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Long-term trends in daily extreme air temperature indices in Ireland from 1885 to 2018

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ABSTRACT

Long-term instrumental series are crucial to analyse extreme air temperature indices and to examine modern climate warming within a historical context. This research provides the first assessment in Ireland of the frequency, duration, intensity and geographical distribution of the daily extreme air temperature indices recommended by the ETCCDI (Expert Team on Climate Change Detection and Indices) and based on long-term rescued, quality-controlled and homogenised data. Prior analysis of air temperature indices in Ireland had focused on the period since the second half of the 20th century, where digital data were readily available. Earlier estimations of long-term air temperature trends in Ireland focused on non-homogenised data from a small network of stations. For this research, 11 long-term (1885–2018) maximum and minimum air temperature series were analysed to assess seasonal and annual trends and construct extreme air temperature indices in Ireland. The non-parametric Mann-Kendall test was employed to test the statistical significance of the maximum and minimum air temperatures and indices trends ($p < 0.05$). Significant increasing trends were assessed in the seasonal and annual maximum and minimum air temperature series in Ireland, with greater increases in the spring and autumn seasons. Significant increasing trends were determined in the warm days (+6.8 days), warm nights (+7.5 nights), warm spell duration index (+3.9 days), growing season length (+22 days), coldest night (+2.7 °C) and coldest day (+1.5 °C) in the period 1885–2018 in Ireland. In the same period, significant decreasing trends were identified in the cold days (−9.3 days), cold nights (−7 nights), frost days (−13.7 days), cold spell duration index (−6.9 days) and diurnal air temperature range (−0.1 °C) in Ireland. The results follow global patterns presented in the Six Assessment Report of the Intergovernmental Panel on Climate Change. The findings of this research will be crucial to assist stakeholders and policymakers in defining climate action, adaptation and mitigation plans in response to shifting trends in air temperature extremes.

1. Introduction

Climate change detection and attribution studies have shown that the release of greenhouse gases associated with human activity has contributed to the rise of surface air temperatures, especially during the second half of the 20th century (IPCC et al., 2021). The rise of surface air temperature associated with anthropogenic activity affected the increase in frequency and intensity of air temperature extremes (e.g. Kiktev et al., 2003; Christidis et al., 2005; IPCC et al., 2021). Global surface air temperature in 2001–2020 was 0.99 [0.84–1.10]°C, and in 2011–2020 was 1.09 [0.95 to 1.20]°C higher than 1850–1900, with greater increases over land (1.59 [1.34 to 1.83]°C) (IPCC et al., 2021).

Recent raw air temperature trends in Ireland display similarities with global air temperature trends and anomalies (McElwain and Sweeney, 2003, 2007; Butler et al., 2007; Cámaro-García et al., 2021). The long-term mean annual air temperature has registered an increase of 0.23 °C per decade in the period 1910–1949, a rise of 0.42 °C per decade in the term 1980–2004, and an increment of 0.7 °C in the interval 1890–2004 (McElwain and Sweeney, 2007). The average surface air temperature series for Ireland (calculated from five long-term series) has increased by approximately 0.9 °C in the period 1900–2019 (Cámaro-García et al., 2021). An increase of 0.5 °C in the annual mean air temperature has been identified in the period 1981–2010 compared to the 1961–1990 climate normal (Walsh, 2017). The number of annual warm spell days increased, whereas the annual number of cold spell days decreased in 1961–2018 in Ireland (Cámaro-García et al., 2021).

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According to regional climate modelling simulations (3.8 and 4 km), the warmest 5% of the daily maximum air temperatures are projected to increase for the period 2041–2060, ranging from 1.0 °C to 1.6 °C (RCP4.5 scenario) and from 1.4 °C to 2.2 °C (RCP8.5 scenario), with greater warming in the south than in the north of the Island of Ireland (Nolan and Flanagan, 2020). The coldest 5% of daily minimum air temperatures are projected to increase as well in 2041–2060, ranging from 0.9 °C to 1.8 °C (RCP4.5 scenario) and from 1.2 °C to 2.4 °C (RCP8.5 scenario), with greater warming in the north than in the south of the Island (Nolan and Flanagan, 2020).

In Ireland, warm spells in the period 1981–2006 led to an excess of 294 deaths (Pascal et al., 2013). The ageing of the population combined with the projected increase in frequency, intensity and duration of warm spells in Ireland is predicted to lead to higher vulnerability to heat extremes (Pascal et al., 2013). Environmental impacts during warm spell events include greater water consumption and water shortages exacerbated when linked with drought events, greater energy demand, crop failures, heat stress in cattle, and a higher risk of forest fires (e.g. Desmond et al., 2017; Mateus, 2021a).

Long-term instrumental observations are crucial to analyse past climate variability (e.g. IPCC et al., 2021). Climate change indices defined by the joint World Meteorological Organization Commission for Climatology (CCI)/World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI) (e.g. Karl et al., 1999; Peterson et al., 2001; Zhang et al., 2011) are fundamental to monitor climate change. The availability of long-term daily data is indispensable to a detailed assessment of changes in the frequency, intensity, duration and distribution of extreme air temperature ETCCDI indices from the global scale (e.g. Alexander et al., 2006; Dunn et al., 2020) to the country level (e.g. Keggenhoff et al., 2014). The long-term assessment and characterisation of past extremes, namely of rare extremes, is paramount to support climate action, mitigation and adaptation policies, reduce vulnerability, enhance resilience, and mitigate the impact of future events in the context of changing climate (e.g. Klein Tank et al., 2009; Desmond et al., 2017).

Ireland has a great legacy of historical meteorological observations with continuous long-term daily maximum and minimum air temperature observations dating from the 19th century and short-term series dating back to the 18th century (Mateus, 2021b). However, until recently (Mateus 2021a; Mateus et al., 2020), the majority of the historical daily maximum and minimum air temperature observations registered pre-1960s in Ireland were not digitised and primarily remained as handwritten registers and publications stored in various archives in Ireland and the UK. The lack of quality control and homogenisation procedures creates uncertainties in assessing air temperature trends and extreme events (e.g. Klein Tank et al., 2009). Prior research on air temperature trends in Ireland employed non-homogenised annual and seasonal data based on mean air temperature (1796–2002) and maximum and minimum air temperature series (1844–2002) from Armagh Observatory (Butler et al., 2005, 2007). Small networks of stations also based on non-homogenised maximum and minimum air temperature series were employed to assess trends in Ireland (McElwain and Sweeney, 2003, 2007; McKeown et al., 2012; Cámaro-García et al., 2021). McElwain and Sweeney (2003) analysed the mean annual Irish air temperature based on 4 stations for the period 1890–2000, and assessed the maximum and minimum seasonal data for 8 stations for 1960–2000. McElwain and Sweeney (2007) examined the mean annual air temperature for Ireland using a network of 4 stations for 1890–2004, and analysed the annual and seasonal maximum and minimum air temperatures for 11 stations for 1961–2005. McKeown et al. (2012) analysed the seasonal and annual mean, maximum and minimum air temperatures for 6 stations for 1875–2011. Cámaro-García et al. (2021) examined the annual mean surface air temperature for Ireland based on 5 stations for 1900–2019. To date, there has been no assessment of the frequency, duration, intensity and geographical distribution of the daily extreme air temperature ETCCDI indices and based on long-term quality-controlled and homogenised data from the late-19th century for Ireland. Previous research on air temperature indices has focused on the period with available digital observations to assess the diurnal air temperature range, the number of frost days, frost season length, heat wave duration and cold wave duration for 11 stations from the 1940s to 2005 (McElwain and Sweeney, 2007). The frequency of 'hot days' defined as a day with mean air temperature greater than 18 °C and 'cold days' outlined as a day with mean air temperature less than 0 °C has been analysed for 8 stations in Ireland from the 1940s to 2000 (McElwain and Sweeney, 2003); however, these definitions differ from the ETCCDI, which makes it difficult to compare results with other countries. Cámaro-García et al. (2021) assessed the cold spell days and warm spell days between 1961 and 2018 for 10 locations. Cold spells have been analysed for 11 stations in Ireland, typically from the 1950s onwards, although the definition employed differs from the ETCCDI (Hickey, 2011).

