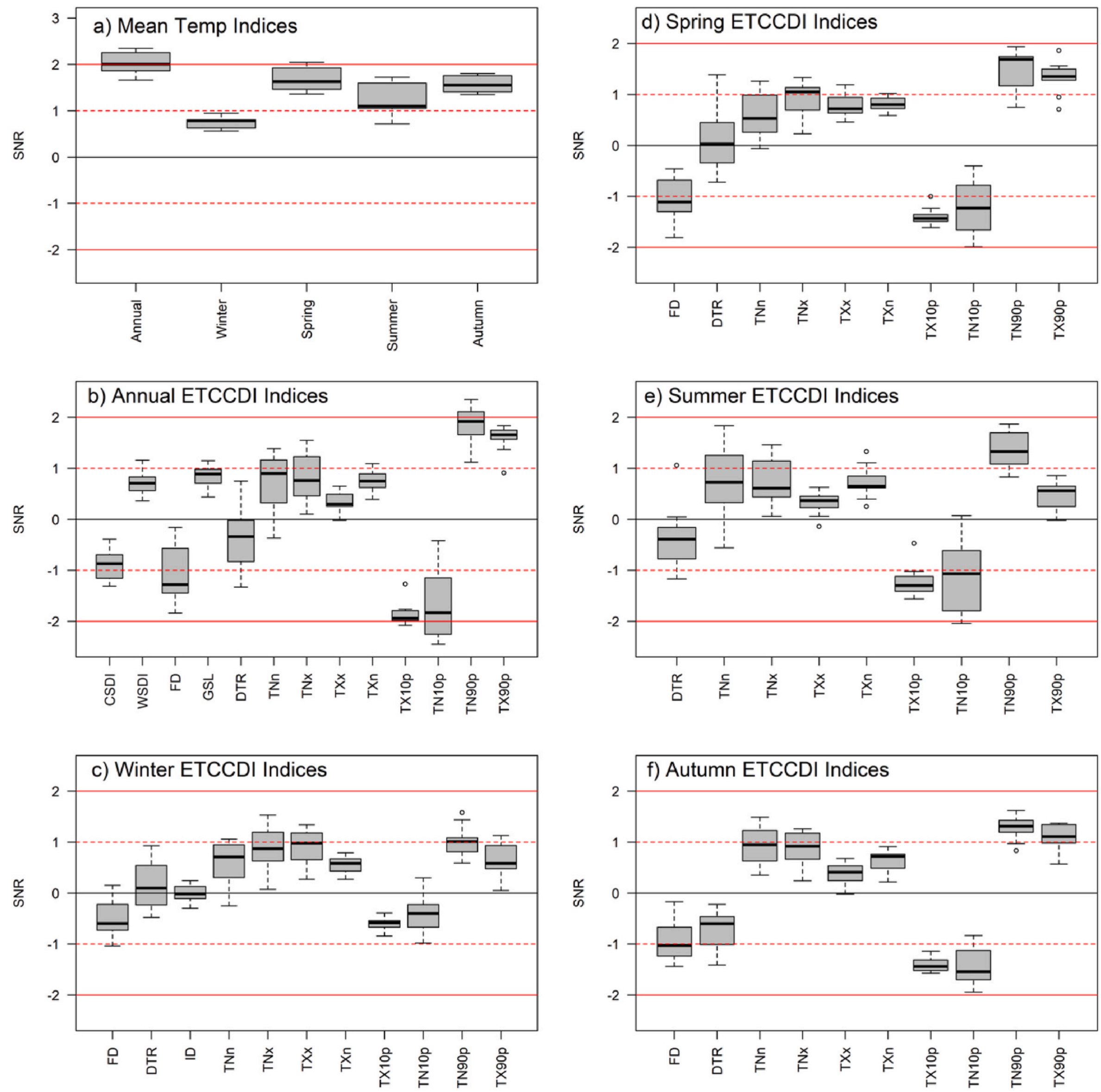

Fig. 3. Boxplots of the signal-to-noise ratio for annual and seasonal mean and ETCCDI indices for the station sample. The dashed horizontal line represents the threshold for unusual relative to early industrial, while the solid horizontal line represents the threshold for unfamiliar climate.

with GMST at all stations. Five stations (Phoenix Park, Birr, Armagh, Belmullet, Dublin) show the emergence of unfamiliar climate, with all other stations showing the emergence of unusual conditions relative to early industrial. ∝ ranges from an increase of 3.9% per degree warming in annual GMST at Markree, to an increase of 8.2% at Belmullet. Warm days (TX90p) show a significant relationship with GMST at all stations with the emergence of unusual climate everywhere except Markree. Increases in warm days per degree warming in GMST range from 3.0% at Markree to 7.6% at Roches Point. Increases in warm nights (TN90Pp) and warm days (TX90p) show the largest SNR of all ETCCDI indices (Fig. 3).

3.1.3. Seasonal ETCCDI temperature indices

Fig. 3 shows the SNR range for each index across stations, while Fig. 5 shows a heatmap of the SNR for all stations and seasons. The Supplementary Information Figs. S1–S4 map the distribution of the SNR for each station by season. For winter [DJF] only five of eleven indices show the emergence of at least unusual conditions since early industrial for at least one station. The number of frost days (FD) shows decreases at all stations but is only classed as unusual at Birr, with all other stations remaining within the normal range. Similarly, the coldest night (TNn) shows increases at all stations, except Belmullet, with only Phoenix Park emerging as unusual. No significant relationship between GMST and TNn is found for Malin Head, Galway and Valentia.

