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RESEARCH ARTICLE

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Climate change impacts on spatial and seasonal meteorological drought characteristics for the island of Ireland

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Abstract

Understanding how climate change is likely to impact on meteorological droughts is key to informing adaptation planning. For Ireland, little research has examined how droughts are likely to change in future. Here we examine changes in the monthly climate water balance, aridity index and changes in magnitude, frequency and duration of droughts using standardized drought indices for the island of Ireland derived from bias-adjusted CORDEX simulations for the 2080s (2070–2099), forced with a high (RCP8.5) and moderate (RCP4.5) emissions pathway. Findings highlight that increases in potential evapotranspiration, driven by increasing temperature, together with changing seasonal rainfall patterns increase aridity in summer with water deficits extending into spring months, especially in the east and midlands by the end of the century. Increases in drought frequency and magnitude are also evident, with greatest increases for RCP8.5. Critically, increases are considerably greater for the standardized precipitation evapotranspiration index (SPEI) than for the standardized precipitation index (SPI), emphasizing the importance of using metrics that capture potential evapotranspiration in monitoring and assessing future drought risk. Summer and spring show the greatest increase in drought magnitude and frequency, most marked in the east of the island. By contrast, multiseasonal droughts, assessed using 6-month accumulation periods show more modest changes in magnitude and duration. The resultant impacts of climate change on drought for Ireland would require considerable adaptation given the vulnerabilities exposed by the 2018 drought.

KEYWORDS

climate change, CORDEX, drought, Ireland, regional, SPEI, SPI

1 | INTRODUCTION

Droughts can be broadly defined as periods of abnormally dry weather that persist for long enough to result in hydrological imbalance (Cook et al., 2004). Recent drought events such as summer 2018 highlight the vulnerability of agricultural and water systems on the island of Ireland to drought (Augustenborg et al., 2022). In the Republic of Ireland, 2018 cereal yields fell 20% on 2017, while dairy farmers experienced a 34% drop in average net margins with expenditure on animal feed nearly 50% higher in 2018 compared to 2017 (Dillon et al., 2019; Falzoi et al., 2019). In the water sector the 2018 drought resulted in widespread hosepipe bans, reliance on water tankers to meet potable water needs in some locations and degraded water quality, with impacts for many ecosystems and species.

In recent decades, the scientific community has given various definitions and interpretations of drought types, of which the most commonly used are meteorological, agricultural, hydrological and socioeconomic droughts (Tallaksen & Van Lanen, 2004). These types of drought occur on different time scales but are closely interrelated. Meteorological, agricultural and hydrological droughts are commonly defined as periods of deficit in atmospheric water balance, soil moisture and streamflow, respectively. These variables can be directly interrelated with precipitation, reductions in crop production, low water levels in rivers, groundwater and reservoirs, respectively (Tallaksen & Van Lanen, 2004). Socioeconomic drought occurs when stakeholders or water resource managers lack the ability to manage (operate) the available resource.

Several studies have developed long-term records of observed and reconstructed meteorological droughts for the island of Ireland, with significant drought rich periods occurring in 1890–1910, 1921–1922, 1933–1934, in the 1940s, and the early and mid-1970s (Murphy et al., 2020a, 2020b; Noone et al., 2017; O'Connor et al., 2022). Clear from newspaper reports is that historical droughts have also had substantial impacts on Irish society, particularly for water resource management and agriculture (Jobbová et al., 2023). Therefore, understanding how climate change is likely to impact on meteorological drought is important for developing adaptation responses to ensure the resilience of these critical sectors.

Assessments of variability and change in meteorological drought from observed records show limited evidence for change when drought indices based only on precipitation are evaluated, emphasizing the importance of increased aridity in recent decades in understanding changes in drought frequency and severity (e.g., Dai & Zhao, 2017; Meresa et al., 2016; Spinoni et al., 2015, 2019; Stagge et al., 2017; Vicente-Serrano et al., 2022a, 2022b). Vicente-Serrano et al. (2020) assessed changes in annual and seasonal meteorological droughts for western Europe using the Standardized Precipitation Index (SPI) extracted from quality assured long-term precipitation records extending back to the 1850s, finding the largest trends towards increased drought magnitude during summer in Britain and Ireland. O'Connor et al. (2022) examined changes in reconstructed meteorological droughts for 51 catchments across Ireland for the period 1767–2016 using SPI. They highlight that while changes in drought characteristics reveal a complex picture with the direction, magnitude and significance of trends dependent on the accumulation period used to define drought and the period of record analysed, a trend towards shorter, more intense summer droughts is evident since 1900. While difficult to attribute such changes to anthropogenic climate change given the influence of natural climate variability on precipitation in the region, such trends emphasize the importance of understanding possible future drought changes.

Anthropogenic climate change and resultant changes in temperature, evapotranspiration and precipitation are expected to increase the likelihood of drought in many regions over the 21st century (Caretta et al., 2022). At the European scale Spinoni et al. (2018) used the EURO-CORDEX ensemble to evaluate changes in annual and seasonal drought characteristics, finding that future changes in drought frequency and severity are related to the intensity of future greenhouse gas emissions. Under the more moderate RCP4.5 they find that drought frequency and severity are most likely to increase in northern Scandinavia and western Europe, whereas under RCP8.5 most of the continent is likely to experience worsening drought. Largest changes were found for spring and summer drought with droughts becoming less frequent in winter over northern Europe due to increases in precipitation. Samaniego et al. (2018) found that in the absence of effective greenhouse gas mitigation, Europe may face large increases in drought severity and extent, with increases in temperature of 3 degrees above preindustrial likely to increase drought affected areas by 40% (±24%).

Despite evident vulnerability to droughts, few studies have assessed projected changes in drought characteristics with climate change for Ireland. One study by Meresa et al. (2023) evaluated future changes in drought for six catchments using 12 CMIP6 climate models finding large increases in the frequency and magnitude of summer meteorological and hydrological drought. In other seasons and on annual timescales little change in drought severity was found, indicating the importance of seasonal evaluation. Therefore, this study seeks to address this gap in knowledge regarding climate change impacts on drought characteristics for the island of Ireland using bias-adjusted EURO-CORDEX climate models. In doing so, we examine projected changes in the magnitude, frequency and duration of droughts at annual and seasonal timescales by the 2080s using the EURO-CORDEX ensemble forced by RCP4.5 (an intermediate emissions pathway) and RCP8.5 (a fossil fuel intensive future). We use two drought indices, including the Standardized

Precipitation Index (SPI) (McKee et al., 1993) and the Standardized Precipitation Evapotranspiration Index (SPEI) (Beguería et al., 2014) to assess the importance of different drought metrics in understanding future changes. Droughts are assessed for 3- and 6-month accumulation periods given their relevance to understanding agricultural and hydrological impacts.

2 | DATA AND METHODS

2.1 | Study area and datasets

As presented in Figure 1a, we classified Ireland into five regions: northern, western, eastern, southeastern and southern. The southwest and western parts of the island receive the highest daily mean precipitation, especially in upland areas, with totals ranging from 5 to 9 mm·day^{-1}. Conversely, eastern and northeastern parts receive the lowest daily mean precipitation, ranging from 1 to 3 mm·day^{-1} (Figure 1b). Daily mean temperature is less spatially variable than precipitation with higher mean temperatures typically experienced in the south and southeast of the island (Figure 1c).

We extract daily gridded air temperature and precipitation data from the EURO-CORDEX ensemble (Giorgi & Gutowski, 2015; Jacob et al., 2014) for 11 GCM/RCM combinations run at 0.11° resolution (~12.5 km; see Table 1) under two Representative Concentration Pathways (RCPs) (RCP45 and RCP85). EURO-CORDEX data were downloaded from the European nodes of the Earth System Grid Federation (ESGF; e.g., https://esgf.llnl.gov).

We use observed gridded (1 km resolution) daily air temperature and precipitation data (Walsh, 2012) for the period 1976–2005 to bias-adjust the EURO-CORDEX model outputs. To match the observed grid cell size (1 km) with EURO-CORDEX climate models (12.5 km), first the observed data was upscaled to 12.5 km. Following Meresa et al. (2021) each of the 11 EURO-CORDEX members were bias-adjusted using double gamma quantile mapping and empirical quantile matching for precipitation and temperature, respectively. We excluded the zero precipitation values before the double Gamma distribution model was fitted to the upper and lower tail of the precipitation distribution. We used the 75th percentile as a threshold to split the precipitation distribution before bias-adjustment,

$$P_{\mathrm{corr,hst}} = F_{\mathrm{Ga}}^{-1}\left(F_{\mathrm{Ga}}\left(P_{\mathrm{raw}}(t), \alpha_{\mathrm{raw,hst}}, \beta_{\mathrm{raw,hst}}\right), \alpha_{\mathrm{Obs}}, \beta_{\mathrm{Obs}}\right), \quad (1)$$

where $P_{\mathrm{corr,hst}}$ is the bias-corrected daily precipitation, $P_{\mathrm{raw,hst}}$ is the raw climate model output and F_{Ga}^{-1} is the inverse cumulative density function of raw climate model precipitation. The Ga subscripts represent the Gamma distributions with two parameters (shape α and scale β) used to correct the wet/dry spell of precipitation characteristics.