The objectives of this study were to assess the magnitude and statistical significance of trends of the maximum and minimum air temperature series in Ireland (arithmetic mean of the 11 stations) and assess geographical differences in the period 1885–2018. Additionally, the research assessed the magnitude and statistical significance of the frequency, duration and intensity of ETCCDI indices for 11 stations in Ireland over the same period. Temporal and geographical trends were analysed, and findings were interpreted with respect to European and global temperature and indices trends.

2. Material and methods

2.1. Study area

Oceanic, topographic, and latitudinal controls influence air temperatures in Ireland (Rohan, 1975). The major controls on Ireland's climate are the proximity of the North Atlantic Ocean and the westerly atmospheric circulation of the middle latitudes (Rohan, 1975). The North Atlantic Current acts to subdue Ireland's temperature range so that temperature extremes in the winter and summer are less than those from more continental countries at similar latitudes (Sweeney, 2014). Despite the small size of Ireland, the contrast in the air temperature gradient between coastal and inland areas is clear. The Atlantic Ocean and the Irish sea influence are greater near the coasts and decrease with the distance inland (Rohan, 1975). Hilly and mountainous terrain also allow shelter from strong winds and direct oceanic influences (Rohan, 1975). The contrast between coastal and inland air temperatures is more prominent in the winter, whereas the latitudinal influence on air temperature is more significant in the summer (Rohan, 1975; Sweeney, 2014). The temporal and geographical distribution of the pressure systems of Icelandic low, the Azores High, and the winter Siberian High also control the variation of the air temperatures in Ireland (Rohan, 1975; Sweeney, 2014).

During warm spells, slow-moving high-pressure systems can persist for a prolonged period over Ireland, blocking the jet stream and associated low-pressure systems to the north and resulting in dry and hot weather. The highest maximum air temperatures surpassing 30 °C are linked with the hot and dry tropical continental air mass, such as during the warm spell of June 2018 (Met Éireann, 2018). Dry cold periods of several days can occur with the extension of the continental anticyclone westwards, blocking the progression of depressions towards Ireland (Rohan, 1975). Strong and persistent negative phases of the North Atlantic Oscillation index (NAO) and the Arctic Oscillation index (AO) have been associated with cold spells in Ireland, such as during the winter of 2010 (e.g. Sweeney, 2014; Mateus, 2021a).

2.2. Daily maximum and minimum temperature data

Historical daily maximum and minimum air temperature observations for 11 long-term registered in the period 1831–1968 were rescued from multiple archives and data-sources, such as manuscripts, newspapers, proceedings and monographs (Mateus et al., 2020, 2021). Quality control and homogenisation of the data series are reviewed in detail in Mateus and Potito (2021). The rescued historical series (1885–1968) were quality-controlled through a semi-automatic quality control procedure consisting of climate consistency, internal consistency, day-to-day step-change and persistence tests (Mateus and Potito, 2021). The quality control tests were written in R software to flag doubtful values, which were manually examined through the inspection of metadata and documentary sources (Mateus and Potito, 2021). A total of 976,786 observations were quality-controlled, and 27,854 (2.9%) of the values were flagged (Mateus and Potito, 2021). The historical quality-controlled series (1885–1960) were merged with the digital series from 1961 onwards for 11 stations (Fig. 1), which were quality controlled by Met Éireann following the same tests (Walsh, 2017) and submitted to additional quality control and homogenisation testing in combination with station metadata through software MASHv3.03 (Szentimrey, 2017; Mateus and Potito, 2021).

2.3. Air temperature trends and daily extreme air temperature indices

Climate change indices were defined by the joint World Meteorological Organization Commission for Climatology (CCI)/World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI) (e.g. Karl et al., 1999; Peterson et al., 2001; Zhang et al., 2011). These ETCCDI indices have been widely used to assess changes in daily climate extremes of temperature at the global scale (e.g. Alexander et al., 2006; Dunn et al., 2020). The ETCCDI indices are employed to assess changes in the frequency, duration, and intensity of daily extreme air temperature events (Table 1). Extreme weather events can be classified according to rarity (assessed on frequency), intensity (determined with threshold exceedance), or socio-economic and environmental impacts (Beniston and Stephenson, 2004). Extreme rare events within the current climate can be defined as starting from the 90th percentile of the distribution and are more likely to have greater socio-economic and environmental impacts (Zwiers et al., 2013). The 16 ETCCDI air temperature indices can be divided into percentile, threshold, absolute and duration-based categories (Table 1).

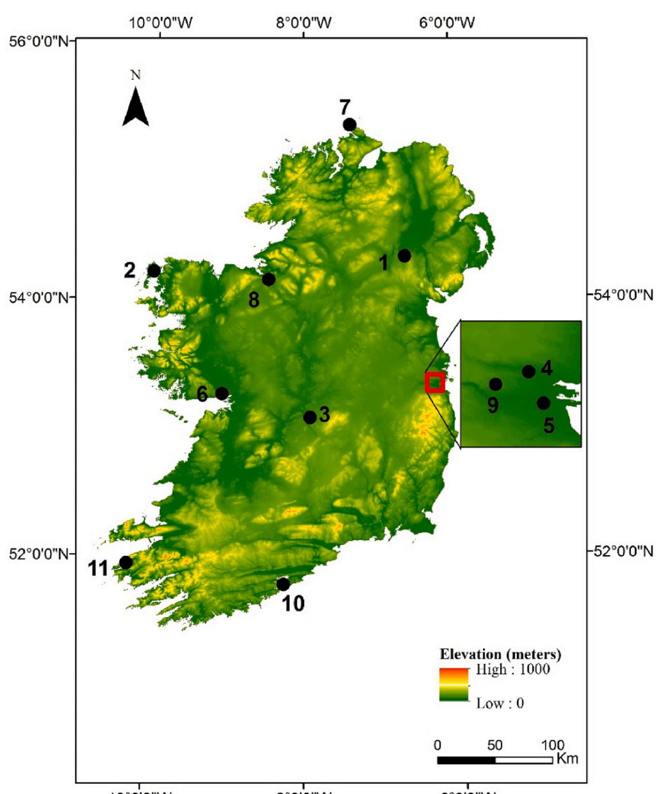

Fig. 1. Location of the long-term daily maximum and minimum air temperature series. 1 – Armagh Observatory, 2 – Belmullet, 3 – Birr, 4 – Botanic Gardens (Glasnevin), 5 – Dublin city, 6 – Galway, 7 – Malin Head, 8 – Markree, 9 – Phoenix Park (Dublin), 10 – Roches Point, 11 – Valentia Observatory. Raster source: NASA SRTM 90m and EUDEM 30m topography raster image.

The extreme air temperature indices were calculated in RStudio. The standard climate normal 1961–1990 was used as the baseline period, following the guidelines of the World Meteorological Organization (Zhang et al., 2011). The threshold-based indices were calculated in relation to standard climate normal 1961–1990 and following the bootstrapping method to avoid inhomogeneities (Zhang et al., 2005, 2011). The seasons were defined as winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November).