The hottest night (TNx) in winter shows increases at all stations, with unusual conditions emerging at Malin Head, Birr, Armagh and Belmullet. All other stations remain in the normal category. The hottest day (TXx) shows increases at all stations, classed as unusual predominantly in the south and southwest at Roches Point, Birr, Galway and Valentia. At Markree and Belmullet, no significant relationship between the hottest day and GMST is found. The largest increase in the hottest winter day per degree warming in GMST is found for Armagh (0.97 °C) and Galway (0.93 °C) (See SI). Warm nights (TN90p) show increases at all stations, classed as unusual at Malin Head and Armagh. In winter, the largest proportion of stations emerging from normal is returned for warm days (TX90p), with increases classed as unusual at six stations (Roches Point, Malin Head, Birr, Galway, Valentia and Belmullet). Galway and Valentia show the largest ∝ with increases in warm days per degree warming in GMST of 9.5% and 8.9%, respectively (See SI).

All ten indices analysed for spring [MAM] show the emergence of

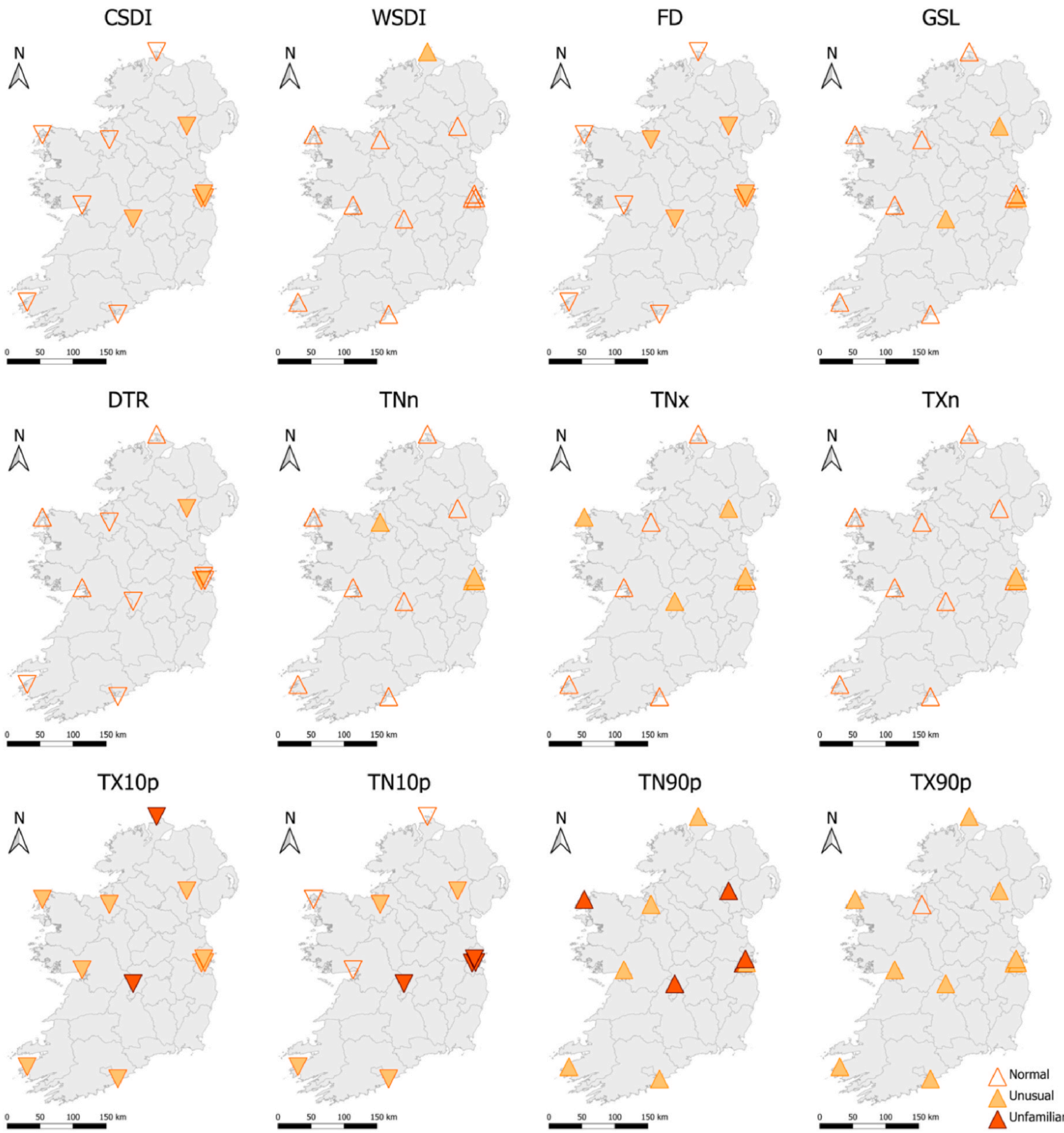

Fig. 4. As Fig. 2 but for annual ETCCDI temperature indices. Only indices showing the emergence of unusual climate for at least one station are plotted. See Table 1 for a full description of indicators.

unusual climate for at least one station (Figs. 3 and 5). The largest proportion of stations showing the emergence of unusual climate is found for cool days (TX10p), cool nights (TN10p), warms days (TX90p) and warm nights (TN90p). For each of these indices all stations show a significant relationship with GMST. For cool days (TX10p), all stations show the emergence of unusual climate relative to early industrial, with changes ranging from −11.4% to −5.7% per degree warming in GMST at Dublin and Roches Point, respectively. For cool nights (TN10p), while all stations show increases, the signal of change has not emerged from normal for stations along the west coast.

Notable summer changes include decreases in the percentage of cool days (TX10p), unusual at all stations except Roches Point (Figs. 3 and 5). Warm nights (TN90p) show increases at all stations, with the emergence of unusual conditions relative to early industrial at all stations except Malin Head and Markree. Notably, the hottest summer day (TXx) only shows a significant relationship with GMST at Armagh, but even here remains within normal conditions relative to early industrial. The hottest summer night (TNx) shows increases at all stations, classified as unusual at Phoenix Park, Dublin, Birr, Armagh and Belmullet. Birr shows the largest increase in the hottest night (1.35 °C) per degree warming in GMST. Notably, no significant relationship between the TNx and GMST is found for Malin Head, Galway, or Markree.