Empirical quantile matching was used to bias-adjust temperature based on pairwise comparison between the empirical cumulative density function (ecdf) of raw climate model outputs and the observed temperature for the reference period (1976–2005). The future temperature data are corrected using the inverse of the ecdf (ecdf^{-1}) and fitted ecdf,

$$T_{\mathrm{corr\_hst}} = \left(\mathrm{ecdf}_{\mathrm{obs}}^{-1}\left(\mathrm{ecdf}_{\mathrm{hst}}\left(T_{\mathrm{raw_{hst}}}\right)\right)\right), \quad (2)$$

where $T_{\mathrm{corr\_hst}}$ is the adjusted temperature, $T_{\mathrm{raw\_hst}}$ is the raw climate model output (unadjusted temperature) and obs is the observed temperature. Bias-adjustment was undertaken on a grid by grid basis with models calibrated for the reference period (1976–2005) and used to adjust future climate simulations. Performance was evaluated using relative bias (RB) (°C), percent bias (PBIAS) (%) and Pearson's correlation coefficient (RR) calculated between the adjusted and observed time series during the reference period. Bias-adjustment was completed for individual grid cells before being compiled to represent five (northern, eastern, western, southeastern, and southern) regions covering the Republic of Ireland (Figure 1a).

2.2 | Drought indices

We employ three drought indices. For each climate model, drought indices were fitted for the reference period (1976–2005) and used to examine changes in drought characteristics for the end of the century (far future period (2070–2099): 2080s) under each RCP. First, we compute the aridity index (AI) based on Budyko (1958) for the reference and future period. The AI is used to investigate the surplus and deficit of water availability as a function of PET and precipitation. AI is the ratio of precipitation to PET at different temporal scales, here monthly. When AI is greater than 1 the climate water balance is in surplus and when less than 1 it is in deficit. We also employ the Standardized Precipitation Index (SPI) (McKee et al., 1993), and the Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) to evaluate changing drought characteristics at annual and seasonal scales. For SPEI, daily potential evapotranspiration was estimated from bias-adjusted temperature using the method of Oudin et al. (2005). Droughts were evaluated for 3- and 6-month accumulation periods,

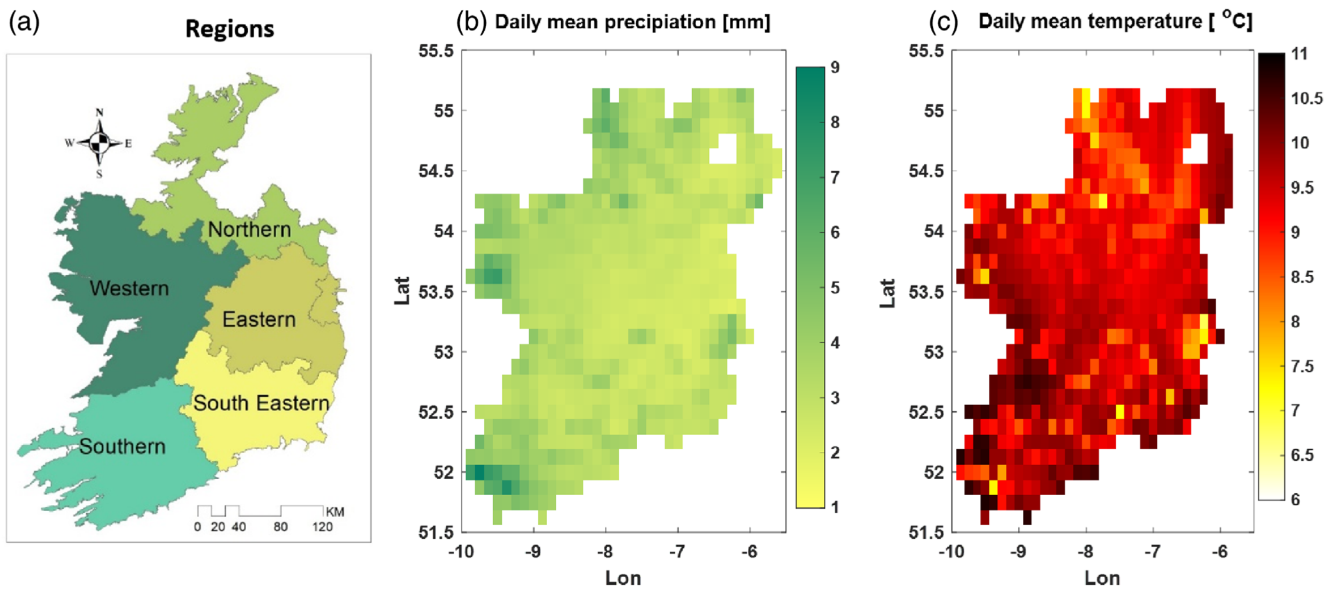

FIGURE 1 Map of regions of Ireland used for drought analysis (a), observed daily mean precipitation (b) and mean daily air temperature (c)

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

Code	GCM	RCM	GCM source
CM1	CNRM_CM5	KNMIRACMO22E	Centre National de Recherches Meteorologiques, France
CM2	CNRM_CM5	RMIBUGentALARO	Center National de Recherches Meteorologiques, France
CM3	CNRM_CM5	CLMcomCCLM4	Center National de Recherches Meteorologiques, France
CM4	EC_EARTH	KNMIRACMO22E	EC-Earth consortium, EU
CM5	HadGEM2_ES	KNMIRACMO22E	Met Office Hadley Centre, UK
CM6	HadGEM2_ES	CLMcomCCLM4	Met Office Hadley Centre, UK
CM7	HadGEM2_ES	DMIHIRHAM5	Met Office Hadley Centre, UK
CM8	MPI_ESM_LR	MPICSCREMO2009	Max Planck Institute for Meteorology, Germany
CM9	MPI_ESM_LR	CLMcomCCLM4	Max Planck Institute for Meteorology, Germany
CM10	NorESM1_M	DMIHIRHAM5	Norwegian Climate Centre, Norway
CM11	GFDL_ESM2G	GERICSREMO2015	NOAA Geophysical Fluid Dynamics Laboratory, USA

selected to be of interest for agriculture and hydrology, respectively. In addition to evaluating the characteristics of individual drought events we also use SPI and SPEI to assess changes in seasonal droughts. We use 3-month accumulations in February, May, August and November to represent drought conditions in winter, spring, summer and autumn, respectively.

In fitting SPI we used a two-parameter gamma distribution to calculate the drought index as follows:

$$f(X;\alpha,\beta)=\frac{1}{\beta^{\alpha}\int_{o}^{\infty}X^{\alpha-1}e^{-x}dx}X^{\alpha-1}e^{-x/\beta},\ \text{for}\,x>0, \qquad (3)$$

where the Z-score standardized value X is accumulated monthly precipitation, a and b are the scale and shape parameters of the Gamma distribution estimated using maximum likelihood estimation (MLE). To derive SPEI, aggregated monthly precipitation (P) and Potential

Evapotranspiration (PET) are used to calculate the climate water balance (MD),

$$\mathrm{MD} = P - \mathrm{PET}. \quad (4)$$

We calculated PE based on the Oudin et al. (2005), temperature-based formula. The PE calculation is expressed as follows:

$$\mathrm{PE} = \begin{cases} \frac{0.408R_e(\mathrm{Temp}+5)}{100} & \text{if } (\mathrm{Temp}+5)>0 \\ 0 & \text{Otherwise} \end{cases}, \quad (5)$$

where PE is potential evapotranspiration, Temp is the mean air temperature at 2 m height (°C), and Re is the extraterrestrial solar radiation ($\mathrm{MJ \cdot m^{-2} \cdot day^{-1}}$) given by the Julian day and the latitude.