The magnitude of seasonal and annual air temperature trends and daily extreme air temperature indices were estimated linearly for the period 1885–2018. The non-parametric Mann-Kendall test (Mann, 1945;

Table 1
Extreme air temperature indices recommended by the ETCCDI. TX (daily maximum air temperature), TN (daily minimum air temperature), TM (daily mean air temperature).

Type	Acronym	Name	Definition	Units
Percentile	TX10p	Cool days	Percentage of days when TX < 10th percentile of 1961–1990.	Days
Percentile	TX90p	Warm days	Percentage of days when TX > 90th percentile of 1961–1990.	Days
Percentile	TN10p	Cool nights	Percentage of days when TN < 10th percentile of 1961–1990.	Days
Percentile	TN90p	Warm nights	Percentage of days when TN > 90th percentile of 1961–1990.	Days
Threshold	FD	Frost days	Annual count when TN < 0 °C.	Days
Threshold	ID	Ice days	Annual count when TX < 0 °C.	Days
Threshold	SU	Summer days	Annual count when TX > 25 °C.	Days
Threshold	TR	Tropical nights	Annual count when TN > 20 °C.	Days
Absolute	TXx	Max TX (hottest day)	Monthly maximum value of TX.	°C
Absolute	TNx	Max TN (hottest night)	Monthly maximum value of TN.	°C
Absolute	TXn	Min TX (coldest day)	Monthly minimum value of TX.	°C
Absolute	TNn	Min TN (coldest night)	Monthly minimum value of TN.	°C
Absolute	DTR	Diurnal temperature range	Monthly mean difference between TX and TN.	°C
Duration	WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile of 1961–1990.	Days
Duration	CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN < 10th percentile of 1961–1990.	Days
Duration	GSL	Growing season length	Annual count between the first span of at least 6 days with TM > 5 °C and first span after July 1st of 6 days with TM < 5 °C.	Days

Kendall, 1975) was employed to test the statistical significance of the air temperatures and indices trends at the 0.05 significance level ($p < 0.05$) against the null hypothesis of no trend, which was performed in the XLSTAT software. The Yue and Wang (2004) option in XLSTAT was used to correct for possible autocorrelation in the time-series. The 10-year moving average has been displayed in the graphs of seasonal and annual maximum and minimum air temperatures and the annual frequency of extreme air temperature indices to highlight decadal-scale variation within the 1885–2018 period.

3. Results and discussion

3.1. Air temperature trends

Ireland presents a significant positive trend in the annual maximum air temperature (+1.0 °C). Examining the seasonal series, greater significant trends were assessed in the spring (+1.4 °C) and autumn (+1.1 °C), followed by the summer and winter (+0.7 °C) series. A greater percentage of the stations with significant positive trends were identified in the annual, spring and autumn series (100%), followed by the winter (91%) and the summer (82%) (Fig. 2). The strongest increasing trends were assessed in the stations located inland and in the east, whereas Roches Point in the southwest is one of the stations with smaller increases in the annual, spring and winter series (Fig. 2). Nevertheless, a few coastal stations had strong and increasing trends in the summer (Malin Head: +1.0 °C) and the winter (Belmullet and Valentia Observatory: +0.8 °C). The strongest positive trends per annual and seasonal series were verified as follows: spring (Dublin city, +1.9 °C), summer (Malin Head and Birr, +1.0 °C), autumn (Dublin city, +1.5 °C), winter (Birr, Belmullet and Valentia Observatory, +0.8 °C) and annual (Botanic Gardens and Dublin city, +1.2 °C).

Ireland displayed a significant increasing trend in the annual minimum air temperature series (+1.1 °C). Greater significant positive trends were assessed in autumn (+1.6 °C) and spring (+1.4 °C), followed by summer (+0.9 °C), and winter (+0.7 °C) series. The geographical distribution of the percentage of stations with significant positive trends was distributed as follows: annual, spring and autumn (100%), summer (82%) and winter (55%) (Fig. 2). The stations located inland (Armagh Observatory and Birr) and in the East (Phoenix Park, Botanic Gardens and Dublin city) registered stronger positive trends, whereas the coastal stations at Galway, Valentia Observatory and Malin Head had smaller increases (Fig. 2). Stronger trends were identified in the spring at Phoenix Park (+2.2 °C) and in the autumn at Phoenix Park and Armagh Observatory(+2.1 °C), whereas weaker trends were registered in the summer at Valentia Observatory (+0.4 °C) (Fig. 2).

The highest positive anomalies of the summer maximum air temperature were verified in 1995, 1976, 1887, 2018, 1899, 1983 and 2006 (Fig. 3), which were associated with intense warm spells (Mateus, 2021a; Mateus and Potito, 2022). The strongest negative anomalies in the winter maximum and minimum air temperature were registered in 1895, 1963, 2010, 1917 and 1947 (Fig. 3), which also correspond with intense cold spells related to considerable socio-economic impacts (Mateus, 2021a; Mateus and Potito, 2022).

Air temperature trends in Ireland display similarities with global trends (IPCC et al., 2021). This research agrees with previous studies that the annual minimum air temperature has increased at a quicker rate than the maximum air temperature series in Ireland (McElwain and Sweeney, 2003, 2007; Butler et al., 2005, 2007; McKeown et al., 2012) and across the globe (e.g. Braganza et al., 2004; Alexander et al., 2006; IPCC et al., 2021). McElwain and Sweeney (2007), analysing the 1961–2005 period, indicated greater increases in the winter (+1.37 °C), followed by the spring (+1.16 °C), summer (+1.07 °C) and autumn (+0.83 °C) maximum air temperature series. However, after analysing the long-term trends from 1885 to 2018 and with more stations, stronger positive trends were assessed in the spring (+1.4 °C) and autumn (+1.1 °C) series in comparison to smaller increases in the summer and winter (+0.7 °C). For the minimum air temperature, McElwain and Sweeney (2007) indicated that in the period 1961–2005, greater increases were assessed in the summer (+1.34 °C), followed by the winter (+1.27 °C) and spring (+1.19 °C) in Ireland. Our longer-term data showed strong increasing trends in the autumn (+1.6 °C) and spring (+1.4 °C), and the smaller in summer (+0.9 °C), and winter (+0.7 °C), showcasing the importance of long-term and homogenised air temperature records for the assessment of trends.

While NAO exerts a strong influence on the Irish climate, the relationship is strongest in the winter and spring. The annual ($r = 0.175$), spring ($r = 0.339$), autumn ($r = 0.269$) and winter ($r = 0.347$) minimum air temperature series, and the spring ($r = 0.247$) and the winter ($r = 0.323$) maximum air temperature series for Ireland in 1885–2018 display statistical significance with the NAO[2]. The percentage of stations with statistical significance between the minimum air temperature and the NAO is distributed as follows: annual (36%: Roches Point, Markree, Galway and Valentia), spring (100%), autumn (91%: all stations with the exception of Malin Head) and winter (100%). The greatest correlations between the minimum air temperature and the NAO are displayed in Markree (spring, $r = 0.384$), Valentia (winter, $r = 0.368$) and Galway (autumn, $r = 0.358$). In the case of the maximum air temperature, statistical significance is represented in 100% of the stations in the winter and 64% in the spring (Phoenix Park Dublin, Botanic Gardens, Dublin city, Armagh, Birr, Roches Point and Malin Head). Dublin city stations displayed the greatest correlations between the NAO and the spring ($r = 0.374$) and the winter ($r = 0.369$) maximum air temperature series. The Irish winter maximum ($r = 0.664$) and minimum ($r = 0.663$) air temperature series have statistical significance with the AO[3] in 1899–2018. The winter maximum and minimum air temperature series registered at the 11 stations have statistical significance with the AO. The greatest correlations between the AO and the winter maximum air temperature ($r = 0.687$) and the winter minimum air temperature ($r = 0.659$) are shown in Dublin city and Galway, respectively.

