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Risk of extreme climate impacts on European Norway spruce forest: drought and frost in the climate emergency

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Abstract

Shifts in weather patterns causing more severe and frequent climatic extreme events, particularly periods of hot drought and late-spring frost, cause stress and damage to many tree species. Here we use 12 members of the UKCP Regional (12km) ensemble to assess the changing risk of tree stress posed by hot droughts and late-spring frosts. As an exemplar tree species, we use Norway spruce (*Picea abies*) to demonstrate a method that links the European distribution of the species to extremes in the projected climate data ensemble at the continental scale. Monthly climate projections were used to calculate the standardised precipitation and evapotranspiration index (SPEI) and bias corrected daily temperature projections were used to calculate a frost buffer of the number of days between last date of spring frost and the date of leafing of Norway spruce. The UKCP Regional climate model ensemble shows substantial changes in the distribution of SPEI likelihood and severity between the pseudo-global warming threshold temperatures of 1^0C and 2^0C indicating concern in relation to drought severity and frequency in Alpine, Atlantic, and Mediterranean biogeographic regions. In addition, late spring frosts particularly in the Atlantic and Continental biogeographic regions will continue to affect sensitive young trees such as Norway spruce. The approach removes the time series estimation of climate extremes providing a single method of estimating effects of the climate emergency across shared socio-economic pathways. Finally, the approach could be useful to direct the deployment of suitable selected forest reproductive material from tree-breeding programmes in Europe.

Keywords Global warming thresholds · Hot drought · Frost buffer · SPEI

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1 Introduction

Climate change is forcing adjustments to both phenological and physiological processes in forest trees as the annual growth and dormancy periods change with seasonal shifts in weather patterns caused by climate warming (Scranton and Amarasekare 2017). Historic changes in the 30-year climate normal period across Europe have been driven by seasonal shifts in the distribution of rainfall, becoming drier in summer months and wetter in winter (Christidis and Stott 2022), accompanied by warmer conditions. In addition, concurrent increases in the magnitude and frequency of extreme weather have occurred globally. In Europe, heatwaves and drought occurred in 2018, 2019, 2022, and 2023. Climate attribution studies show that climate change has made extreme heat more likely, for example that experienced in North America, China, and Europe in summer 2023 (Zachariah et al. 2023). In July 2022 Europe experienced the most severe drought in 500 years (Toreti et al. 2022) and an attribution analysis estimated that climate change made the northern hemisphere root-zone soil moisture droughts of 2022 twenty times more likely (Schumacher et al. 2022).

Hot and dry summers have become more frequent, e.g., 2016, 2018 (Barriopedro et al. 2020). The sequence of intense summer heatwaves and accompanying droughts have been caused by a shift in the position of the summer jet stream (Büntgen et al. 2021) with increased ‘blocking’ of the jet in the mid-latitudes of the northern and southern hemispheres forming stationary regional heat dome conditions (Rousi et al. 2022). Droughts in Europe throughout this period combined with elevated temperature anomalies were as severe as any experienced over the last 250 years (Rakovec et al. 2022).

Changes in the seasonal distribution of precipitation; increased warmth and dryness, and earlier budburst over the last 50 years are having a detrimental effect on many European forest tree species (Allen et al. 2015). This is occurring through abiotic impacts to both the physiology and phenology of broadleaves and conifers (Urli et al. 2013, 2015; Hayatgheibi et al. 2021; Svystun et al. 2021). The abiotic drought impacts on tree physiology include: xylem embolism, which has a weak phenotypic resistance in response to drought in many tree species (González-Muñoz et al. 2018); drought stress causing reduced carbon uptake and growth from increased evapotranspiration (Reichstein et al. 2013; Xenakis et al. 2021). Furthermore, biotic attacks associated with climate abiotic triggers exert greater stress on trees and forests (Santini et al. 2013; Hlásny et al. 2021) through drought, waterlogging, frost, and wind damage (Seidl et al. 2017).

Frost damage can also threaten forest ecosystems and is expected to be more severe under future climates. For example, Svystun et al. (2021) analysed the projected change of spring warmth (growing degree days) in Nordic countries driving Norway spruce (*Picea abies (L.) H. Karst., 1881*) bud burst and concluded that although future frost events may be fewer, a greater proportion of young trees may be affected after bud burst. It is mainly young trees in the early establishment phase of a stand (Hannerz 1999, p12-13) that are at a greater risk of frost damage, as young trees have been found to flush earlier (Vitasse et al. 2014). The pattern of late spring frost in Illinois, US, was investigated on 20 woody species from 1993 to 2012 (Augspurger 2013), and showed that a feature of frost damage was the association with warm temperatures in March followed by a frost in April. Menzel et al. (2006) reported a similar result across Europe over the period 1971–2000, they found that a strong advance in leafing occurred in countries which had a warmer preceding month. In a meta-analysis, a delay in flowering was found when late spring frost after leafing occurs in the Northern Hemisphere (Qiu et al. 2024). In a similar Northern Hemisphere meta-analysis, Wang et al. (2025) reported that late spring frost in a given year reduces photosynthetic productivity and causes an average 7-day delay in leafing the following year leading to a second year of reduced productivity.