MD was then fitted using a three parameter log-logistic distribution as defined by Vicente-Serrano et al. (2010),

$$f(\mathrm{MD}; \beta, \gamma) = \frac{\left(1 + \frac{\gamma(\mathrm{MD}-\alpha)}{\beta}\right)^{-(1/\gamma+1)}}{\beta\left[1 + \left(1 + \frac{\gamma(\mathrm{MD}-\alpha)}{\beta}\right)^{\frac{1}{\gamma}}\right]^2}, \quad (6)$$

where β, α, Υ are the scale, location and shape parameters, respectively, and estimated using MLE. The estimated log-logistic probabilities were then transformed into a standard normal distribution. Distribution fitting for both SPI and SPEI was performed over a 30-year reference period (1976–2005), in accordance with standard 30-year time slices.

2.3 | Calculation of drought characteristics

For SPI/SPEI at 3- and 6-month accumulation periods, we used the threshold of −1 for the onset of drought conditions and classify drought termination when SPI/SPEI values return to zero following other Irish and UK studies of historical and future drought (e.g., Barker et al., 2016; Noone et al., 2017; Reyniers et al., 2023). Drought magnitude (DM) was calculated as the sum of all negative values from drought onset to termination (return to zero) (Spinoni et al., 2020; Zhang et al., 2018). Drought frequency (DF) refers to the probability of drought occurrence in a given period, estimated using the ratio of the number of months in drought to the total number of months in a specific 30-year period (i.e., reference and future period). Drought duration is the sum of all months from the beginning to the end of a specific drought event within a specific 30-year period, with mean duration for each 30-year period calculated by dividing the sum of drought event durations by the number of drought events,

$$\mathrm{DM} = -1 * \sum_{i=1}^{n} \mathrm{DX}_i, \text{where } \mathrm{DX}_i \leq -1, \quad (7)$$

$$\mathrm{DF} = \frac{N_d}{\mathrm{NT}_d}, \quad (8)$$

where for the chosen accumulation period, DM is drought magnitude, DX_i are standardized values (e.g., SPI or SPEI), n stands for the time period (e.g., reference or far future, each with 348 months). DF is drought frequency, N_d is the number of drought months and NT is the total number of months. DM and DD are calculated for each region as the sum of the average DM and DD for the reference and future timeslice.

We also assess changes in the average magnitude of seasonal droughts using a three-month accumulation period for the last month of each season. For each season in the 30-year reference and future periods we identified years for which SPI/SPEI<−1, then summed these negative values and divided by the number of years classified as in drought.

3 | RESULTS

3.1 | Performance of climate model bias-adjustment

Figure 2 shows a comparison between observed and bias-adjusted temperature and precipitation. Overall, PBIAS and RR show better performance in correcting daily temperature than precipitation. Higher RR scores are associated with lower PBIAS and vice versa. For instance, the southwestern part of the island shows a higher RR (>0.55) and around zero PBIAS (between 10% and −10%). However, the performance of the bias-adjustment method differs across regions and climate models. The performance of CM1, CM4, CM7 and CM10 is better at reproducing the higher precipitation values in the south, western and northwest parts of the island, while CM2, CM3, CM5, CM6, CM8, CM9 and CM11 perform better in the eastern and southeastern parts. This may come from the difference in precipitation characteristics in each climate model. The climate models with higher variability may have substantial differences in dry and wet spell climate characteristics. This may result in a higher PBIAS and weaker RR compared with the observed climate characteristics, which indicates that the extreme distribution and magnitude have a significant impact on adjusting the climate features.

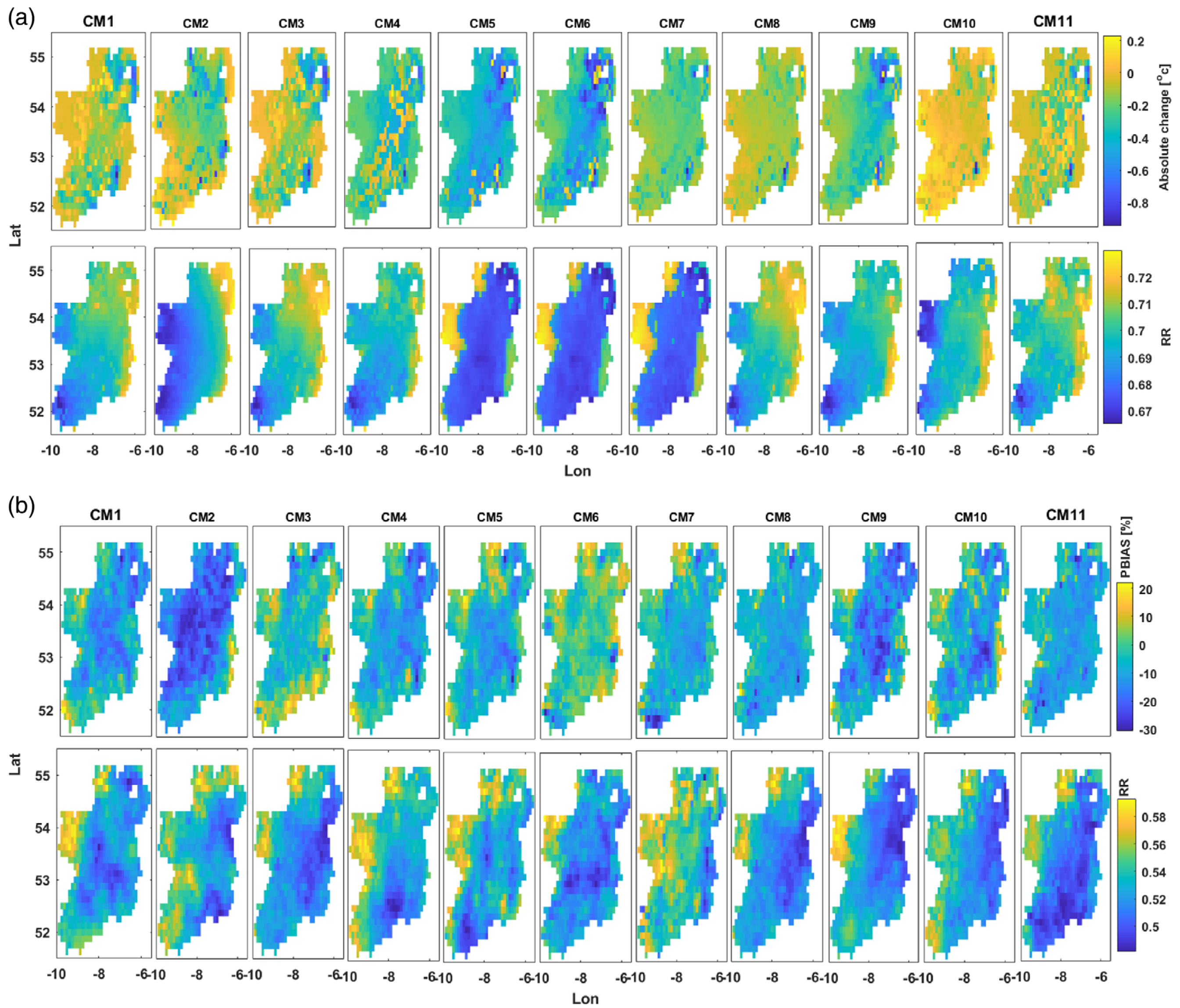

FIGURE 2 (a) The absolute difference (first row) and Pearson correlation (second row) between bias-adjusted and observed air temperature. Each column represents a climate model with respective codes explained in Table 1. (b) Percent bias (PBIAS) (first row) and Pearson correlation (second row) between bias-adjusted and observed precipitation. Each column represents a climate model with respective codes explained in Table 1

3.2 | Changes in the annual cycle of precipitation and potential evapotranspiration

Figure 3 shows the regional monthly climate water balance for the reference period (1976–2005) and far future (2080s (2070–2099)) for RCP4.5 and RCP8.5. Mean monthly precipitation exceeds PET in 7 months (January, February, March, September, October, November and December), while the mean monthly PET exceeds precipitation in 3 months (June, July and August). Monthly mean PET and precipitation are similar in April and May. A similar pattern was noted for the end of century using RCP4.5 and RCP8.5. However, water surpluses and deficits were increased proportionally with increases in winter precipitation and summer dryness, especially under RCP8.5. Furthermore, by the end of century deficits were found to extend into spring months of April and May.