3.2. Extreme air temperature indices

The annual number of ID registered significant decreasing trends at Phoenix Park (−0.1 days), Botanic Gardens (−0.1 days) and Birr (−0.2 days) (Fig. 4). The results follow the findings of Alexander et al. (2006), who reported a significant decreasing trend in ID in 27.4% of the global area. More ID were registered at Birr (100), Armagh Observatory (78), Phoenix Park (65), and Markree (49). The highest number of ID was recorded in 2010 (Fig. 5), one of the coldest periods on record: 13 at Birr, 11 at Armagh Observatory, 10 at Galway, 9 at Phoenix Park, 8 at Markree, 4 at Dublin city, and 3 at Botanic Gardens, which were associated with cold spells (Mateus, 2021a; Mateus and Potito, 2022). In Ireland, ID are projected to decrease by 68% in the RCP4.5 scenario and by 78% in the RCP8.5 scenario in 2041–2060 (Nolan and Flanagan, 2020).

The number of FD displayed a significant decreasing trend in Ireland in the annual (−13.7 days), spring (−5.8 days), autumn (−3.4 days) and winter (−4.9 days) series. The annual FD registered significant decreasing trends at 82% of stations, and greater trends were verified at Birr (−30.8 days), Phoenix Park (−27.9 days) and Armagh Observatory (−24.1 days) (Fig. 4). Significant decreasing trends in the number of FD were confirmed in 82% of stations in autumn, 73% in spring and 64% in winter. The years with the highest average number of FD in Ireland were 2010 (69.8), 1892 (58.3), 1895 (54.8), 1917 (54.2), 1963 (48.3), and

[2] Hurrell Wintertime SLP-based Northern Annular Mode (NAM) index data provided by the Climate Analysis Section, NCAR, Boulder, USA. Updated regularly. https://climatedataguide.ucar.edu/climate-data/hurrell-wintertime-slp-based-northern-annular-mode-nam-index (Last accessed on 6/05/2021).

[3] https://crudata.uea.ac.uk/cru/data/nao/nao.dat (Last accessed on 6/05/2021).

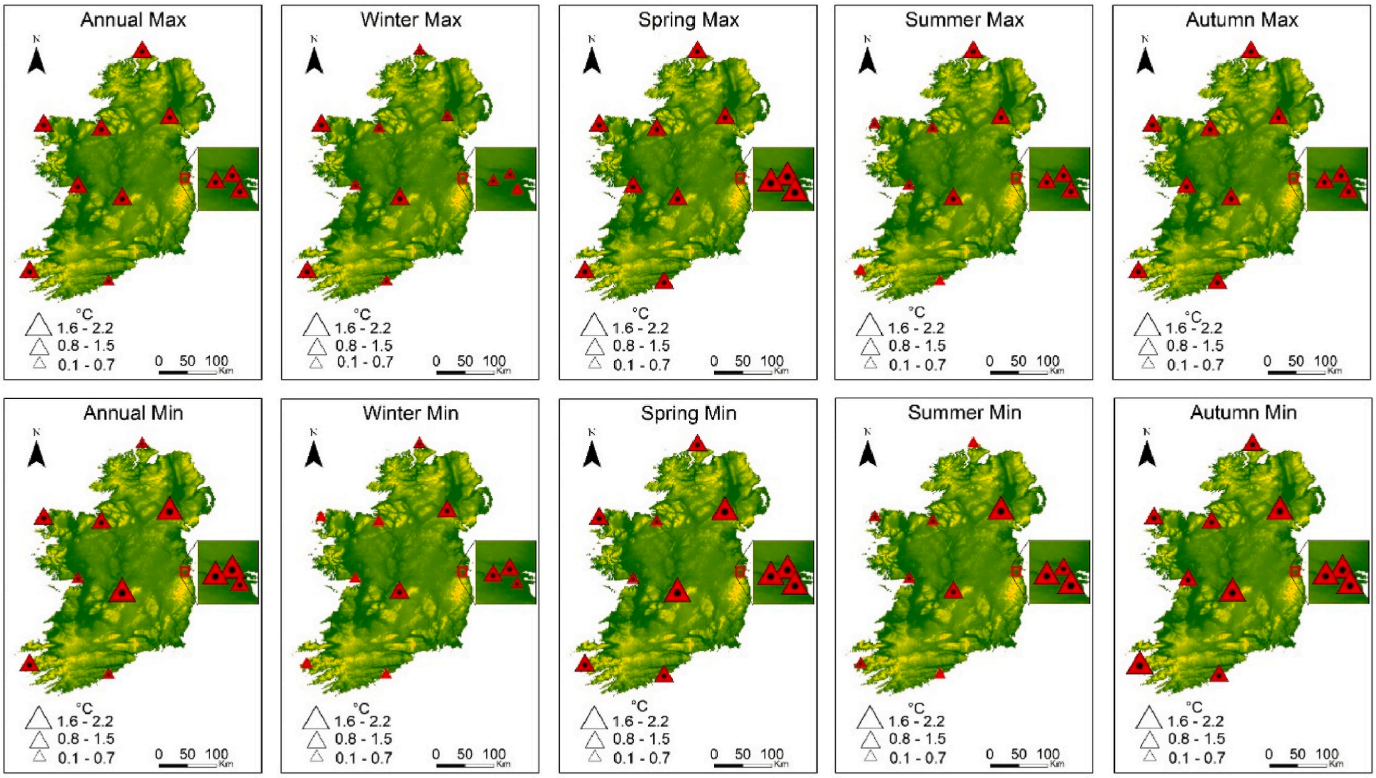

Fig. 2. Seasonal and annual maximum and minimum air temperature trends in Ireland from 1885 to 2018. Symbols: red triangle – positive trend but not statistically significant, red triangle with a middle black dot – significant positive trend ($p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

1886 (47.9) (Fig. 5), which also correspond to years with intense cold spells on record (Mateus, 2021a; Mateus and Potito, 2022). The significant decreasing trends of FD in Ireland in 1885–2018 agree with the findings of McElwain and Sweeney (2007), who identified a significant decreasing trend in the annual FD over the period 1961–2005. The warming of the minimum air temperature in winter and spring is associated with decreasing trends in Ireland's number of FD in 1961–2005 (McElwain and Sweeney, 2007). The Irish trends follow global trends (Alexander et al., 2006; Tebaldi et al., 2006) and Western European trends (Alexander et al., 2006) in the second half of the 20th century. The annual number of FD is projected to decrease by 45% for the RCP4.5 scenario and by 58% in the RCP8.5 scenario in the period 2041–2060 in Ireland (Nolan and Flanagan, 2020).