Several studies have examined the drought and the frost sensitivity for a range of tree species. A study by Niinemets and Valladares (2006) used a Delphi approach across each of the northern hemisphere continents to assess drought, shade, and waterlogging tolerance. Frost avoidance was studied in oak phenotypes (Dantec et al. 2015) sampled at elevation gradients which showed good safety margins (avoidance) at lower elevation and decreasing safety margins with increasing elevation. A study involving lodgepole pine (*Pinus contorta* Doug ex Loud.) in North America (Montwé et al. 2018) showed material from northern latitudes was more sensitive to late spring frost.

Studies of extreme events under current or future projected climates require access to Regional Climate Models (RCM) and monthly and daily temporal resolution climate projections offering temperature minima for studies of frost damage to predict the date of bud burst. After testing and validating models of the flushing of tree species, Linkosalo et al. (2006) showed that simple temperature sum models (thermal time models) using the parameter' accumulated day degrees' (sometimes also called 'growing degree days', GDD) were more accurate in predicting the bud burst event for a range of species than models that include a chilling parameter to simulate rest in dormancy.

Our hypothesis is that the UKCP Regional Climate Model ensemble will show an increase in the frequency and magnitude of a) extreme heat and drought and b) spring frost occurrence, likely to affect forest stands in Europe. To illustrate the modelling approach we use Norway spruce (*Picea abies*) as an example species. Norway spruce has a wide distribution across European biogeographic regions extending across the UKCP Regional climate model's geographical domain. The study demonstrates a novel methodological approach of combining climate ensemble data to demonstrate the uncertainty of the effects of climate extremes. The novelty of the approach is to de-coupled the temporal dimension of climate projections from the analysis and instead link the occurrence of extreme events to a 21-year period that encompasses the year in which global warming threshold temperatures above the temperature of the pre-industrial period are projected to occur in each of the individual members of the ensemble. We believe this approach will help forest policy and practitioner stakeholders across Europe to improve plans to adapt forest management under climate change.

2 Method

Our study brings together various data sets to model the likelihood of extreme abiotic damage to forest trees by combined heat and drought, and the likelihood of late spring frost after a predicted flushing/leafing date. We used nine of the eleven European biogeographical regions (European Environment Agency 2016) to perform a regional analysis across Europe, namely: Alpine, Anatolian, Arctic, Atlantic, Boreal, Continental, Mediterranean, Pannonian, and Steppic (Fig. 1). The two remaining regions 'Black Sea' and 'Macaronesia' lie outside the climate model's geographical domain.

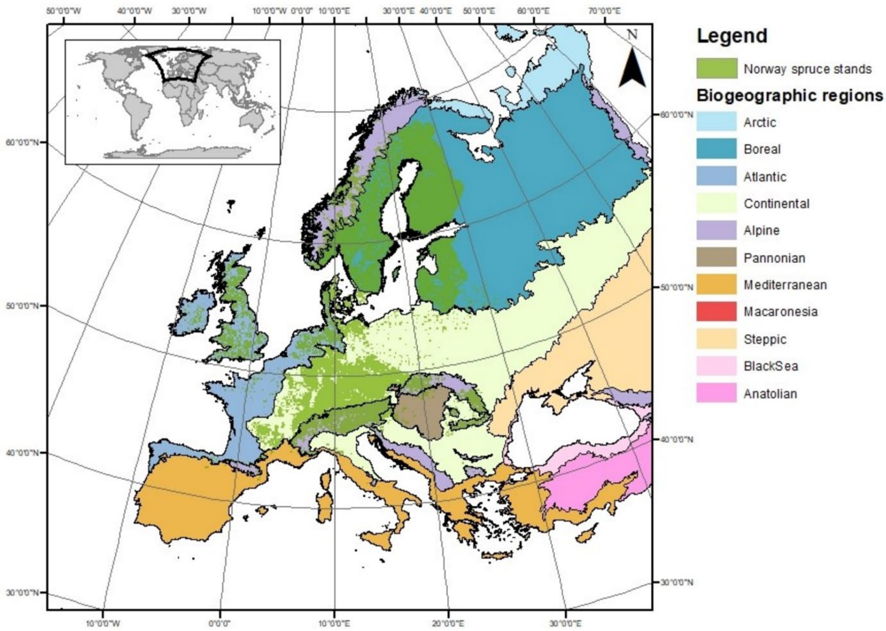

Fig. 1 Area of Norway spruce in Europe (as 12 km resolution pixels) (Mauri et al. 2017) from the Joint Research Centre map of European Country National Forest Inventories (NFI) over the biogeographic regions of Europe (European Environment Agency – 2016) © EuroGeographics, © FAO (UN)