Eight of ten indices show the emergence of unusual climate relative to early industrial in at least one station in autumn (Figs. 3 and 5). Both the hottest (TXx) and coldest (TXn) day indices remain in the normal category, with many stations showing no significant relationship between TXx and GMST. All stations show the emergence of unusual climate for cool days (TX10p). Decreases in autumn cool days per degree warming in GMST are greatest for Dublin (−10.2%). Cool nights (TN10p) also show widespread decreases, emerging as unusual at all stations except Galway and Belmullet. Similarly, warm days (TX90p) and nights (TN90p) show widespread increases and the emergence of unusual conditions at most stations. Increases in autumn warm days is greatest at Roches Point, with an increase of 11.9% per degree warming

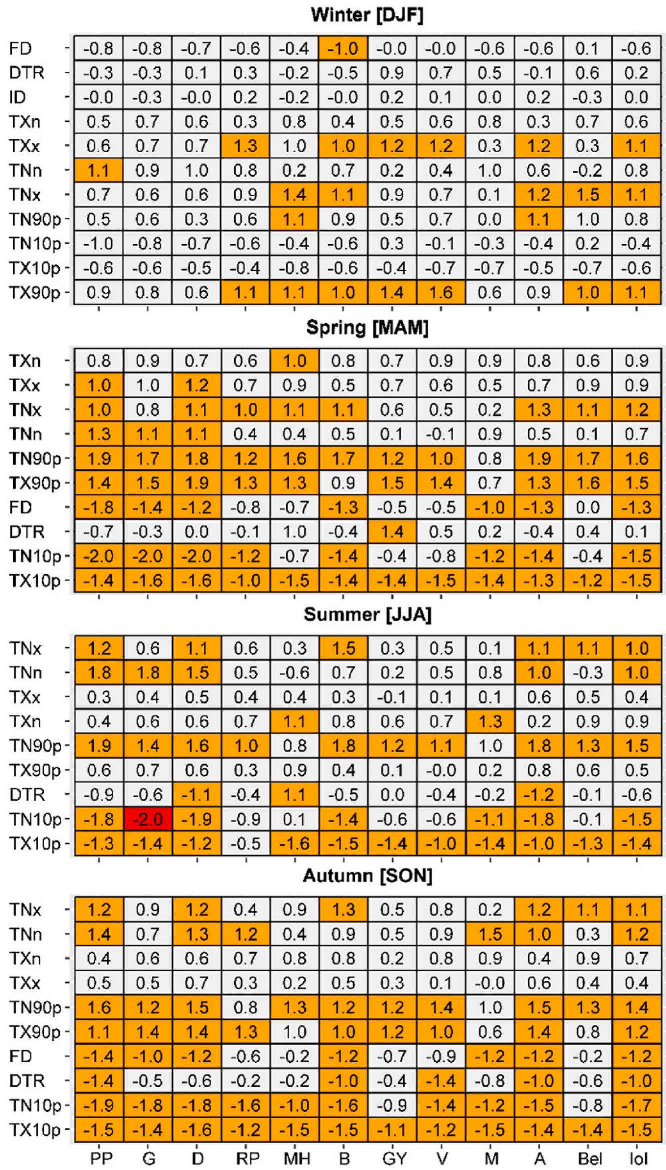

Fig. 5. Heatmap showing the Signal to Noise Ratio (SNR) for seasonal ETCCDI temperature indices at each station. SNR values are categorised as Normal (no shading), Unusual (orange shading) and Unfamiliar (red shading). Stations are abbreviated as Phoenix Park (PP), Glasnevin (G), Dublin (D), Roches Point (RP), Malin Head (MH), Birr (B), Galway (GY), Valentia (V), Markree (M), Armagh (A), Belmullet (Bel), and the composite series representing the Island of Ireland (IoI). Supplementary Figures S1–S4 map the SNR for each index/season/station. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in GMST.

3.2. Precipitation indices

Results for annual and seasonal precipitation totals are mapped in Fig. 6, with boxplots showing the SNR range across the 12 stations presented in Fig. 7. Fewer precipitation indices show the emergence of a clear signal given the large variability (noise) of precipitation (Hawkins et al., 2020), despite sometimes large percentage changes per degree warming in GMST ($\propto$) (Fig. 8). For annual totals, stations are dominated by increases. Valentia, Mullingar, Markree and Malin Head show the emergence of unusual climate relative to early industrial. Cork, Roches Point and Armagh annual totals show no significant relationship with GMST. For stations that do show a significant relationship largest increases (%) in precipitation per degree warming in GMST are returned for Mullingar (12.1), Valentia (11.8), Markree (10.9) and Malin Head (10.4) (see SI). All other stations show $<$ 10% increases in annual precipitation totals per degree warming in annual GMST.

Winter precipitation totals are also dominated by increases (Fig. 6). However, only Malin Head shows the emergence of unusual climate relative to early industrial, with increases at other stations classed as normal and yet to emerge from variability (although the SNR for Markree is 0.98 and at the upper limit of the normal classification). Regression models show no significant relationship with GMST at Roches Point, Cork, Athboy and Armagh. For other stations, the largest increases (%) in winter totals per degree warming in GMST are evident for Malin Head (25.2), Markree (19.7), Mullingar and Galway (both 18.3) (see Fig. 8 and SI Tables).

For spring, summer and autumn, no stations show the emergence of unusual climate relative to early industrial and remain within normal range (Fig. 7). Overall, spring totals show increases, and summer totals decreases at most stations. However, in spring, only Valentia, Shannon, Mullingar and Markree show a significant relationship with GMST. The largest increase in spring totals per degree warming is returned for Markree (10.3%) (see Fig. 8 and SI). In summer, no station shows a significant relationship with GMST. Autumn totals show a significant relationship with GMST at most stations, with the exception of Roches Point, Cork and Armagh. All stations show increasing trends, but do not as yet emerge from variability (Fig. 7). The largest increases (%) in autumn totals per degree warming in annual GMST are returned for Mullingar (17.2) and Valentia (17.0) (Fig. 8 and SI).