In Ireland, the number of SU displayed a significant positive trend in the spring (+0.1 days). The annual number of SU registered a significant positive trend at Roches Point (+0.4 days) (Fig. 4). Seasonally, significant positive trends were verified in the spring at Birr (+0.2 days) and Belmullet (+0.2 days) and summer at Roches Point (+0.3 days). The years with the highest average number of SU in Ireland were 1995 (12.0), 1976 (8.4), 1989 (7.4), 2018 (7.2), and 1983 (6.5) (Fig. 5), which also were associated with intense warm spells (Mateus, 2021a; Mateus and Potito, 2022). Birr exhibited the highest sum of annual summer days (379), whereas Roches Point had the lowest (28) in the period 1885–2018. A greater percentage of stations displayed significant increasing trends in the SU in the spring (18%) in comparison to summer (9%). Due to the maritime climate of Ireland, SU are not common, occur predominately in the summer and are associated with slow-moving high-pressure systems and tropical continental air mass. The frequency of SU has increased significantly in Western Europe and other areas globally in the period 1951–2003 (Alexander et al., 2006), which agree with the Irish trends.

Ireland registered a significant positive trend in the autumn TXx (+1.0 °C). The annual TXx displayed a significant positive trend at Roches Point (+1.0 °C) (Fig. 4). Significant increasing trends in the TXx were assessed in 55% of stations in winter and spring and 36% in autumn. The findings agree with Alexander et al. (2006), who indicate that TXx has warmed globally in the latter half of the 20th century. The official highest TXx recorded in the Republic of Ireland (33.3 °C) was observed on the 26th June 1887 at Kilkenny Castle (Met Éireann, 2019) during a warm spell (Mateus, 2021a; Mateus and Potito, 2022). On the 16th of July 1876, a maximum air temperature of 33.4 °C was reported at Phoenix Park (Mateus et al. 2020) during a warm spell (Mateus, 2021a; Mateus and Potito, 2022), although the thermometer was not registered on a Stevenson screen (Rohan, 1975). Other TXx over 32 °C and 33 °C were registered in the 19th century, but non-standard instrumentation was employed (Mateus et al., 2020).

The TXn had a significant increasing trend in the annual (+1.5 °C), spring (+1.7 °C), summer (+1.4 °C), autumn (+1.2 °C) and winter (+1.4 °C) series in Ireland. All stations display significant increasing trends in the annual TXn, with greater increases at Botanic Gardens (+1.9 °C), Birr (+1.6 °C) and Dublin city (+1.5 °C) (Fig. 4). Significant increasing trends in the TXn were identified in 100% of stations in spring, 73% in winter, 64% in autumn and 45% in summer. The findings agree with Dunn et al. (2020), who remarked that the TXn has warmed in many regions globally, including the Western Europe, in the period 1950–2018.

The annual TNx had a significant increase trend at 55% of stations, and greater trends were assessed at Birr (+1.7 °C), Dublin city (+1.5 °C), Armagh Observatory (+1.4 °C) and Phoenix Park (+1.3 °C) (Fig. 4). The autumn TNx presented a significant increasing trend (+1.1 °C) in Ireland. Significant increasing trends in the TNx were determined in 73% of stations in autumn, 64% in spring, and 55% in the winter and summer. The results concur with increasing trends in the TNx verified in many regions globally and in the Western Europe in 1950–2018 (Dunn et al., 2020).

The TNn registered a significant increasing trend in the annual

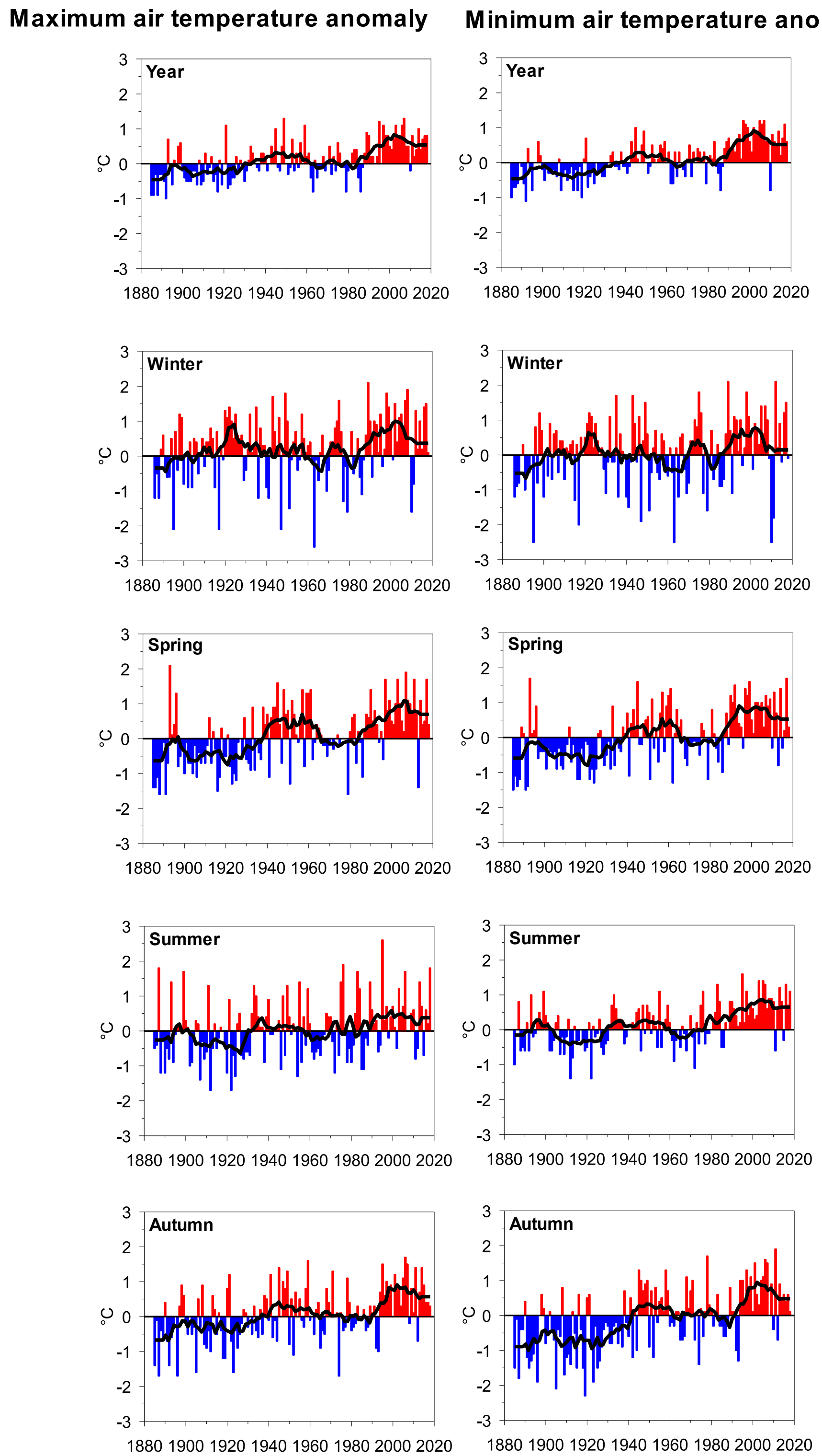

Fig. 3. Seasonal and annual maximum and minimum air temperature anomalies and 10-years moving average (black line) in Ireland from 1885 to 2018.

(+2.7 °C), spring (+1.7 °C), summer (+0.9 °C), autumn (+2.4 °C) and winter (+2.3 °C) series in Ireland. A total of 73% of stations displayed significant increasing trends in the annual TNn, with greater trends at Phoenix Park (+3.3 °C) (Fig. 4). Significant increasing trends in TNn were estimated in 73% of stations in autumn, 64% in winter and spring, and 45% in summer. The results agree with Dunn et al. (2020), who noted that TNn have warmed globally by almost 4 °C since the latter half of the 20th century. The official lowest TNn (−19.1 °C) in the Republic of Ireland occurred on the 16th January 1881 at Markree (Met Éireann, 2019) during one of the most intense cold spells on record (Mateus, 2021a; Mateus and Potito, 2022).