Figure 4 shows the spatial distribution of the annual AI for each climate model for the reference period and end of century under both RCPs. For the reference period AI varies from 1 to 6.5 across the island, and is typically lower in the eastern and central regions with a mean value of around 1.0–1.5. Northern, southern, and western parts of the island show higher AI values, indicating wetter conditions and a larger surplus in the annual climate water

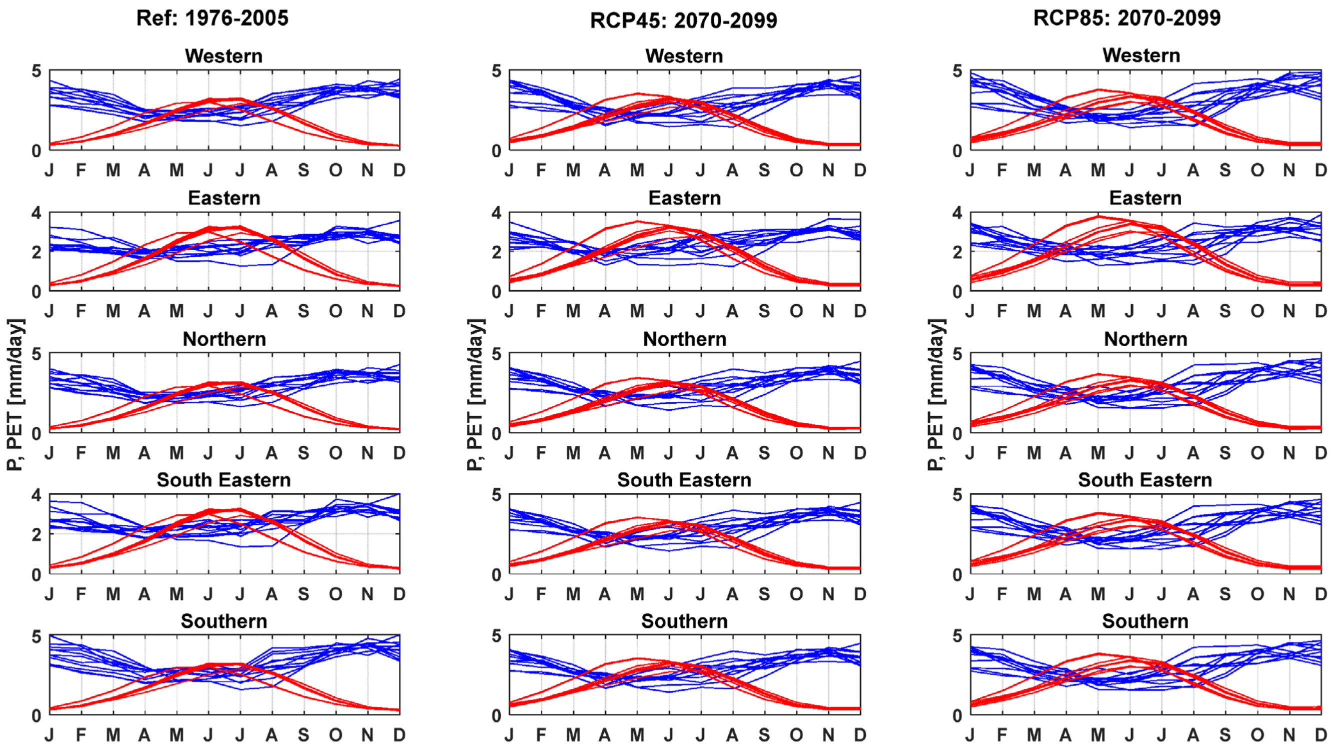

FIGURE 3 Regional monthly climate water balance of mean potential evapotranspiration (PET; red lines) and precipitation (P; blue lines) for the 11 GCMs/RCMs ensemble members

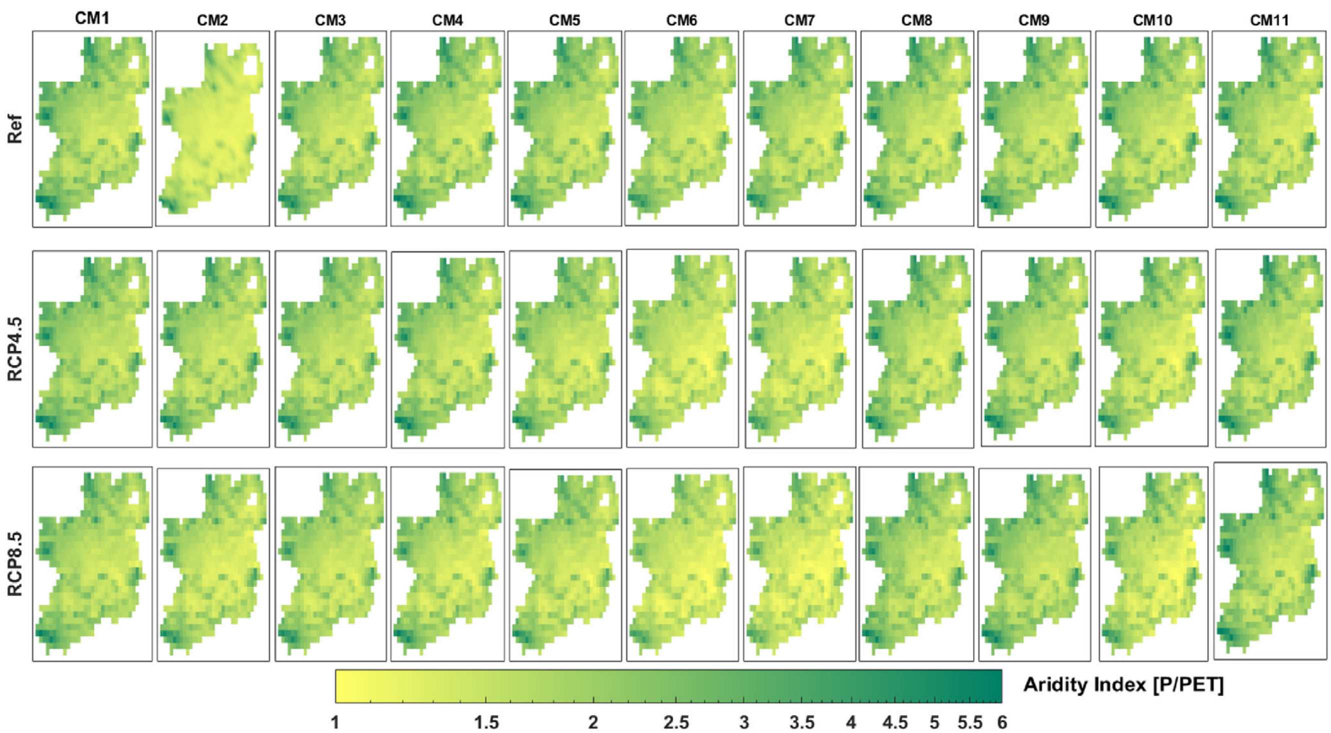

FIGURE 4 Aridity index (average annual P/PE) for the 11 GCMs/RCMs ensemble members. The colour bar is represented as logarithmic value

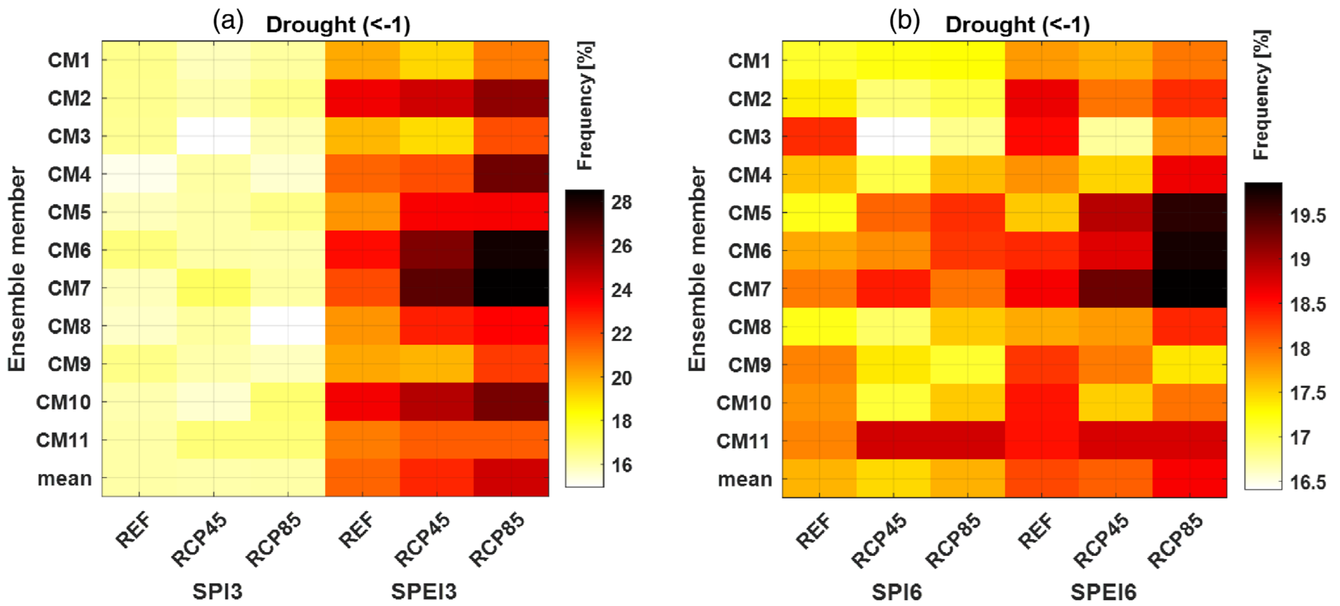

FIGURE 5 Spatially averaged projections of drought frequency for the island of Ireland using SPI and SPEI at 3-month accumulation time scale (a) and 6 months (b) for each ensemble member and the ensemble mean for the reference period and each RCP by the 2080s