SNR maps for annual precipitation extremes are also shown in Fig. 6. All indices are dominated by increasing trends, but few stations show the emergence of at least unusual conditions relative to early industrial climate. For maximum 1-day precipitation amounts (RX1day), few stations show a significant relationship with GMST (3/30 stations). This increases to 11/30 stations for maximum 5-day precipitation amounts (RX5day), but only Malin Head shows the emergence of unusual climate with an increase of 16.8% in RX5day per degree warming in GMST (Fig. 8). Other stations which show a large $\propto$ but fall short of classification outside normal include; Foulksmills (14.6%; SNR: 0.81), Inagh Mt. Callan (15.4%; SNR 0.99), Ballyhaise (16.0%; SNR: 0.83), Athlone (15.2%; SNR: 0.91), and Killaloe Docks (14.2%; SNR: 0.91) (Fig. 8).

Very wet day totals (R95pTOT) show a significant relationship with GMST at 18/30 stations, with changes classed as unusual relative to early industrial at six (Mallow, Newport, Drumsna, Malin Head, Carndolla, Kilkenny Lavistown). The percentage change in R95pTOT per degree warming in GMST for these stations ranges from 33.8% at Mallow to 46.5% at Carndolla (Fig. 8 and SI). For extremely wet day totals (R99pTOT), 12/30 stations show a significant relationship with GMST with two stations in the southeast (Foulksmills and Kilkenny Lavistown), showing the emergence of unusual climate relative to early industrial. Two further stations (Inagh and Mullingar) have SNR values close to unusual at 0.94 and 0.98, respectively (Fig. 6). Large increases in R99pTOT per degree warming in GMST are evident for these four stations, ranging from 60.6% at Inagh to 67.9% at Mullingar (Fig. 8 and SI).

For the Simple Daily Intensity Index (SDII), 18/30 stations show a significant relationship with GMST, with 9 stations showing the emergence of unusual climate relative to early industrial. With the exception of Malin Head, these stations tend to be located south of a diagonal line from Mayo to Wexford (Fig. 6). Of all stations showing a significant relationship with GMST, the average increase in intensity is 8.2% per degree warming, which is in line with the Clausius-Clapeyron relationship of 6–7% per degree warming (Pall et al., 2007). Stations with the highest SNR show increases per degree warming in GMST ranging from 7.6% at Roches Point (SNR:1.00) to 13.7% at Kilkenny Lavistown (SNR: 1.72) (Fig. 8).