We analyse climatic extreme events focusing on drought and late spring frost from the UK Met Office (UKMO) RCM ensemble for the whole of Europe, UKCP Regional (12 km). This is a 12-member perturbed physics model ensemble which has been dynamically downscaled by the UKMO from the global climate model, HadGEM3-GC3.05, using the UKMOs fine-scale model, HadREM3-GA7-05 (Murphy et al. 2019). UKCP Regional comprises 26 climate variables stored in a 12 km rotated-pole grid for 1981–2080 and is the highest spatially coherent resolution projection available for pan-European climate studies whether from the UK Climate Projections or other international climate model centres (see https://euro-cordex.net). Only RCP 8.5 is available for the UKCP Regional, however we use a pseudo-global warming threshold (PGWT) temperature approach (Hanlon et al. 2021) to understand future extreme events. The PGWT aligns different RCMs from the UKCP Regional ensemble by the 'future' date that each member is predicted to reach a warming threshold temperature of 1.5 °C, 2.0 °C, 2.5 °C, etc. above the pre-industrial mean global temperature (Hanlon et al. 2021). The approach focuses on the uncertainty of RCMs using temperature threshold points rather than a time series of climate change. The advantage of using a PGWT method is the inclusion of a large ensemble of models, the disadvantage is the removal of the time series of climate change. UKCP Regional was available for Europe between 18°W and 42°E, and 28°N and 74°N. Consequently, the Boreal and Continental biogeographic regions are not fully covered by climate data, as these regions extend to 61°E.

2.1 Bias correction of daily temperature using ERA5 data

We used growing degree days (GDD) above 5 °C equivalent to active accumulated temperature (Xu et al. 2021) using daily mean temperature extracted from the UK Regional projections and accumulated when the mean 5-day temperature was greater than 5 °C. Identifying frost days and GDD involves applying a threshold to temperature data (minimum and mean, respectively). For this reason, bias correction of the climate model projections is needed, whereby differences between the climate model and observations in the recent past are used to adjust the climate model projections in the future. We used the scaled distribution mapping method – SDM (Switanek et al. 2017), which scales the projected changes across the distribution of values. The SDM approach causes lower inflation/deflation of the mean and standard deviation compared to other methods of bias correction such as quantile mapping and delta quantile mapping that employ a stationary error correction function. The SDM scales the projected distribution to changes in magnitude, rain-day frequency and event likelihood, and preserves the climate change signal in changes to the mean and the distribution of the data. Here, bias correction of minimum and mean daily temperature was performed using daily ERA5 data (Hersbach et al. 2020) with a reference period of 1981–2010.

2.2 Pseudo-global warming threshold (PGWT) years

Climate change projections are important for the long term management of forests and in this study we focused on simplifying the message by aligning our analysis to pseudo-global warming threshold temperatures (PGWT) as described by Hanlon et al. (2021). To achieve this alignment, we calculated extreme climate values for the 21-year period centred on each threshold year given by Hanlon et al. (2021) that indicated the year in which a given exceedance temperature above the pre-industrial period occurred (see online supplementary material Table A1). This allows a comparative analysis of the ensemble for 10 years prior, and 10 years following the threshold year. This is a more complete sampling of climate projection extremes than calculating mean values over thirty years or comparing projections from different models on a time basis. This is meaningful in a situation in which greenhouse gas emissions can change and global warming points may shift in time as abatement and emissions reductions proceed into the future.

2.3 Drought index (SPEI)

The Standardised Precipitation and Evapotranspiration Index – SPEI drought index (Vicente-Serrano et al. 2010; Beguería et al. 2014) was used to determine changes in drought frequency and intensity across European bioclimatic regions. We chose the SPEI because it has been widely used in key studies to quantify drought with available climate data (Vicente-Serrano et al. 2012; Spinoni et al. 2018; Tirivarombo et al. 2018). The main feature of SPEI is the ability to standardise the water balance (precipitation—P and potential evapotranspiration—Et0) across space and time, using log-logistic algorithms. Potential evapotranspiration was calculated using precipitation, maximum and minimum temperature in the Hargreaves-Samani evapotranspiration equation (Hargreaves and Samani 1985):

$$Et0 = 0.0023 \times solRad \times (Tmean + 17.07) \times ((Tmax - Tmin) - (0.0123 \times P))^{0.5441}$$

where solRad = monthly extra-terrestrial solar radiation (MJ/m2), Tmean = mean monthly temperature (°C), Tmax = maximum monthly temperature (°C), Tmin = minimum monthly temperature (°C), and P = total monthly precipitation (mm).