balance. Overall, aridity is projected to increase in the 2080s under RCP4.5 and RCP8.5 with CM4, CM5, CM6, CM7 and CM10 showing substantial increases in aridity in the future compared to other climate models. Increases in aridity are greatest in the eastern and central parts of the island, currently the driest regions.

3.3 | Changes in drought frequency

Changes in drought frequency for each accumulation period (3 and 6 months) were evaluated for the 2080s relative to the reference period using SPI and SPEI. Figure 5 shows the average changes in drought frequency between the reference and far future periods across the island for each climate model and the ensemble mean. For SPI-3 only modest changes are simulated. However, more substantial changes are evident when considering SPEI-3, indicating the importance of evaporative losses for future drought frequency. Both RCPs show increasing drought frequency for SPEI-3 for the end of the century, and individual climate models show a wide range of differences in percent change in drought frequency; the highest changes were noted by CM6 and CM7, and the lowest by CM1, CM3 and CM9. For SPI-6 modest increases in the frequency of droughts are projected with substantial differences between climate models; some showing decreases in frequency and others increases. For SPEI-6, again large differences are evident across climate models, with the ensemble mean indicating greater increases in frequency than for SPI.

The spatial variation of changes in drought frequency from the ensemble mean is presented in Figure 6. For SPI-3 increases in drought frequency are evident in the south and southwest under RCP4.5, with decreases in frequency in the northeast. Larger changes are evident for SPEI-3. Increases in frequency for SPEI-3 droughts are evident for the midlands and east of the island, greatest under RCP8.5. For SPI-6 increases in frequency in the southeast and west under RCP4.5, with decreased frequency in the northeast are simulated. For RCP8.5 little change is evident along the eastern seaboard, with increases in frequency across much of the western half of the island. For SPEI-6 largest changes are evident under RCP8.5 with increases in frequency throughout much of the midlands, east and north of the island.

Figure S1a,b, Supporting Information shows the spatial pattern of drought frequency using 11 climate models and SPI-3 and SPEI-3 drought indices. The spatial difference between climate models is clearly observed, with CM6 and CM7 showing a higher frequency compared with the others using SPI. On the other hand, CM4, CM7, CM8 and CM9 show greater increases in drought frequency using SPEI (Figure S1a,b).

3.4 | Changes in the magnitude and duration of drought events

Changes in drought magnitude and duration were evaluated for the 2080s relative to the reference period using

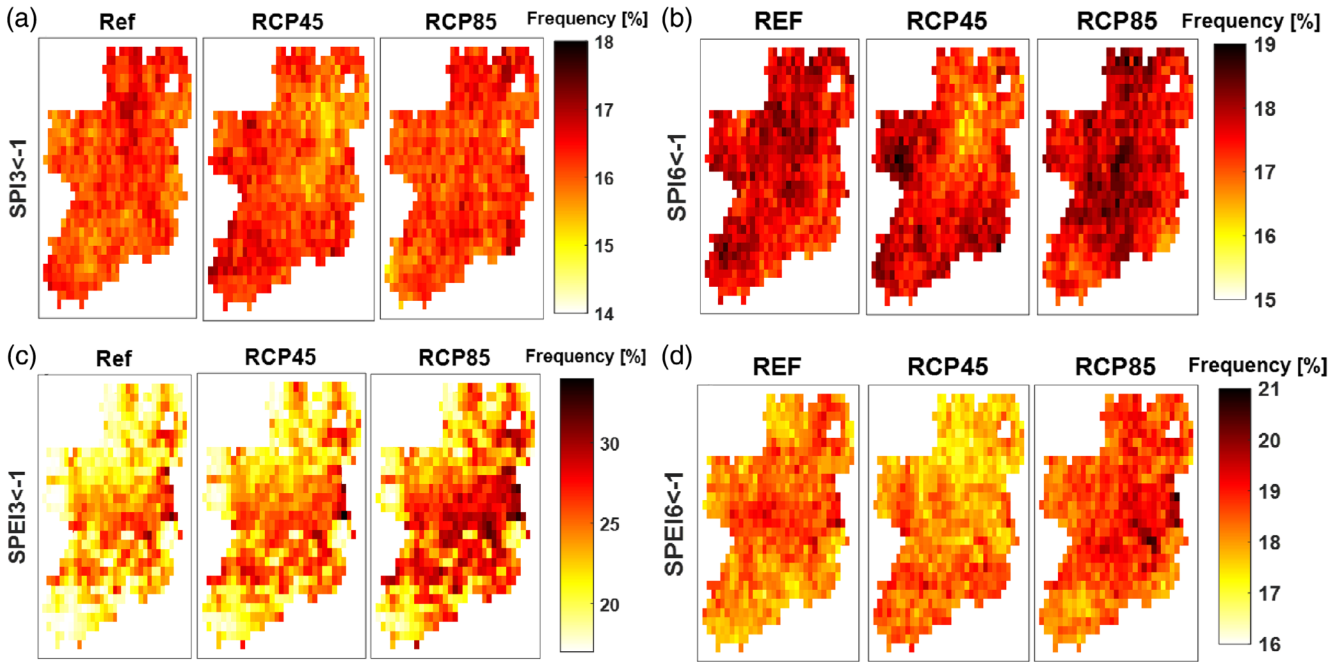

FIGURE 6 Ensemble mean changes in drought frequency for SPI-3 (a), SPEI-3 (b), SPI-6 (c) and SPEI-6 (d) for the reference period and each RCP (RCP45 and RCP85) for the 2080s (far future)

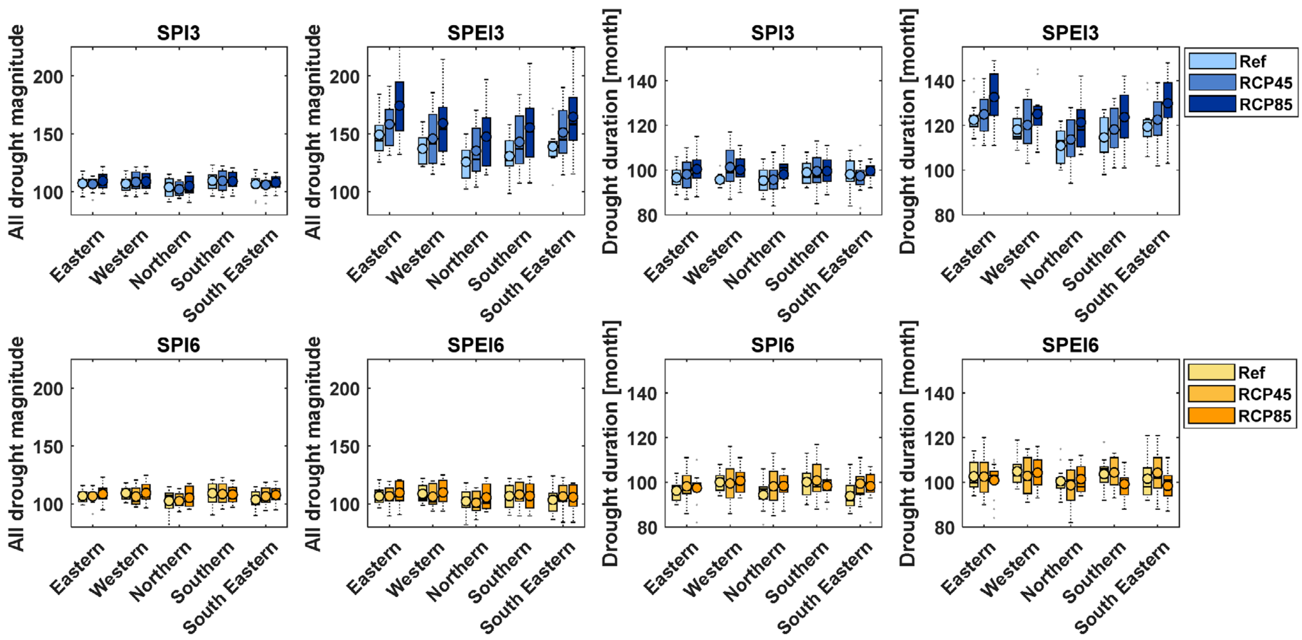

FIGURE 7 Changes in the magnitude and duration of drought events identified using SPI/SPEI at 3-month (blue) and 6-month (orange) accumulation periods for each RCP and region. Each box shows the interquartile range simulated from 11 CORDEX ensemble members for that region. The circles indicate the ensemble mean, and the horizontal line the median