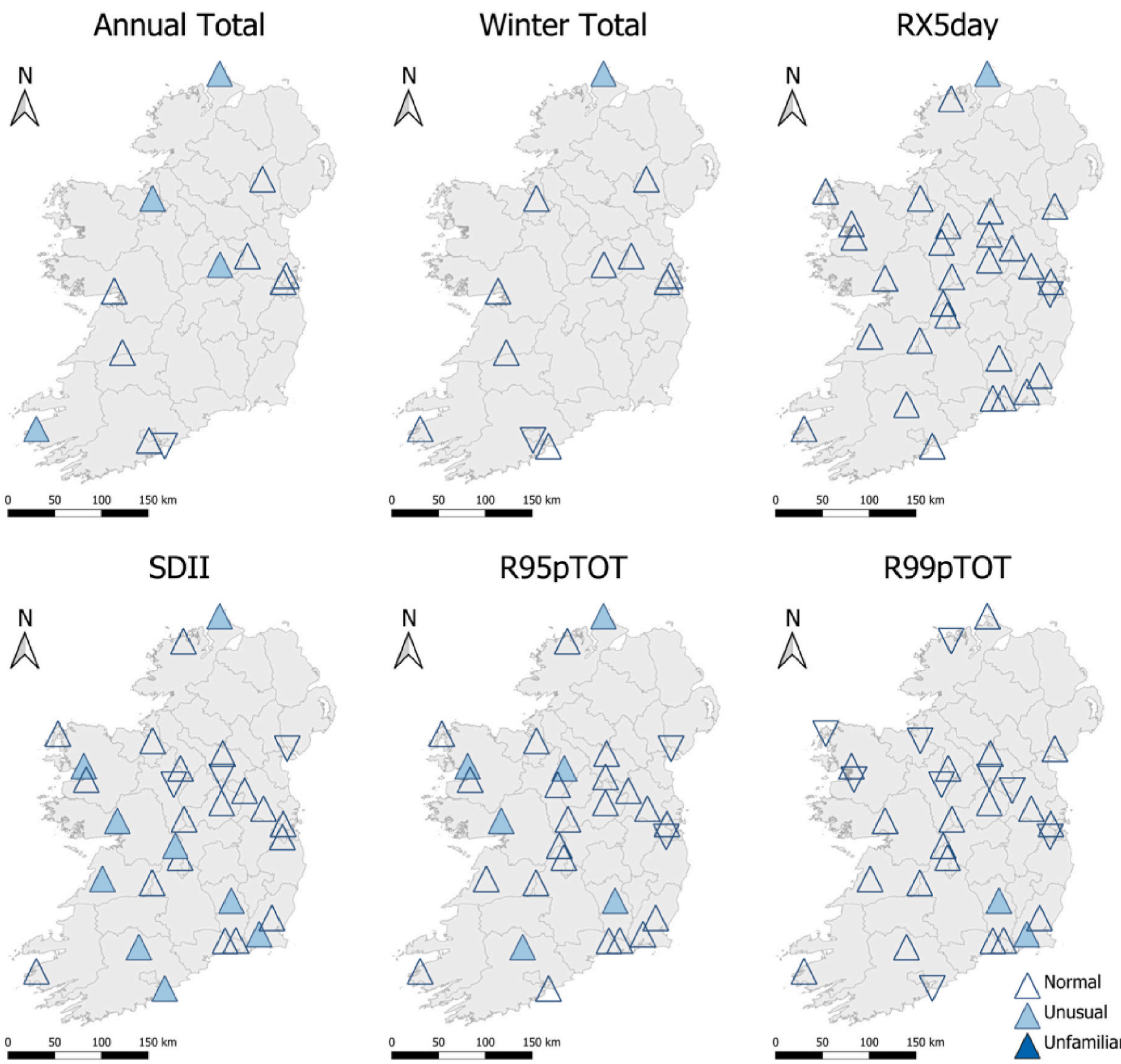

Fig. 6. Signal to Noise Ratio (SNR) for precipitation indices. SNR values are categorised as 0 = Normal, 1 = Unusual, 2 = Unfamiliar with darker triangles indicating unusual and unfamiliar. The direction of the triange refelects the direction of the long term trend. Only indices showing the emergence of unusual climate for at least one station are plotted. See Table 2 for a full description of indicators.

3.3. *Island of Ireland composite series*

To evaluate the SNR at the island scale, we employ composite series for each indicator, calculated as the mean across all available station series. Results for each temperature and precipitation indicator are shown in Fig. 9. Four indices show the emergence of unfamiliar climate (SNR > 2) at the island scale. Annually, cool days (TX10p) and cool nights (TN10p) have decreased to unfamiliar levels with a SNR of −2.00 and −2.05, respectively. The 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 6.8% per degree warming in GMST, while the annual mean temperature for the island of Ireland shows an increase of 0.88 °C per degree of global warming (see SI).

Numerous indices show the emergence of unusual climate relative to early industrial (Fig. 9). The number of frost days (FD; SNR -1.31), cold spell duration index (CDSI; SNR -1.29), warm days (TX90p; SNR 1.73) and the hottest night time temperature (TNx; SNR 1.12) show changes that are unusual relative to early industrial climate. Spring (SNR 1.75), summer (SNR 1.35) and autumn (SNR 1.62) mean temperature each emerge as unusual at the island scale, with both spring and autumn showing a rate of warming greater than 1 °C per degree warming in GMST (see SI). For summer mean temperature, warming is more muted at 0.76 °C per degree warming in GMST. Growing season length (GSL; SNR 1.13) also emerges as unusual at the island scale, with an increase of 18.2 days per degree warming in GMST. Of the precipitation indicators assessed, the Simple Daily Intensity Index (SDII; SNR 1.30), maximum 5-day precipitation amounts (RX5day; SNR 1.00) and very wet day totals (R95pTOT; SNR 1.10) emerge as unusual relative to early industrial. Increases in each precipitation index per degree warming in GMST are 5.6% (SDII), 8.5% (RX5day) and 18.3% (R95pTOT) (see SI).

A number of indices show consistent changes across seasons. Increases in warm days (TX90p) are classed as unusual in winter, spring and autumn. Increases in the hottest night (TNx) and warm nights (TN90p), and decreases in cool nights (TN10p) and cool days (TX10p) each emerge as unusual relative to early industrial climate in spring, summer and autumn. Only in winter do increases in the hottest day (TXx) emerge as unusual at the island scale, while decreases in the number of frost days (FD) is classed as unusual in spring and autumn. A total of ten indicators show no significant relationship with GMST at the island scale. For temperature, these include the hottest day (TXx) annually and in summer and autumn, cool nights (TN10p) in winter,

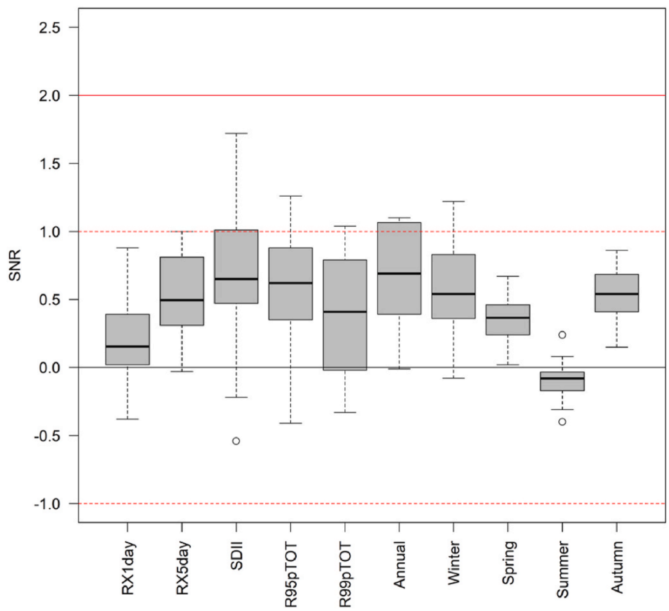

Fig. 7. Boxplots of the signal-to-noise ratio for annual and seasonal precipitation totals, together with annual ETCCDI precipitation indices from the station sample. The dashed horizontal line represents the threshold for unusual climate relative to early industrial, while the solid horizontal line represents the threshold for the emergence of unfamiliar climate. See Table 2 for a full description of indicators.

winter ice days (ID) and the diurnal temperature range (DTR) in winter and spring. For precipitation, spring and summer totals and RX1day show no significant relationship with GMST.

4. Discussion

As highlighted by Sutton et al. (2015), GMST is a remote concept to most people, with regional and local changes in climate affecting people and ecosystems most directly. Moreover, internal variability is the dominant factor in people's experience of day-to-day and year-to-year variations in weather, particularly in mid-latitude regions such as Ireland. Therefore, it is important to assess how the magnitude of forced changes through increased greenhouse gases compares relative to internal variability at the local scale. For Ireland, the largest SNR was found for annual mean temperature with warming for the island of Ireland composite series estimated at 0.88 °C per degree increase in GMST and the SNR categorised as unfamilar relative to early industrial climate. For the island as a whole, a lower rate of warming than GMST is likely due to the moderating influence of North Atlantic and the Atlantic Multi-decadal Oscillation (AMO), in particular on annual mean temperature (McCarthy et al., 2015). Nonetheless, five stations, typically eastern and midland stations, show a rate of warming greater than GMST with an increase of 1.14 °C in annual mean temperature per degree warming in GMST at Phoenix Park and in excess of 1 °C at Armagh, Birr, Dublin and Glasnevin.