The DTR registered a significant decreasing trend in the annual (−0.1 °C) and autumn (−0.5 °C) series in Ireland. Phoenix Park (−0.6 °C), Birr (−0.5 °C), Armagh Observatory (−0.6 °C), Botanic Gardens (−0.4 °C) and Dublin city (−0.3 °C) had a significant decreasing trend in the annual DTR, whereas Malin Head (+0.3 °C) and Galway

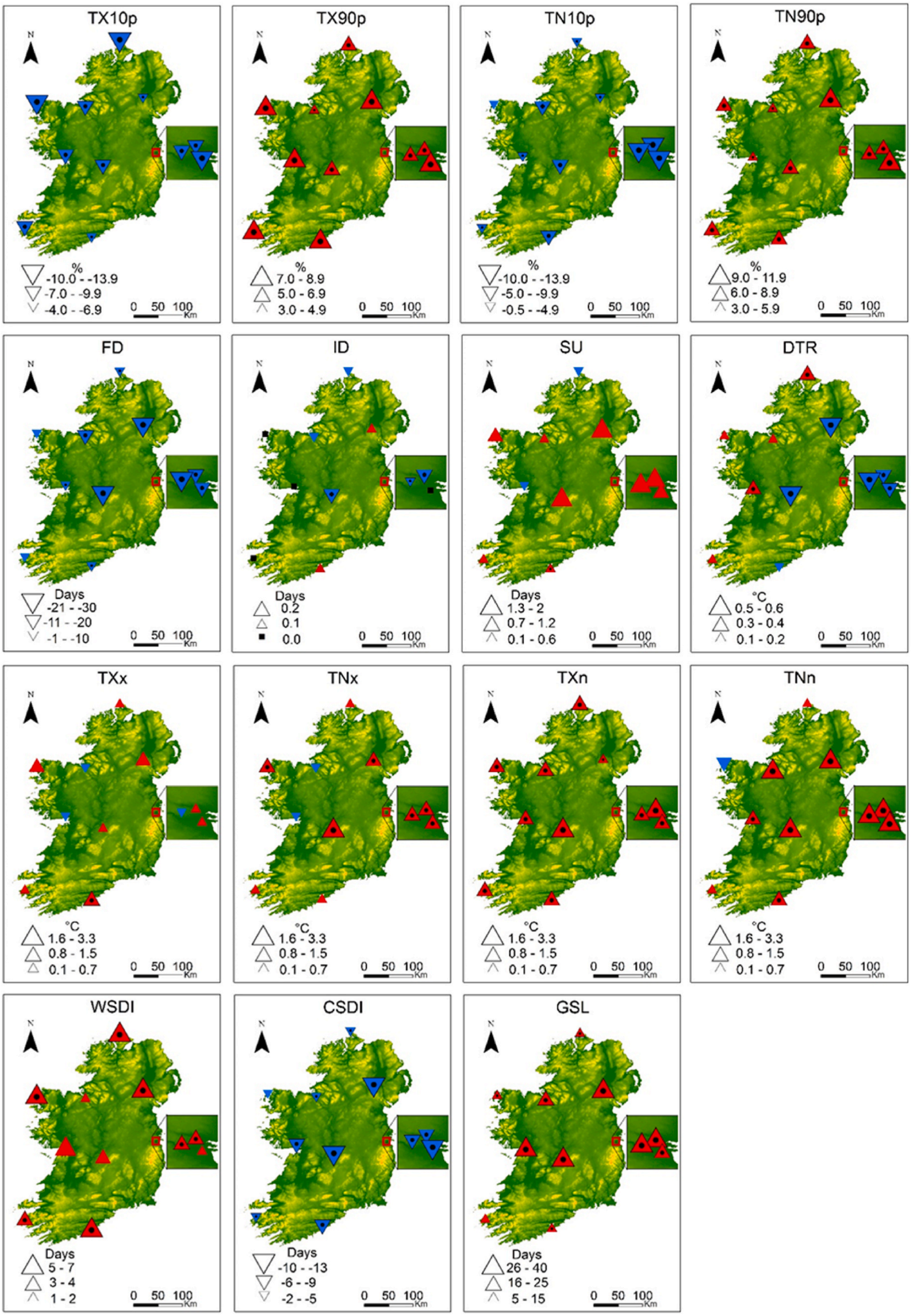

Fig. 4. Daily extreme air temperature indices in Ireland in 1885–2018. Symbols: red triangle – positive trend but not statistically significant, red triangle with a middle black dot – significant positive trend ($p < 0.05$), blue triangle – negative trend but not statistically significant, blue triangle with a middle black dot – significant negative trend ($p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