The standardisation procedure using a reference period ensured the SPEI values at different sites have the same mean value ($\mu = 0$) and standard deviation range, recorded at the same location but at separate times. The consequence is that SPEI values can be compared across space and time. We used the thirty-year period 1981–2010 as a reference period to standardise and align the mean and variance for each pixel of the 12 km grid of Europe. Negative values of SPEI indicate dry climatic conditions and our definition of drought categories is modified from a scale described by Um et al. (2017), where: slight (SPEI = −1 to 0); moderate (SPEI = −1.5 to −1); severe (SPEI = −2.0 to −1.5); extreme (< −2.0). There are various combinations for calculating SPEI, over 1-month, several months, one or more years, based on an antecedent period relative to a given month. We calculated SPEI for a 6-month period with a focus on the growing season (April – September) and during which drought affected stands of Norway spruce become increasingly stressed and liable to attack by bark beetles (such as *Ips typographus*) in Europe. Since SPEI is a standardised index, we determined that the temperature, rainfall, and evapotranspiration data used in the calculation did not need to be bias-corrected. SPEI was calculated using the "SPEI" R package (Beguería et al. 2014) and spatial data were managed using the "terra" package (Hijmans 2025) in R language (R Development Core Team 2023).

We examined extreme drought events spatially predicted over time by determining the mean minimum SPEI across all 12 UKCP Regional ensemble members for the baseline period 1981–2010, and the future period 2041–2070. We further explored the development of drought intensity and frequency using a Loess density function (Cleveland 1979) on minimum SPEI of each RCM member over the 21-year period centred on the year (10 years prior and 10 years post the PGWT) in which the PGWT temperature occurs (Table A1—online supplementary material).

2.4 Hot summer drought periods

We combined summer drought years with years featuring hot summer conditions. Droughts were defined with SPEI values less than or equal to −1.5. Hot summers were arbitrarily defined as having a mean maximum monthly temperature of 25 °C in any of the three summer months of June, July, or August. For this analysis we used all UKCP Regional ensemble members for the six biogeographic regions in which Norway spruce was present (Fig. 1) from European NFI records. The analysis was performed separately as a proportion of the total area of Norway spruce in each of the nine biogeographic regions.

2.5 Projected frost dates

Our daily bias-corrected mean temperature data provided the basis for calculating the thermal sum, expressed as Growing Degree Days – GDD (day degrees equal to or above a mean daily temperature of 5 °C) to drive the phenology of plant leafing. We used as an example the mean thermal sum of tested Norway spruce provenances—200 GDD (200-degree days above + 5 °C—Svystun et al. 2021). The GDD for leafing was calculated for each of the 12-members of the UKCP Regional ensemble and for every 12 km pixel across the European grid for the 10 years prior to, and 10 years following the date of each PGWT year. This analysis gave the date for the beginning of leafing separately in each pixel and each year. The last date of frost was set with a minimum air temperature of 0 °C or below and the last frost was extracted for each of the 21 years of the 12 RCM ensemble members. In calculating the thermal sum, we checked the mean temperature for 5 days after the first recorded day with a mean temperature of 5 °C. If the mean temperature of the subsequent 5 day period was below 5 °C, the GDD accumulation was retarded by a day, and this procedure was repeated until the mean 5 day temperature was not less than 5 °C. We calculated a positive frost buffer for each pixel based on the number of days from the last date of frost to the date the GDD accumulation reached 200 GDD. If the last date of frost occurred after the 200 GDD date a negative frost buffer occurred.

2.6 Detailed climate of Norway spruce sites in Europe

We used the actual distribution of Norway spruce (from European National Forest Inventory - NFI data) assembled and published by the Joint Research Centre (Mauri et al. 2017) to focus attention on the area containing stands of Norway spruce in each biogeographic region. A Norway spruce zone raster mask was designated by selecting all 12 km pixels in which point locations from the JRC presence vector map occurred (Fig. 1). In applying the approach, the required heat sum can be set to a different value from empirical studies on tree species or provenances, or from literature.

3 Results

3.1 Drought (SPEI) and heat

We found that the SPEI had a maximum difference of 0.05 between values calculated using monthly data from the UKCP Regional between 1981–2010 (Online Supplementary Material—Figure A1) over which the standardisation was performed. In addition, the standardisation showed average minimum SPEI values between −2 and −3 for all the 12 km pixels in Europe for the period 1981–2010 with a small standard deviation (between 0 and −0.5). SPEI values calculated from the 30-year period 2041–2070 revealed a decrease of the minima to −3 and −4 in Temperate, Atlantic, Continental, and Mediterranean regions, while in the Boreal region the mean SPEI minimum values continued as for the 1981–2010 period. This indicated that the standardisation period for SPEI brought the mean and standard deviation of values to within the expected range (mean = 0 and −1 < st.dev. < + 1), and that future projections showed SPEI decreasing except in the Boreal Region.