Notably, while warming is evident for all seasons, the signal does not emerge from variability for winter at any station, nor in the island of Ireland series. Winter mean temperature returns the lowest signal and largest noise component, averaged across stations. Mateus and Potito (2022) find that winter temperature indices show the strongest correlation with the winter North Atlantic Oscillation (NAO) index. Summer mean temperatures show the lowest noise component averaged across stations. While many stations show the emergence of unusual climate, the rate of warming is less than 1 °C per degree increase in GMST. Seasonally, the largest SNR in mean temperature is observed for the shoulder seasons of spring and autumn. Both show greater noise than winter and summer, but the signal of change is larger in both seasons, especially in spring. These findings are consistent with Osborn et al. (2017), who find that long-term warming in spring, summer and autumn for central England is even more apparent after accounting for local scale variability, whereas warming in winter is weaker and less apparent after local variability is accounted for.

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. For the island of Ireland composite series, annual cool days (TX10p), cool nights (TN10p) and warm nights (TN90p) show the emergence of unfamiliar conditions (SNR > 2) relative to early industrial climate. Seasonally, the SNR across stations tends to be smallest for winter and largest for spring. As for mean temperature, 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 (Matthews et al., 2016), 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. That the emergence is clearer for the 90th percentile occurrence TX10p/TX90p and TN10p/TN90p than the most extreme values may highlight that the variability in the most extreme values is still considerably larger than any emerging signal, whereas the more 'common' extremes exhibit much clearer changes.

For precipitation, fewer stations/indicators show the emergence of a climate change signal from local scale noise. Similar to findings by Hawkins et al. (2020), this is likely due to the large interannual and multidecadal variability of precipitation, relative to temperature indices. Increases in precipitation are evident annually and for winter, spring and autumn. Increases in annual totals emerge as unusual relative to early industrial climate at Valentia, Mullingar, Markree and Malin Head. In winter, precipitation totals are strongly correlated with the winter NAO index (Murphy et al., 2018), with only increases at Malin Head emerging as unusual. However, many stations show substantial increases in winter totals per degree warming in GMST (e.g., 25.2% at Malin Head and 19.7% at Markree). With continued warming, such increases in winter precipitation would have substantial consequences for fluvial and groundwater flooding (Morrissey et al., 2020; Meresa et al., 2021; Murphy et al., 2023), even if global temperature increase is maintained at no more than 2 °C. While modest decreases in summer precipitation are found, no station shows a significant relationship with GMST, with associated uncertainty as to how climate change is likely to impact summer precipitation and associated drought and water resource management challenges (Meresa et al., 2022, 2023). McCarthy et al. (2015) and Sutton and Dong (2012) demonstrate the strong relationship between variability in the AMO and summer precipitation totals in Ireland.

Annual ETCCDI precipitation indices show a significant relationship with GMST at numerous stations. Hawkins et al. (2020) show the signal of change in extreme precipitation has emerged from variability in parts of northern and western UK. In Ireland, we find similar results for rainfall intensity, whereby for SDII more than half of stations show a significant relationship with GMST, with 9 showing the emergence of unusual climate relative to early industrial. The average increase in intensity for stations showing a significant relationship with GMST is 8.2% per degree warming, consistent with the Clausius-Clapeyron relationship of 6–7% per degree warming (Pall et al., 2007). For other extreme precipitation indices, we find less evidence for the emergence of a clear climate change signal. While Min et al. (2011) find evidence of increases attributable to human activity in RX1day and RX5day precipitation across many northern hemisphere land areas, no Irish station shows the emergence of a signal for RX1day and only Malin Head and the Island of Ireland composite series show the emergence of unusual climate for RX5day precipitation.