SPI and SPEI at 3- and 6-month accumulation periods under RCP45 and RCP85. Figure 7 shows changes in drought magnitude and duration over each 30-year period by region. For SPI-3 a wide range of change is simulated across models for event magnitude. The largest increases are evident for RCP8.5 but changes in the ensemble mean are relatively modest in all regions. Similar results are evident for SPI-3 drought duration with a tendency towards longer droughts, but the ranges of change are wide and changes in the ensemble mean are

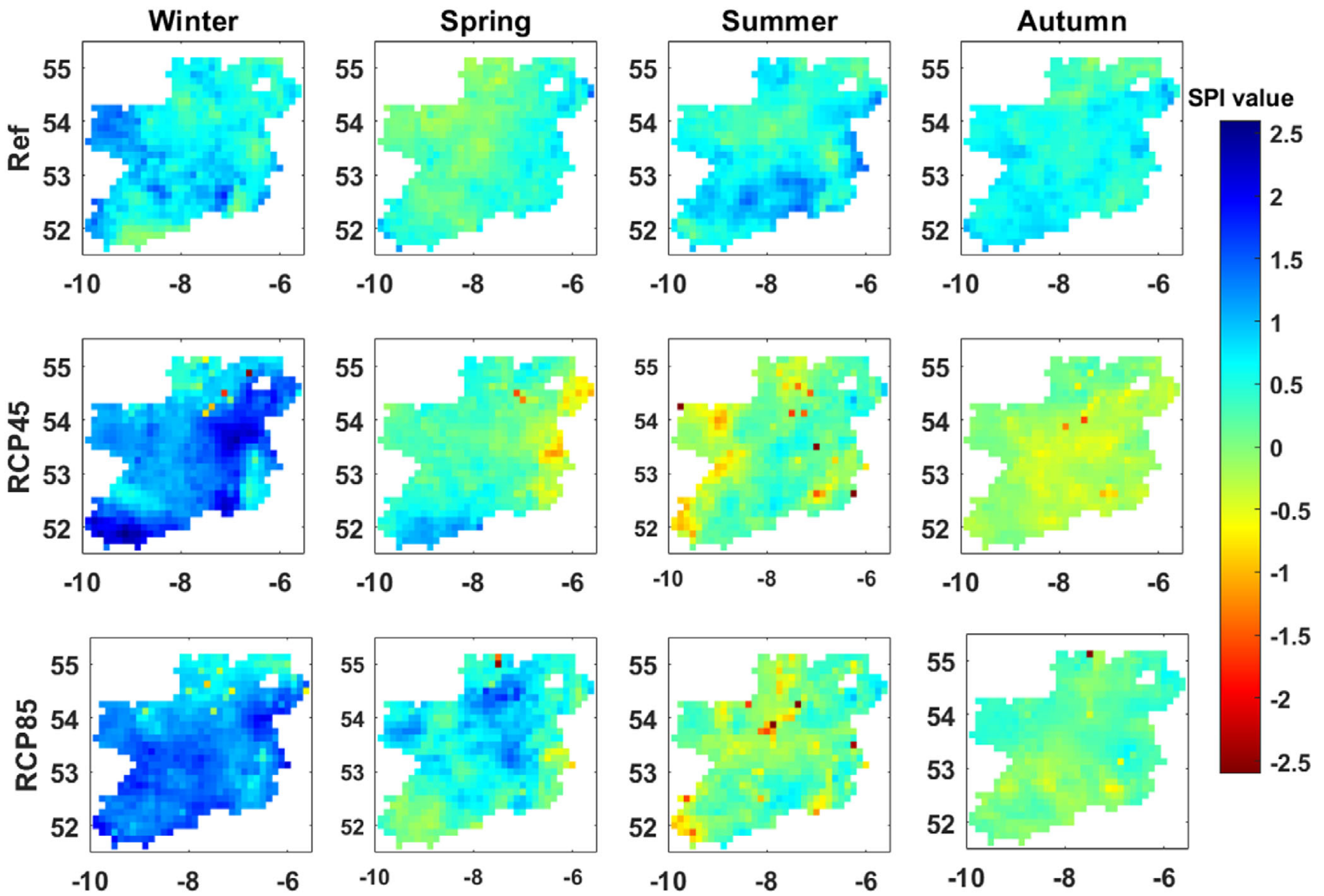

FIGURE 8 Ensemble mean projected changes in seasonal average SPI values for the reference period and far future (2080s) under RCP4.5 and RCP8.5. Each season is represented by SPI-3 for the last month of the season (i.e., summer is August SPI-3)

modest. A clearer signal of change emerges for SPEI-3 in each region, whereby increases in magnitude are evident for all regions and greatest under RCP8.5. Largest increases in SPEI-3 drought magnitude are simulated for the eastern, southern and southeastern regions. In terms of drought duration again a clearer signal towards longer droughts is evident using SPEI-3, with greatest increases under RCP8.5 and largest increases in duration evident for the eastern, southern and southeastern regions.

For SPI-6 events little change in magnitude is discernible across regions and RCPs, with future changes largely within the range simulated for the reference period. For SPEI-6 while only modest changes in the ensemble mean are returned for each region, the upper range of simulations increases for each region, especially under RCP8.5. SPI-6 events show modest increases in duration under RCP8.5, greatest in the southeast and north. There are suggestions of modest decreases in duration in the south. For SPEI-6 little change in duration is evident for the ensemble mean in each region; however, the range increases for RCP4.5. For RCP8.5 there is a tendency for decreases in duration of SPEI-6 events in the southern and southeastern regions. Overall, the range of changes in drought characteristics using SPEI-6 is greater than SPI-6 across all regions.

3.5 | Changes in seasonal drought magnitude

Figure 8 shows the average SPI values for each season for the reference period and 2080s under each RCP using the ensemble mean of 11 CORDEX simulations. In winter increases in average SPI values are evident under both emissions pathways, associated with increasing winter precipitation, indicating a decrease in winter droughts. Spring is also marked by an increase in average SPI values, though not as large as winter. Under RCP4.5 largest increases are evident for the southwest (Figure 8), while under RCP8.5 increases in average SPI values are more widespread, in line with greater precipitation increases under this higher emissions pathway. For summer, the