For the nine largest (in area) European biogeographic regions, the twelve UKCP Regional ensemble variants aligned at four PGWT temperatures (+ 1 °C to + 4 °C at 1 °C intervals) provide the SPEI probability density distribution at each of these points (Fig. 2). The SPEI drought distributions show a broadening of the range and an attenuation of the median value with increasing PGWT as the climate emergency intensifies. Across all biogeographic regions, drought regimes defined by intensity and probability density of mean minimum 6-month (April to September growing season) SPEI follow similar patterns. At a PGWT of

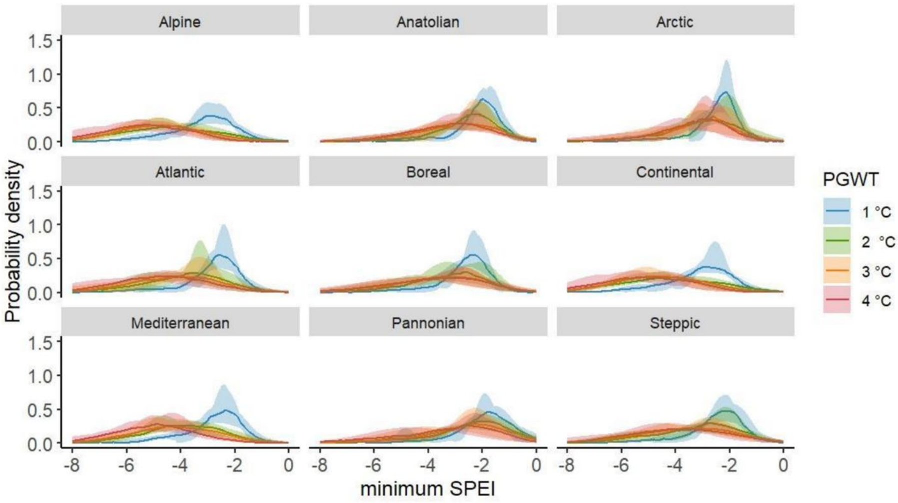

Fig. 2 Distribution of the mean SPEI minima for the 6-month growing season (April-September inclusive) of 12 UKCP Regional (12 km) ensemble members at four points of the pseudo global warming threshold (PGWT) range of 1–4 °C at 1 °C intervals for the five largest biogeographic regions in Europe. Bold lines represent the median of the ensemble members and shadow area represent the modelled 95% range from a fitted ‘loess’ locally weighted smoothing function

+1 °C, reached in 2020[1], SPEI minima probability densities peak between values of −3 to −2. The extent of the SPEI range intensity varies by region with the Boreal (Fig. 2) experiencing the smallest shift in drought intensity, from the most frequent mean minimum SPEI at PGWT of +1 °C with a SPEI value of −2.24 showing a probability density of 0.79, to a SPEI of −2.3 with a 0.43 probability density at the +4 °C PGWT temperature. In contrast, the Mediterranean (Fig. 2) is projected to experience more severe droughts, with the most frequent mean minimum SPEI of −2.41 showing a probability density 0.76 at the 1 °C PGWT, which will shift to −5.3 SPEI with a probability density of 0.39 at the 4 °C PGWT.

While Fig. 2 shows a range of uncertainty across the ensemble members, the behaviour of SPEI with PGWT temperatures is robust. The uncertainty range increases as PGWT increases and SPEI distributions broaden and attenuate. Uncertainty shown by the range of minimum SPEI values increased for SPEI calculated over a shorter 3-month spring period (Online Supplementary Material – Figure A2a ‘3-month’ & A2b ‘6-month’) but the median of the minimum SPEI values remain similar for 3- and 6-month period calculations. For all the regions the probability of more negative SPEI values (drier conditions) increases with increasing PGWT.

We examined the minimum, median and maximum SPEI averages from UKCP Regional member 1 for all pixels in the nine biogeographic regions (Figure A2 supplementary material), and again for pixels that coincided with Norway spruce stands in six biogeographic regions (Fig. 3). Both figures show a slight decrease in the minimum SPEI with PGWT indicating extreme drought events will increase in magnitude with increasing PGWT temperatures. However, the maximum SPEI increase occurs at different rates across the regions, and for Norway spruce presence pixels (Fig. 3) increases in four of the regions (Alpine, Atlantic,

[1] https://climate.nasa.gov/news/2878/a-degree-of-concern-why-global-temperatures-matter/

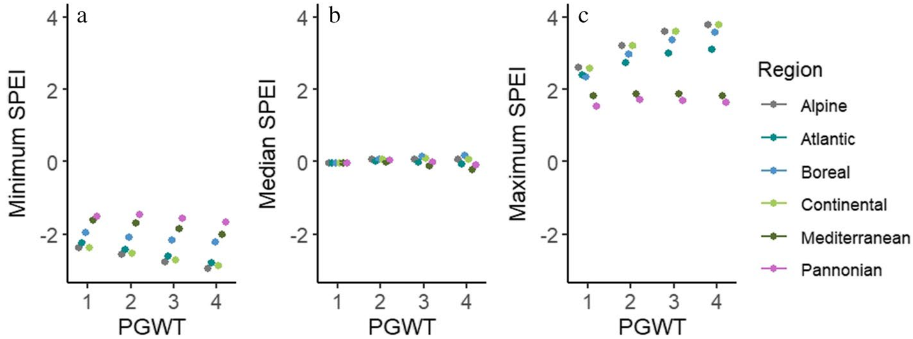

Fig. 3 Projected changes in the **a** mean minimum **b** mean median and **c** mean maximum standardised precipitation and evapotranspiration index (SPEI) with standard errors (very small values), for pseudo-global warming thresholds where pixels coincide with stands of Norway spruce from the National Forest Inventory in European biogeographic regions calculated from UKCP Regional (12 km) ensemble member 1