The emergence of a climate change signal in observations depends on

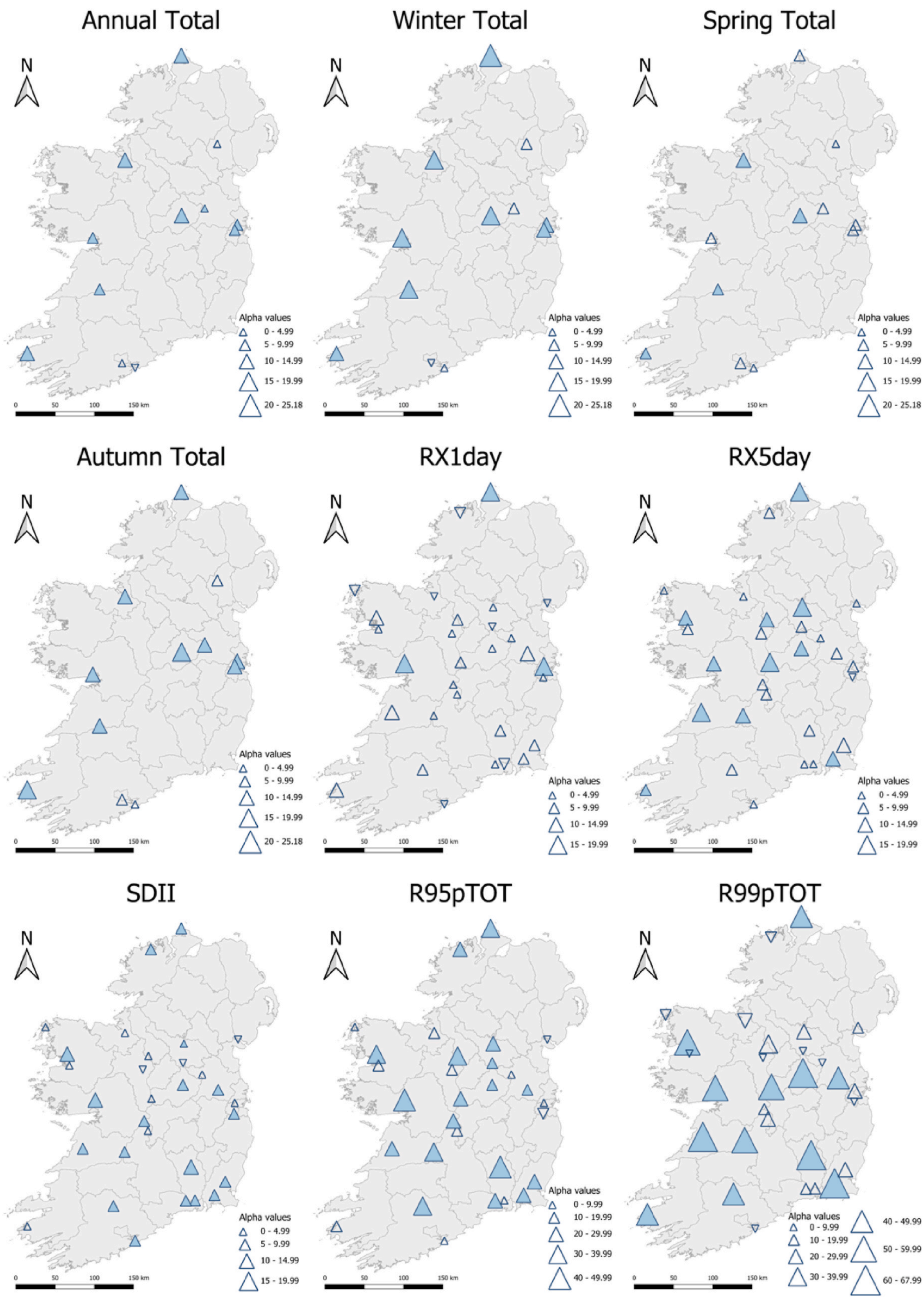

Fig. 8. Alpha (∝) values as % change per degree warming in GMST for annual and seasonal precipitation totals and annual ETCCDI precipitation extremes for each station. The size and direction of the triangle representing each station shows the magnitude and direction of change, while empty triangles indicate no significant (0.10 level) relationship with GMST. Note that summer precipitation totals are not shown, as no station shows a significant relationship with GMST.

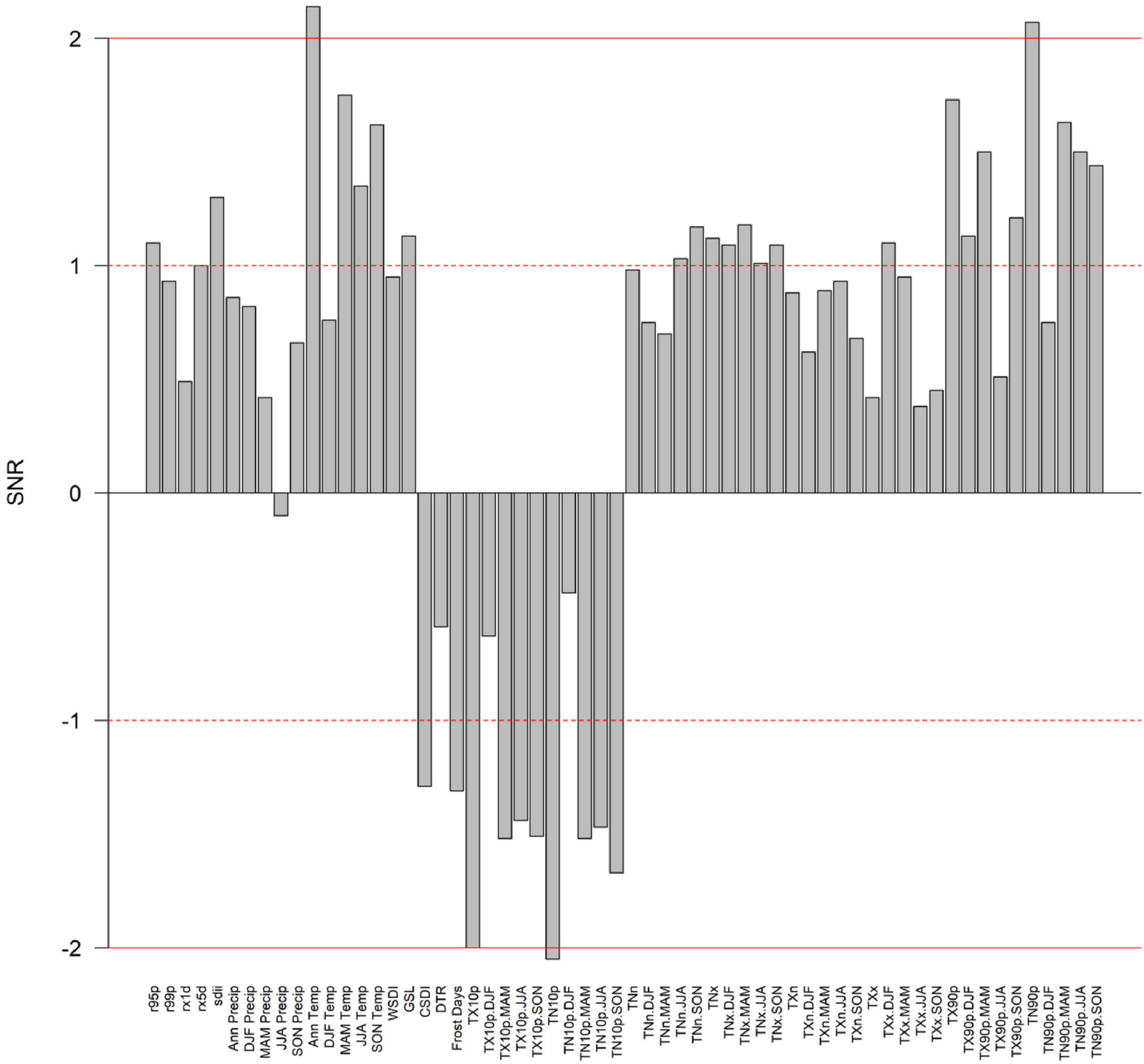

Fig. 9. Barplot of the signal to noise ratio for each indicator for the Island of Ireland series. The sign of SNR shows the direction of the long-term trend. The dashed horizontal line represents the threshold for the emergence of unusual climate, while the solid horizontal line represents the threshold for the emergence of unfamiliar climate relative to early industrial. See Tables 1 and 2 for a full description of indices.