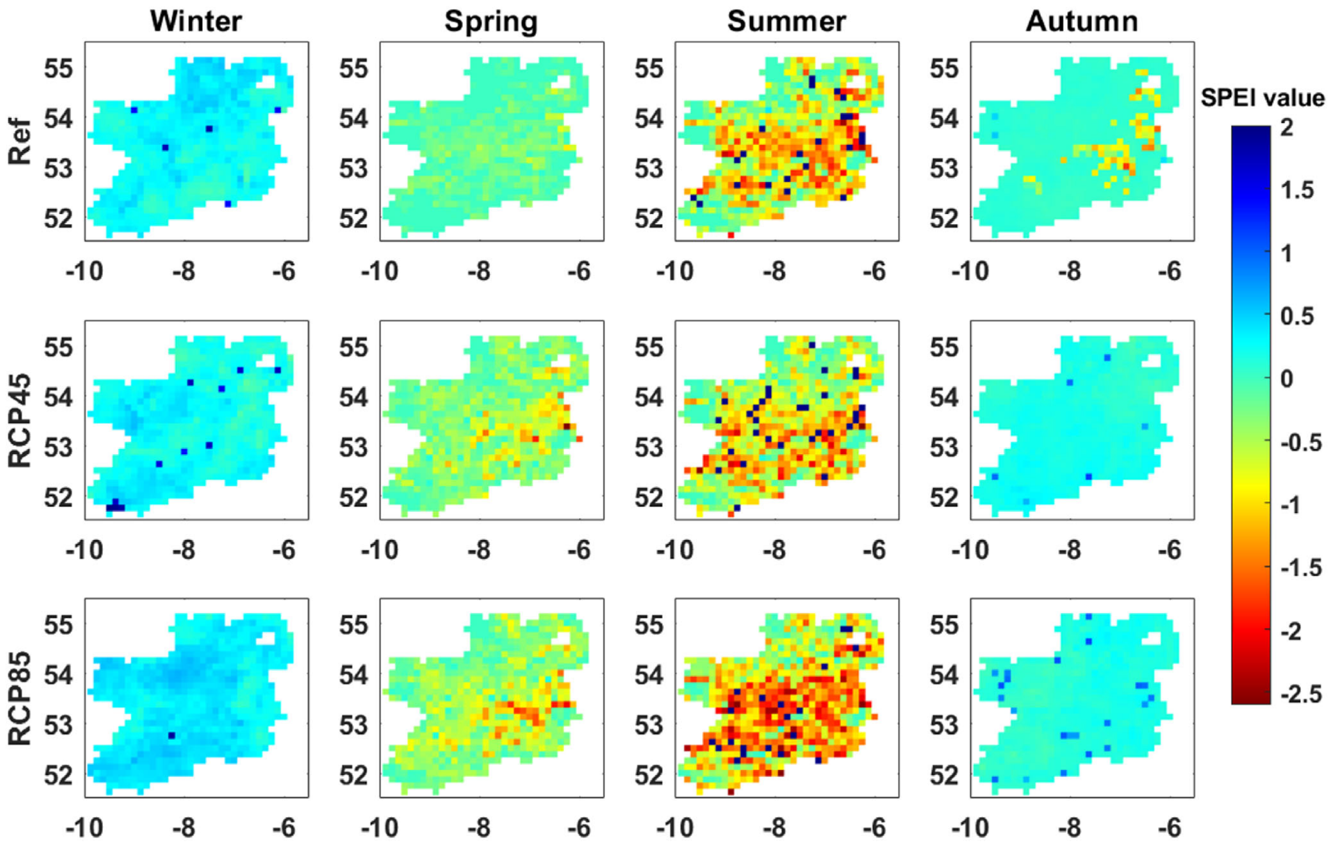

FIGURE 9 Ensemble mean projected changes in seasonal average SPEI values for the reference period and 423 far future (2080s) under RCP4.5 and RCP8.5. Each season is represented by SPEI-3 for the last month of 424 the season (i.e., summer is August SPEI-3)

ensemble mean indicates substantial reductions in average SPI across the island under both RCPs, associated with increases in summer drought conditions. Autumn also shows widespread decreases in average SPI for each emissions pathway. Notably, the decreases in autumn SPI are more marked under RCP4.5 than for RCP8.5. For the latter, increases in precipitation are more likely, especially in the later months of autumn.

For SPEI similar patterns of change are evident across seasons (Figure 9). In winter an increase in average SPEI is evident across regions. For spring little change is evident in most regions, however a decrease in average SPEI is simulated by the ensemble mean in the southeast under RCP8.5, indicating an increase in drought. Summer shows the largest changes, with substantial decreases in summer SPEI, especially for RCP8.5 across much of the southern half of the island. These changes are consistent with larger increases in temperature and hence evapotranspiration for the higher emissions pathway. For autumn changes are modest with a slight increase in average SPEI values, especially for RCP8.5.

Overall, both Figures 8 and 9 show a consistent finding of increasing summer drought in the far future under both climate scenarios. Moreover, the spatial extent and magnitude of increases in summer and spring droughts using SPEI are greater than for SPI. This is due to the significant water loss from evaporation during the late spring and summer seasons. In contrast, changes in autumn are similar between SPEI and SPI for both RCP45 and RCP85.

Changes in the magnitude of seasonal drought events were also evaluated using both drought metrics for each region to further investigate regional differences (Figure 10). For winter, decreases in drought magnitude are simulated for all regions under RCP45, though for RCP8.5 an increase in the upper range relative to the reference period is evident (Figure 10). Similar results are returned for SPEI. In spring decreases in event magnitude for SPI are simulated for all regions, greatest under RCP8.5. The opposite is the case for event magnitude using SPEI, whereby increases in magnitude are simulated, especially in the east, southeast and south under RCP8.5. All regions show an increase in drought magnitude in summer and an increase in the range relative to the reference period for SPI. For SPEI, large increases in magnitude are

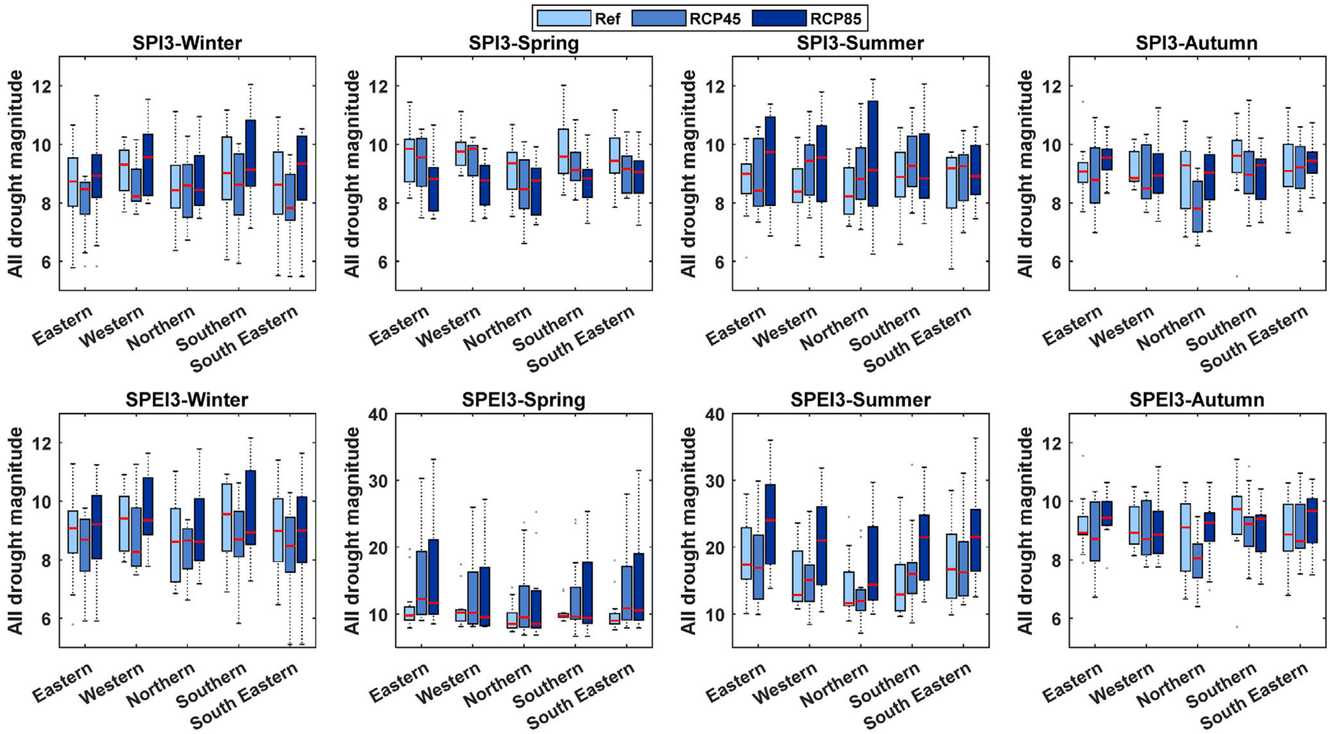

FIGURE 10 Projected changes in seasonal drought magnitude for SPI (top) and SPEI (bottom) for each region. Box plots show the interquartile range simulated from 11 CORDEX ensemble members for that region. The horizontal lines indicate the ensemble mean

returned under RCP8.5, though more moderate under RCP4.5. For autumn, decreases in drought magnitude are simulated for the northern region for both SPI and SPEI under RCP4.5, with only small changes simulated of other regions for both drought indicators in terms of the mean. We do note an increase in the upper and lower ranges for autumn, especially for SPI.