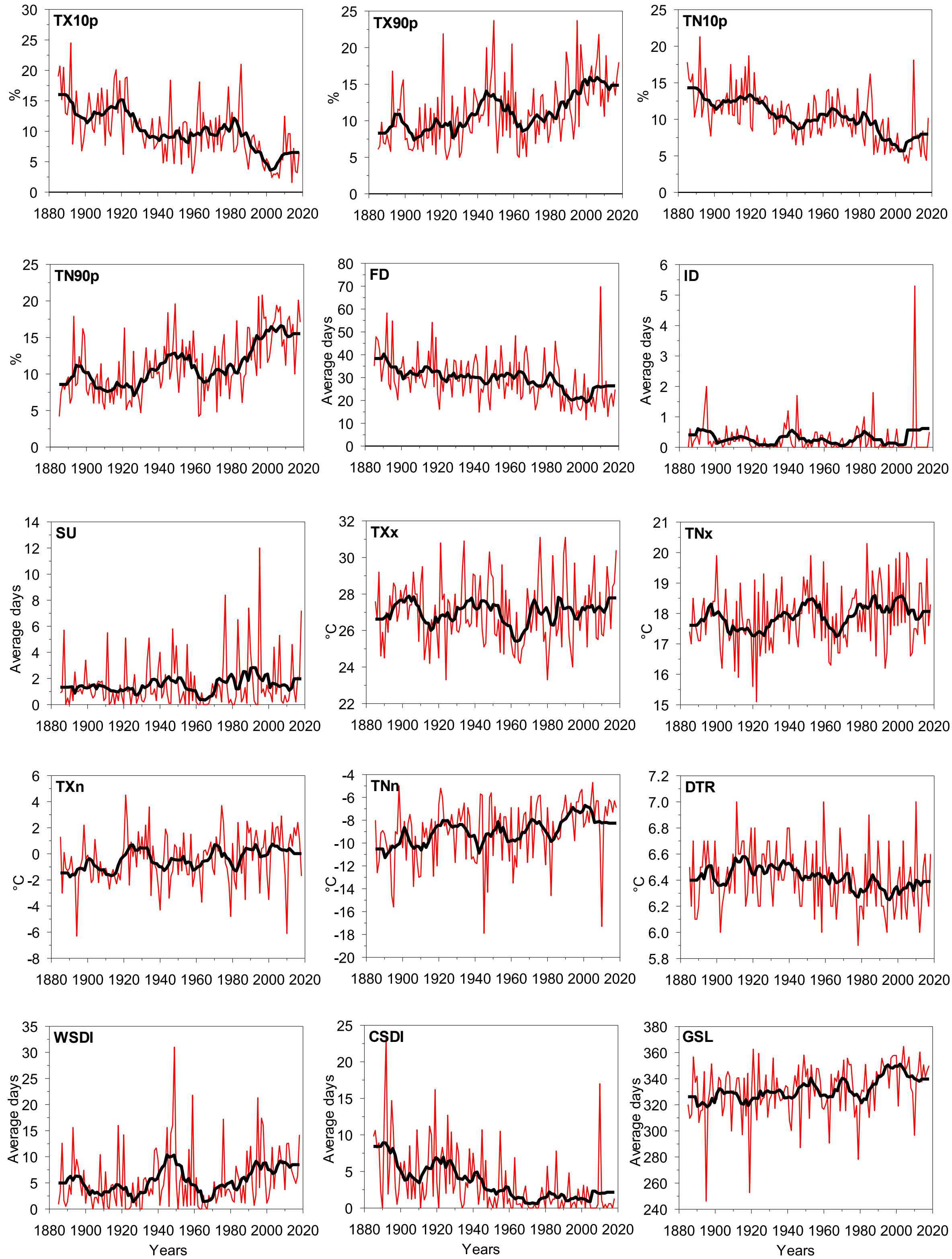

Fig. 5. Extreme air temperature indices and 10-years moving average (black line) in Ireland in 1885–2018.

(+0.3 °C) had a significant increasing trend (Fig. 4). Significant decreasing trends in the DTR were determined in 64% of stations in autumn, 45% in summer, 27% in winter and 18% in spring. McElwain and Sweeney (2007) reported both decreasing and increasing DTR trends in different stations and seasons in the period 1961–2005. The DTR has decreased globally due to a higher increase in the daily minimum air temperature in relation to the daily maximum air temperature, particularly during the second half of the 20th century (e.g., Braganza et al., 2004; Alexander et al., 2006; Dunn et al., 2020).

The TN10p had a significant decreasing trend in the annual (−7.0%), winter (−2.5%), spring (−9.1%), summer (−5.5%) and autumn (−11.1%) series in Ireland. Except for Belmullet, the remaining 91% of stations presented significant decreasing trends in the annual TN10p (Fig. 4). These findings follow Alexander et al. (2006), who remarked that 74% of the global land area displayed a significant decreasing trend in the annual number of TN10p in recent decades. TN10p has decreased globally by about 20 days since 1951 (Alexander et al., 2006). Decreasing trends in the TN10p have been reported globally from 1950 to 2018 (Dunn et al., 2020). In Ireland, the bottom 5% of daily minimum air temperatures (assessed to evaluate cold winter nights) is projected to increase ranging from +0.9 °C in the southwest to +1.8 °C in the north in the RCP45 scenario and from +1.2 °C to +2.4 °C respectively in the RCP85 scenario in 2041–2060 (Nolan and Flanagan, 2020).

The TX10p registered a significant decreasing trend in Ireland in the annual (−9.3%), winter (−4.7%), spring (−12.8%), summer (−9.2%) and autumn (−10.7%) series. 100% of stations display significant decreasing trends in the annual TX10p, with greater trends at Malin Head (−12.1%), Belmullet (−11.2%) and Dublin city (−10.5%) (Fig. 4). Significant decreasing trends in the TX10p were verified in 100% of the stations in the spring and autumn, and 91% in the winter and summer. The TX10p has decreased globally by around 40 days since 1901 and 15 days since the late 1970s (Dunn et al., 2020). The results follow the findings of Simolo et al. (2012), who remark a decrease in TX10p in Europe in the recent decades.

The TN90p had a significant increasing trend in the annual (+7.5%), winter (+3.8%), spring (+10.1%), summer (8.0%) and autumn (+8.1%) series in Ireland. All stations have significant increasing trends in the annual TN90p, with greater trends at Armagh Observatory (+10.1%) and Dublin city (+9.3%) (Fig. 4). Significant increasing trends in TN90p were assessed in 100% of the stations in autumn, 91% in spring, 82% in summer and 36% in winter. These findings follow global trends, as 73% of the global land area showed an increase in the annual TN90p in the period 1951–2003 (Alexander et al., 2006). In Western Europe, 60% of stations registered a significant warming trend from 1901 to 1999 (Moberg and Jones, 2005).

The TX90p had a significant increasing trend in the annual (+6.8%), spring (+9.0%), autumn (+8.5%), and winter (+6.4%) series in Ireland. 100% of stations registered significant positive trends in the annual TX90p, with greater trends at Roches Point (+8.3%), Galway (+7.8%), Valentia Observatory and Belmullet (+7.7), Dublin city (+7.3%) and Armagh Observatory (+7.0%) (Fig. 4). Significant increasing trends in the TX90p were evaluated in 100% of the stations in the spring and autumn seasons, 73% in winter and 9% in summer. Globally, there has been an increase in the total land area affected by TX90p during the second half of the twentieth century (Seneviratne et al., 2014). The TX90p has increased globally by around 40 days since 1901 and 30 days since the late 1970s (Dunn et al., 2020). In Europe, TX90p have increased in frequency (Simolo et al., 2012). In Ireland, the top 5% of daily maximum air temperatures (evaluated to analyse warm summer days) is projected to increase by +1.6 °C in the south and +1.0 °C in the west in the RCP45 scenario and by +2.2 °C and +1.4 °C, respectively, in the RCP85 scenario in 2041–2060 (Nolan and Flanagan, 2020).

The GSL days registered a significant increasing trend in Ireland (+22.0 days). With the exception of Valentia Observatory, the remaining stations registered significant increasing trends (Fig. 4). The greatest trends occurred at Birr (+36.6 days) and Armagh Observatory (+34.7 days) (Fig. 4). The results concur with Frich et al. (2002), who remarked that the GSL had increased globally in the second half of the 20th century. In Ireland, the growing season is projected to start 15 and 24 days early for the RCP4.5 and RCP8.5 scenarios, respectively, in 2041–2060 (Nolan and Flanagan, 2020).

The annual average WSDI had a significant increasing trend in Ireland (+3.9%). A total of 64% of stations registered significant increasing trends with greater trends at the coastal stations at Belmullet (+6.5%), Roches Point (+5.1%) and Malin Head (+4.7%) (Fig. 4). The findings agree with Cámaro-García et al. (2021), who found an increase in the WSDI in 1961–2018 in Ireland. Summertime warm spells have globally been increasing in frequency, intensity, and duration in 1950–2011 (Perkins et al., 2012). Significant increases in the occurrence of warm spells were assessed in parts of Europe in 1951–2003 (Alexander et al., 2006).

The annual average CSDI displayed a significant decreasing trend in Ireland (−6.9%). Except for Belmullet, the remaining stations display significant decreasing trends (Fig. 4). The greatest trends were verified at Dublin city (−12.6%) and Birr (−10.7%) (Fig. 4). The results agree with Cámaro-García et al. (2021), who identified a decrease in the CSDI in 1961–2018 in Ireland. In 1951–2003, significant decreasing trends in cold spells occurred in many geographical areas globally (Alexander et al., 2006).

A total of 1 TR was registered at Botanic Gardens (20.3 °C) and Dublin city (20.1 °C) on 14 July 1983 during a warm spell. TR are a rare occurrence due to the maritime climate of Ireland and have occurred six times in the digital record (Met Éireann, 2021). On the 21st and 22nd of July 2021, two TR nights were registered at Valentia Observatory during a warm spell, which was the first time two consecutive TR were registered in Ireland (Met Éireann, 2021). Significant positive trends in the frequency of TR were identified in many geographical areas globally (Alexander et al., 2006).