Boreal, Continental), but remains constant in the Mediterranean and Pannonian regions. This indicates that the natural variation of the climate from year-to-year will continue with both drier and wetter summers, and this has the effect of balancing the years with increasingly drier summers to maintain a steady SPEI value of 0 for the average of the median SPEI values across PGWT temperatures. For each region and PGWT temperature (from UKCP Regional RCM member 1 only) the mean area of hot droughts affecting Norway spruce in the 21-year period (Table 1a) remained fairly small with values in the Alpine, Atlantic, Boreal and Continental regions between 0% and 3.0% of the Norway spruce area. Larger proportions of the Norway spruce area were affected by hot droughts in the Mediterranean and Pannoian regions, varying between 8 and 12% of the Norway spruce stands. For all regions the standard errors were large, reflecting the stochastic nature of hot droughts from year to year within the twenty-one year period of calculations.

A further analysis of the change in spatial extent of hot drought occurrence across Europe (Online Supplementary Material—Figure A3) shows for each biogeographic region with Norway spruce stands, the proportion of pixels with: a SPEI value equal to or less than −1.5 representing moderate to extreme drought; a growing season maximum monthly temperature equal to or greater than 25 °C; the combined occurrence of SPEI and maximum temperature thresholds. In each region the proportion of Norway spruce area for which projected maximum temperatures exceed 25 °C increases steadily with PGWT temperatures. In both the Mediterranean and Pannonian regions, the Norway spruce zones are small, but the area affected by elevated temperature is relatively high (greater than 50%) for PGWT temperatures of 2 °C and above. UKCP Regional projections indicate that in the least affected region (Boreal), at most 10% of the Norway spruce area is projected to be affected by hot droughts. The Boreal region holds the core of the Norway spruce stand range (32,392 pixels). The Continental and Atlantic regions hold 39% of the spruce range (combined area = 27,675 pixels) across which the area affected by hot droughts could be in excess of 5% of the spruce area by the PGWT temperature threshold of 2 °C. Surprisingly the UKCP Regional projections show that 5% of the area of Alpine stands of Norway spruce may be affected by hot droughts at a PGWT temperature of 2 °C above the pre-industrial temperature average.

A clearer demonstration of the projected occurrence of hot droughts is seen by examining the frequency (Fig. 4) over the 21 years surrounding each PGWT year, for all the pixels con-

Table 1 Projected mean percentage area of spruce affected by a) hot drought conditions and b) late spring frost based on UKCP Regional climate projection (RCM member 1 only) for six European biogeographic regions where Norway spruce stands occur, and four pseudo-global warming threshold (PGWT) temperatures above pre-industrial levels

a) Hot drought affected area (mean ± se-km^2)					
Region	Spruce area (km^2)	PGWT 1 degC	PGWT 2 degC	PGWT 3 degC	PGWT 4 degC
Alpine	25,632	256 ± 77	333 ± 590	205 ± 692	256 ± 666
Atlantic	21,456	901 ± 64	644 ± 451	622 ± 558	536 ± 665
Boreal	78,132	625 ± 0	391 ± 1,484	78 ± 1,016	156 ± 1,016
Continental	36,588	805 ± 805	1,024 ± 1,720	292 ± 2,415	512 ± 2,268
Mediterranean	960	84 ± 102	95 ± 51	61 ± 60	86 ± 74
Pannonian	1,152	48 ± 165	129 ± 121	130 ± 130	113 ± 118
b) Late spring frost affected area (mean ± se-km^2)					
Region	Spruce area (km^2)	PGWT 1 degC	PGWT 2 degC	PGWT 3 degC	PGWT 4 degC
Alpine	25,632	769 ± 282	1,384 ± 590	1,845 ± 692	2,101 ± 666
Atlantic	21,456	321 ± 64	1,802 ± 451	1,952 ± 558	3,326 ± 665
Boreal	78,132	0 ± 0	3,203 ± 1,484	2,266 ± 1,016	4,062 ± 1,016
Continental	36,588	1,792 ± 805	5,780 ± 1,720	8,561 ± 2,415	9,257 ± 2,268
Mediterranean	960	279 ± 102	148 ± 51	263 ± 60	367 ± 74
Pannonian	1,152	410 ± 165	487 ± 121	497 ± 130	364 ± 118

taining stands of Norway spruce, by biogeographic region, and separately for each member of the climate ensemble. Hot droughts might affect 5–10% of the Norway spruce area and the frequency of hot droughts is predicted to change substantially from approximately 10% per 21-year period at the PGWT + 1 °C (varying by biogeographic region) to 30–40% per 21-year period at PGWT + 2 °C, particularly in the Alpine, Atlantic, and Continental biogeographic regions, with a smaller increase in frequency for the Boreal region. However, the ensemble shows considerable uncertainty in the frequency range with possible hot-drought frequencies of 50% by PGWT + 2 °C, shown by some of the RCM members.