4 | DISCUSSION

This work assessed projected changes in drought magnitude, frequency and duration for the island of Ireland by the 2080s using 11 regionalised climate models from the EURO-CORDEX ensemble. Findings indicate increased drought risk with climate change, driven by changing seasonal dynamics of precipitation and potential evapotranspiration. In general, the CORDEX ensemble indicates a transition to wetter winters and drier summers, with increased PET losses in summer and extending into the latter spring months. The extent of future changes is dependent on greenhouse gas emissions, with more substantial changes and greater seasonality (wetter winters, drier summers) in precipitation evident for the high emissions pathway RCP8.5 relative to the middle of the road RCP4.5 pathway. This pattern of change is consistent with previous work assessing climate change impacts for hydrology on the island using different climate model ensembles (e.g., Kay et al., 2021; Meresa et al., 2022; Murphy et al., 2023; Nolan et al., 2017).

We find substantial differences in future drought characteristics using SPI and SPEI at different accumulation periods. SPEI indicates increased drying in comparison to SPI, highlighting the importance of evaporative losses in assessments of future drought risk, especially for drought magnitude in spring and summer. Similar findings have been reported for the UK and Europe (Ionita & Nagavciuc, 2021; Politi et al., 2022; Reyniers et al., 2023; Stagge et al., 2017). Even the direction of change in spring drought magnitude (assessed using a 3-month accumulation period) depends on whether SPI or SPEI is employed, with the former showing decreases in magnitude and the latter increases, highlighting the importance of changes in evaporative losses to future drought impacts (Vicente-Serrano et al., 2020). Given the impact that spring drought can have for grass growth in an agricultural system heavily dependent on grass fed dairy, integration of SPEI into drought assessments and monitoring is critical to assessing future impacts and adaptation responses and monitoring ongoing changes in observations.

Future changes in drought characteristics are also dependent on the accumulation period used. We deploy SPI and SPEI at 3- and 6-month accumulation periods, with the shorter accumulation period indicating greater changes in drought frequency, magnitude and duration, particularly for SPEI. Changes at the 6-month accumulation period are more modest under both emissions pathways because of changes in seasonal precipitation totals, with increases in winter, spring and autumn precipitation across individual climate models. Notably, greatest uncertainty in the direction of change in future precipitation is indicated for the shoulder seasons of spring and autumn (Meresa et al., 2022), with these uncertainties being important for multiseasonal drought assessments, as indicated by SPI-6. This is also likely to be the reason why changes in drought duration are more modest than changes in magnitude and frequency.

Our assessment finds that increases in drought magnitude and frequency are driven by changes during summer, with decreased drought magnitude and duration in winter. This is consistent with the work of Spinoni et al. (2018) who used an indicator combining SPI, SPEI and the reconnaissance drought indicator to assess future droughts at the European scale using the CORDEX ensemble. They highlight widespread (including western Europe) increases in drought frequency and intensity in spring and summer, with more modest changes in autumn and decreased drought frequency in winter in northern Europe. Our findings are also consistent with recent studies that highlight a tendency towards shorter, more intense meteorological and hydrological droughts during summer for Ireland from long-term observations and reconstructions (Meresa et al., 2023; O'Connor et al., 2022; Vicente-Serrano et al., 2020). Such short and intense summer droughts are typically perceived as flash droughts, with significant impact on atmospheric aridity and the depletion of soil moisture, with associated challenges for management (Qing et al., 2022).

Our analysis examined spatial variations in future drought changes. Largest changes in the aridity index were found for the driest regions during the reference period, that is, eastern and central parts of the island. Furthermore, greatest increases in drought magnitude were also found for the eastern region. Given the impacts of the 2018 drought (Falzoi et al., 2019), future changes in drought characteristics would pose substantial challenges for water management. At present, growing water demand coupled with aging infrastructure has resulted in a reduced margin and security of water supply for Dublin, a major European city (Kelly-Quinn & Baars, 2014; Wilby & Murphy, 2018). Continued growth in water demand, together with increases in drought frequency and magnitude are likely to further complicate water management in the region. O'Connor et al. (2023) linked drought metrics (SPI-3) with drought impacts classified from historical newspaper archives (Jobbová et al., 2023) for Irish catchments, finding that in summer, reporting of impacts related to agriculture and water supply were likely even at modest SPI-3 deficits. Given such vulnerability, increases in the magnitude and frequency of droughts reported here are likely to require adaptation across sectors, particularly for agriculture and water management.

Adaptation planning could stress test water resource plans and adaptation options to changes in drought characteristics identified here (e.g., Murgatroyd et al., 2022) and/or use the projected changes to inform development of drought storylines (e.g., Chan et al., 2022; Gessner et al., 2022). Using a larger ensemble of climate models that sample differences in initial conditions could provide a more comprehensive understanding of extreme characteristics and the role of natural climate variability, especially in capturing seasonal drought variability (Kelder et al., 2022). Groundwater also plays an important role in water provision across the island, particularly in the midlands. Decreases in winter drought frequency and magnitude with increased precipitation may increase recharge potential. However, impacts are likely to be moderated by aquifer characteristics. Poorly productive aquifers with limited permeability are unlikely to accept additional recharge, while those with high recharge coefficients are likely to be more sensitive to changes in winter rainfall (Cantoni et al., 2017; Williams & Lee, 2008), with the impact of increased meteorological drought in spring and summer possibly offset by increased storage. However, additional research is required to better understand how changes in meteorological drought may propagate to other components of the hydrological system (e.g., Meresa et al., 2023). The 2018 drought also resulted in degraded water quality, affecting sensitive riverine species and habitats (Mellander & Jordan, 2021). The impact of future drought changes on water quality through impacts on point and diffuse sources is poorly understood.

Our research is subject to several limitations. CMIP5 models, upon which the CORDEX ensemble is based, show substantial disagreement compared with observed trends in meteorological droughts, with a tendency to overestimate drying in mid-to-high latitudes (Knutson & Zeng, 2018; Vicente-Serrano et al., 2022a, 2022b). The latest generation of CMIP6 models show better performance in reproducing long-term precipitation trends (Vicente-Serrano et al., 2022a, 2022b). An important limitation of climate models for assessing future drought risk includes a tendency to underestimate drought persistence at monthly to decadal scales in the mid-latitudes and the large intermodel spread in simulated precipitation deficits (Seneviratne et al., 2021). The large intermodel spread in precipitation among climate models is mostly related to uncertainty in how atmospheric circulation responds to climate change (Shepherd, 2014). Moreover, uncertainties in drought projections are affected by consideration of plant physiological responses to increasing atmospheric CO_2 and soil moisture–atmosphere feedbacks (Ishola et al., 2020; Vicente-Serrano et al., 2022a, 2022b). As highlighted above, future drought changes are sensitive to estimates of PET. We use a simple temperature-based method (Oudin et al., 2005) to estimate PET losses. Future research should investigate the sensitivity of our findings to different approaches to estimating PET and atmospheric evaporative demand.

Finally, we only assess changes in drought at 3- and 6-month accumulations. Multiyear droughts are often associated with significant social and economic impacts (Murphy et al., 2020a, 2020b), while Wilby et al. (2016) highlight the relatively high likelihood of extended, multiyear dry spells in the east of Ireland even under current climate conditions. Furthermore, as Laimighofer and Laaha (2022) highlight, it is also important to consider the uncertainty associated with the application of standardized drought indices, including sensitivity to period used for standardization and the distributions applied. Future research should also investigate climate change impacts for longer accumulation periods than assessed here, including multiyear droughts, to which groundwater systems are highly vulnerable.

5 | CONCLUSION

This research evaluated climate change impacts on drought magnitude, frequency and duration for the island of Ireland for the 2080s simulated by the CORDEX ensemble, together with the widely used SPI and SPEI drought indices. We find increased drought magnitude, frequency and duration, especially using SPEI relative to SPI and for the high emissions pathway (RCP8.5) relative to the more moderate RCP4.5. Results highlight the importance of temperature and associated increases in potential evaporation, and greenhouse gas emissions to future drought risk. Greatest changes in magnitude were found for summer using SPEI-3, especially in the east and midlands of the island. Changes in drought duration and multiseasonal droughts as assessed using SPI/SPEI-6 were more moderate given increases in precipitation outside of summer. The drought of summer 2018 highlighted the vulnerability of Ireland to drought impacts, especially in the agriculture and water sectors. The increases in drought magnitude and frequency, as found here, would pose substantial adaptation challenges.

AUTHOR CONTRIBUTIONS

Hadush Meresa: Conceptualization; investigation; writing – original draft; visualization; methodology; software; formal analysis; data curation; resources. **Conor Murphy:** Conceptualization; investigation; funding acquisition; writing – review and editing; validation; project administration; supervision; visualization.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data and materials are available from the corresponding author on request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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