A greater percentage of stations (91% vs 64%) and stronger trends were displayed in the CSDI in comparison to the WSDI (Fig. 4), which is at least partially explained by greater warming in the minimum air temperature than the maximum air temperature record. Stronger significant trends and a greater percentage of stations (100% vs 9%) were identified in the TXn compared to the TXx (Fig. 4). In the case of the minimum air temperature, the TNn registered a greater percentage of stations (73%) and stronger intensity of significant trends in relation to the TNx (55%) (Fig. 4). A greater percentage of stations and stronger significant trends have been assessed in the cold extremes TXn, TNn, FD, ID and CSDI in comparison to the hot extremes SU, TXx, TNx and WSDI, which is supported by greater warming in the minimum air temperature series. All stations displayed significant positive trends in the TX10p, TX90p and TN90p (Fig. 4). With the exception of the Belmullet, the remaining 91% of stations registered significant positive trends in the TN10p (Fig. 4), which can indicate possible homogenisation issues at Belmullet, as discussed by Mateus and Potito (2021). These findings agree with Dunn et al. (2020), who report that the changes in the TN90p and TN10p are on average stronger than those in the TX90p and TX10p globally in the period 1950–2018.

The annual indices TN10p ($r = -0.246$), CSDI ($r = -0.276$), FD ($r = -0.484$), TNn ($r = 0.187$), TXn ($r = 0.205$), ID ($r = -0.378$) and GSL ($r = 0.263$) displayed statistical significance with the NAO from 1885 to 2018. The percentage of stations that displayed statistical significance is distributed as follows: FD (100%), CSDI (82%, except Birr and Belmullet), GSL (82%, except Markree and Armagh), TN10p (73%: except the stations in the Dublin area – Phoenix Park Dublin, Botanic Gardens and Dublin city), and TNn (64%: Botanic Gardens, Malin Head, Galway, Valentia, Markree, Armagh and Belmullet), TXn (64%: Phoenix Park Dublin, Botanic Gardens, Dublin city, Malin Head, Markree, Armagh, Belmullet) and ID (64%: Phoenix Park Dublin, Botanic Gardens, Dublin city, Birr, Galway, Markree and Armagh). The stations with the greatest correlations between the annual CSDI and GSL and NAO are Markree ($r = -0.302$) and Malin Head ($r = 0.317$), respectively.

The NAO shows a stronger relationship with the extreme air temperature indices in Ireland during the winter: TX10p ($r = -0.272$), TN10p ($r = -0.353$), FD ($r = -0.404$), ID ($r = -0.171$), TNn ($r = 0.172$), TNx ($r = 0.196$), TXn ($r = 0.198$), TX90p ($r = 0.249$) and TN90 ($r = 0.243$). 100% of the stations display statistical significance between the TX10p, TN10p, FD and TN90p and the winter NAO. Additionally, statistical significance is shown in TX90 (91%, with the exception of Valentia), TNn (82%, with the exception of Birr and Galway), TXn (64%: Phoenix Park Dublin, Botanic Gardens, Dublin city, Birr, Valentia, Armagh and Belmullet), TNx (55%: Phoenix Park Dublin, Botanic Gardens, Dublin city, Birr, Galway and Markree) and ID (36%: Phoenix Park Dublin, Glasnevin, Birr and Armagh). The greatest relationships between the NAO and the winter air temperature indices per station are distributed as follows: FD (Valentia, $r = -0.428$), TN10p (Valentia, $r =$

−0.389), TX10p (Armagh, r = −0.310), TX90p (Markree, r = 0.309), TNx (Markree, r = 0.301), TNn (Malin Head, r = 0.284), TN90p (Roches Point, r = 0.264), TXn (Armagh, r = 0.251) and ID (Phoenix Park Dublin and Botanic Gardens, r = −0.189).

The influence of winter AO on the long-term indices is also apparent. With the exception of the DTR and the TXx, the remaining indices for Ireland have statistical significance with winter AO in 1899–2018: TX10p (r = −0.522), TN10p (r = −0.573), FD (r = −0.659), ID (r = −0.349), TNn (r = 0.474), TNx (r = 0.339), TXn (r = 0.550), TX90p (r = 0.566) and TN90p (r = 0.542). All stations display statistical significance between the TX10p, TN10p, FD, TNn, TNx, TXn, TX90p, TN90p and the winter AO in 1899–2018. In the case of the ID, 73% of the stations (with the exception of the coastal stations at Roches Point, Valentia and Belmullet) show statistical significance with the AO in the same period. The greatest correlations between the winter AO and the indices per station is distributed as follows: FD (Botanic Gardens, r = −0.605), TN10p (Malin Head, r = −0.579), TX90p (Dublin city, r = 0.545), TN90p (Belmullet, r = 0.545), TXn (Birr, r = 0.528), TX10p (Armagh, r = −0.547), TNn (Malin Head, r = 0.513), TNx (Belmullet, r = 0.397), and ID (Phoenix Park Dublin, r = −0.381).

In summary, positive trends were identified in the seasonal and annual maximum and minimum air temperature series and in the annual TXn, TNn, TN90p, TX90p, WSDI and GSL and negative trends in the annual FD, DTR, TN10p, TX10p and CSDI in Ireland. The findings of this research follow state of the art for Europe and the globe (e.g. Alexander et al. 2006; Tebaldi et al., 2006; Frich et al. 2002; Perkins et al., 2012; Simolo et al., 2012; Seneviratne et al., 2014; Dunn et al., 2020; IPCC et al., 2021). The long-term trends in air temperature and indices follow the projections for Ireland (Nolan and Flanagan, 2020).

4. Conclusion

The Irish instrumental record is unique, presenting a homogenised long-term network of stations with daily maximum and minimum air temperature series, making it one of the key long-term records in Europe and the globe, which is crucial to analyse trends in frequency, intensity, duration and distribution of extreme air temperature indices. This research presents the first attempt to assess long-term trends in the seasonal and annual maximum and minimum air temperature series and the frequency, duration, intensity and geographical distribution of the daily extreme air temperature indices recommended by the ETCCDI based on long-term rescued, quality-controlled and homogenised data in Ireland. The assessment of trends in long-term extreme air temperature indices is crucial to assist stakeholders and policymakers in defining climate action, adaptation and mitigation policies and reducing the vulnerabilities of future extreme events. The analysis of extreme air temperature indices on a long-term instrumental record is paramount to reduce the uncertainty of historical changes in extreme events and to support the prediction of future changes (Zwiers et al., 2013).

A total of 86 maximum and minimum air temperature records registered in the 19th century and 3 kept in the 18th century were catalogued but not available in a digital format, and there is the potential for the existence of other historical records in need of rescue (Mateus, 2021b). Despite the rich heritage of historical meteorological observations, different non-standard instrumentation and observation practices, short-term series, and lack of station metadata make the homogenisation of the early daily instrumental records a challenging task. Further work should extend the temporal and geographical distribution of daily maximum and minimum air temperature observations by rescuing, quality-controlling, and homogenising data which is at present available in paper data-sources, in order to assess trends in air temperature and extreme air temperature indices prior to 1885.

Author contributions

CM – conceptualization, CM – data curation, CM – formal analysis, CM & AP – funding acquisition, CM – investigation, CM – methodology, AP – supervision, CM – writing – original draft, CM & AP - writing – review & editing.

Role of the funding source

The funding source had no involvement in the collection, analysis and interpretation of data, writing, nor in the decision to submit the article for publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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