3.2 Bud-burst date, last day of frost and security buffer

Our analysis of the daily minimum temperatures showed an advance of bud-burst (start of leaf expansion) in Norway spruce earlier in the year with increasing PGWT temperatures (Figure A4 supplementary material), the median budding date was earlier in each biogeographic region under climate change with a linear trend recognised for all the regions except Continental, Mediterranean, and Pannonian. The analysis also showed changing distributions of budding dates among the regions. In particular, the Alpine, Boreal, Continental, Pannonian and Steppic regions showed an attenuation of the peak in the frost buffer dis-

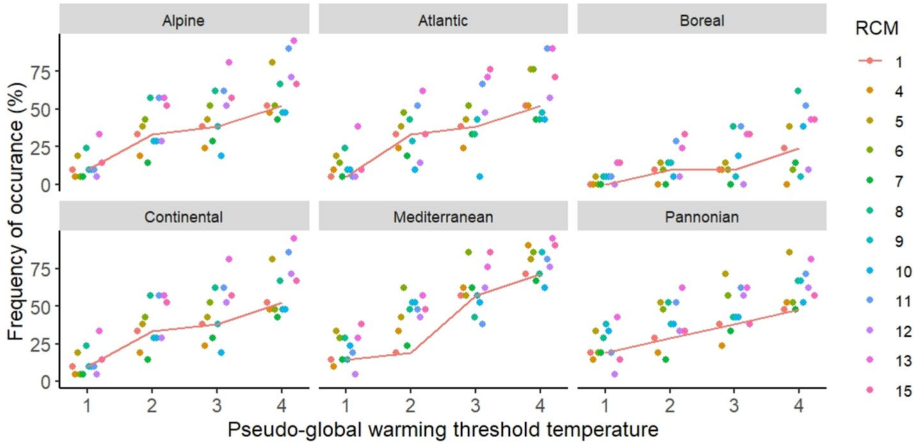

Fig. 4 Percentage of years where hot droughts affect 5% or more of the Norway spruce area for the 21 years surrounding pseudo-global warming threshold (PGWT) temperature across the 12 ensemble members of UKCP Regional (12 km) for biogeographic regions in Europe where Norway spruce stands occur. Three regions have no NFI surveyed Norway spruce stands: Arctic, Anatolian and Steppic. Lines indicate the median frequency of RCM1 that is considered the middle of the range of ensemble members

tribution with lower median probability density values and a broadening range of uncertainty with increasing PGWT. In contrast, the Arctic, Atlantic, and Mediterranean regions showed a narrowing of the distribution and an increase in the median probability density with increasing PGWT.

We found the median date of last frost advanced in the spring. The range of the distribution of values broadened (Online Supplementary Material—Figure A5) in most regions except in the Atlantic, and Mediterranean. Here the probability density median value increased slightly, whereas in the other seven regions the median decreased with increasing PGWT temperature.

To assess the potential for frost damage to Norway spruce we combined the last date of frost and the initiation date of budburst datasets to examine the change in the frost buffer period as an indicator of the probability frost damage, results are shown in Fig. 5. The bold lines represent the median values, and the shaded areas represent the range from the minimum to the maximum value for a given PGWT.

All European biogeographical regions that hold Norway spruce stands show slight changes in the frost buffer under climate change. The Anatolian, Boreal, Continental, Pannonian and Steppic regions indicate an increase in the buffer against frost damage. The shape and extent of the frost buffer distribution range and its variability varies from region to region. There is a general attenuation of the peak in the distribution and an increasing variability from year to year with increasing PGWT. In more detail, Fig. 6 shows the part of the frost buffer from −25 to +25 days representing the critical frost risk edge of the buffer. Again, the bold line represents the median and the shaded area the minimum to the maximum range for a given PGWT. The frost buffer variability is small in the Arctic, Alpine and Continental regions, compared to much larger variability in other regions. Variability in the Anatolian, Atlantic, and Boreal regions remained high across all 4 PGWT temperatures. For the Atlantic region, the buffer shifts towards negative values with increases in PGWT