the indicator of interest and the spatial and temporal scale of analysis (Sutton et al., 2015). Here we find that the emergence of at least unusual climate relative to early industrial is more common for temperature indices than for precipitation, given the large variability of the latter. Development of our Island of Ireland composite series typically smoothes out local scale noise evident for individual series. For some indices, analysis at the Island of Ireland scale can result in the detection of a climate signal even where few contributing stations return a clear signal (e.g., RX5day precipitation). While useful for our purposes, we recognise that the island of Ireland series may not be truly representative due to the sparsity of long-term stations, especially for precipitation, given its greater spatial variability relative to temperature.

GMST is a powerful predictor of forced climate response, with all of the warming in GMST attributable to human activity (Haustein et al., 2017; Chen et al., 2021; IPCC et al., 2021). However, not all indices/stations show a significant relationship with GMST and care should be taken in extending our results to other indices/stations. The method deployed allows linearly scaling local changes in forced climate responses to changes in GMST, a key metric for international mitigation and adaptation policy and impacts assessment. This has utility in linking forced local scale changes to observed warming at a global scale and to key international policy objectives associated with the Paris Agreement (e.g., stabilisation of global mean temperatures at 1.5 or 2 °C above pre-industrial). However, care is required in this regard as GMST as a predictor provides little information about internal variability at the local scale and future forced changes in local climate may be non-linear (Sutton et al., 2015). Future work might compare linearly scaled changes from observations presented here with those derived from pattern-scaled climate model projections (e.g., Osborn et al., 2016). Finally, this work was only possible due to efforts taken by previous research to rescue and quality-assure long-term records of temperature (Mateus et al., 2020, 2021; Mateus and Potito, 2021, 2022) and precipitation (Noone et al., 2016; Ryan et al., 2018, 2021, 2022). Continued efforts at data rescue of existing series in paper format (Mateus, 2021) would further increase confidence in the homogenisation methods deployed in creating these datasets and help to fill spatial gaps in our analysis. In addition, future work could focus on evaluating seasonal precipitation indices. Given that Ryan et al. (2022) only focus attention on assessing the homogeniety of annual precipitation series, we limited our attention to those.

5. Conclusion

Detection of forced climate change signals in observations is critical for public communication and informing robust adaptation responses. By regressing local scale changes onto global mean surface temperature following the method of Hawkins et al. (2020), this research identified the emergence of a climate change signal from background noise in long-term, quality-assured observations of precipitation and temperature across the island of Ireland. Thirty four of the annual and seasonal indices examined show the emergence of at least unusual conditions relative to early industrial climate. The largest changes were found for annual mean temperature, with changes categorised as unfamiliar relative to early industrial at six of eleven stations and at the island scale. While many stations show the emergence of unusual climate for spring, summer and autumn mean temperature, no forced signal of change was found for winter. Analysis of annual and seasonal ETCCDI extreme temperature indices revealed large changes in cool/warm days/nights, classed as unfamilar relative to early industrial for many stations and at the island scale. No forced signal of change was found for the hottest day annually or in summer. Increases in annual precipitation totals emerge as unusual relative to early industrial climate for western stations, while large increases in winter totals per degree warming in GMST are apparent, indicating increased flood risk with continued warming. Changes in summer precipitation show no relationship with GMST. Changes in rainfall intensity emerge as unusual at 30% of stations, with increases per degree warming in global mean surface temperature consistent with the Clausius-Clapeyron relationship. Our analysis allows linearly scaling local changes in forced climate responses to changes in global temperature, a key metric for international mitigation and adaptation policy and impacts assessment.

Author statement

Conor Murphy: Conceptualisation, Funding acquisition, Methodology, Software, Formal Analysis, Writing- Original Draft, Writing - Review & Editing. Amy Coen: Visualisation, Formal Analysis, Writing- Original Draft. Ian Clancy: Formal Analysis, Writing- Original Draft. Victoria Decristoforo: Formal Analysis, Writing- Original Draft. Steven Cathal: Formal Analysis, Writing- Original Draft. Kevin Healion: Formal Analysis, Writing- Original Draft. Csaba Horvath: Visualisation. Christopher Jessop: Formal Analysis, Writing- Original Draft. Shane Kennedy: Formal Analysis, Writing- Original Draft. Rosalynd Lavery: Formal Analysis, Writing- Original Draft. Kevin Leonard: Formal Analysis, Writing- Original Draft. Ciara McLoughlin: Formal Analysis, Writing- Original Draft. Rory Moore: Formal Analysis, Writing- Original Draft. Daire O'Hare-Doherty: Formal Analysis, Writing- Original Draft. Ricky Paisley: Formal Analysis, Writing- Original Draft. Bipendra Prakash: Formal Analysis, Writing- Original Draft. Julie Vatu: Formal Analysis, Writing- Original Draft. Peter Thorne: Writing - Review & Editing, Carla Mateus: Data Curation, Writing - Review & Editing. Ciara Ryan: Data Curation, Writing - Review & Editing. Simon Noone: Data Curation, Writing - Review & Editing.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Conor Murphy reports financial support was provided by the Irish Environmental Protection Agency and Met Éireann.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2023.100608.

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