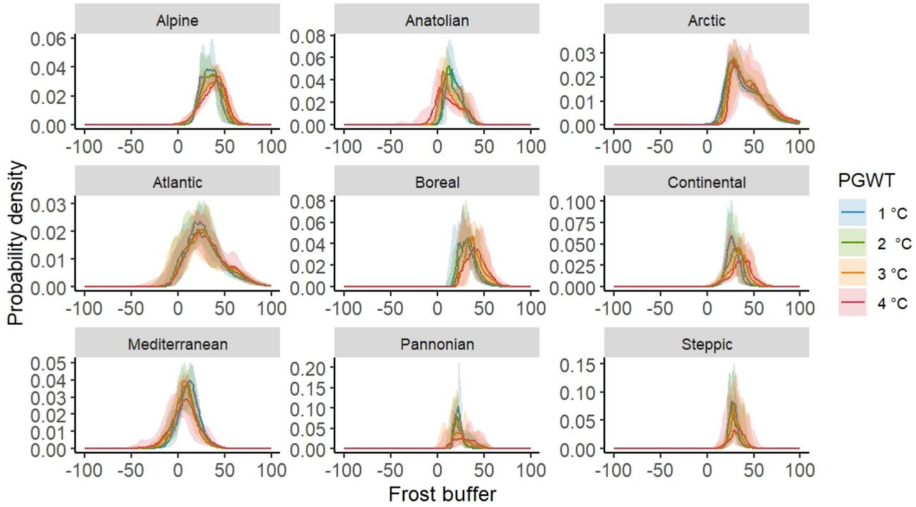

Fig. 5 The distribution of change in the frost damage security buffer between the last day of frost and the start of budburst in Norway spruce in each European biogeographical region by pseudo-global warming threshold (PGWT) temperatures. Negative changes to the left indicate a reduction in the buffer and a greater risk of frost damage whereas positive changes to the right indicate a reduction in the risk of frost damage. The bold lines show the median of the distribution, and the shaded region indicates the minimum and maximum range values. Values include all 12 ensemble members for the 21 years of the PGWT for all grid squares in the biogeographical region

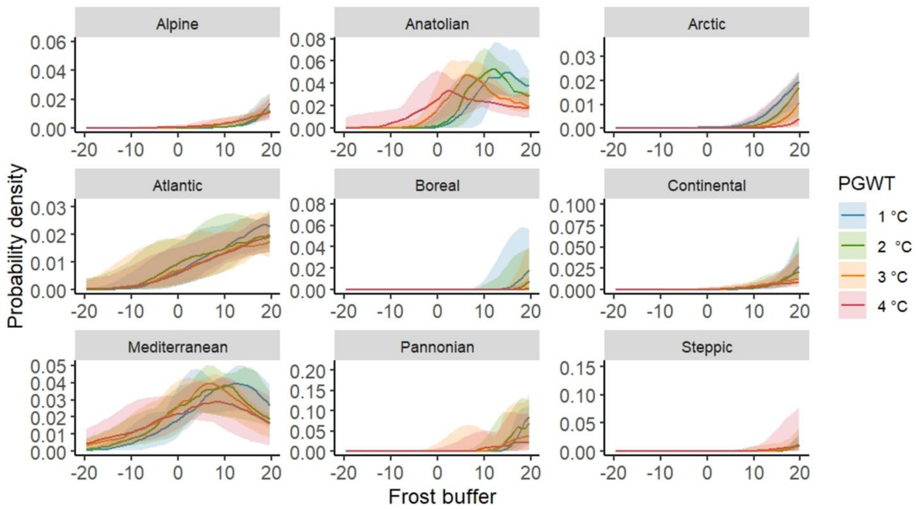

Fig. 6 Detail of the Norway spruce frost buffer (shown in Fig. 5) at the late frost/early bud-burst edge of the distribution showing changes in the buffer for increasing PGWT in each European biogeographical region. The bold lines show the median of the distribution, and the shaded region indicates the minimum and maximum of the range. Negative changes to the left indicate a reduction in the buffer and a greater risk of frost damage whereas positive changes to the right indicate a reduction in the risk of frost damage. Values include all 12 ensemble members for the 21 years of the PGWT for all grid squares in a biogeographical region

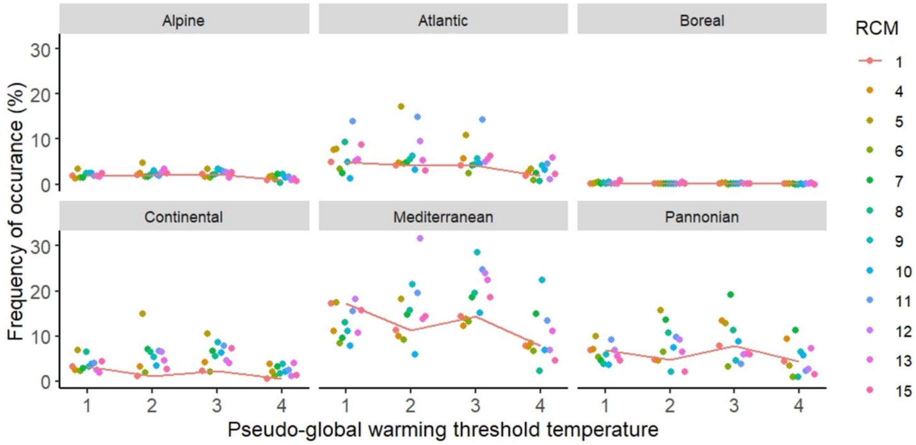

Fig. 7 Median percentage of years surrounding pseudo-global warming threshold (PGWT) temperatures in which the last spring frost falls within the period of leafing for 5% or more affected stands in each region, using the 12 ensemble members of UKCP Regional (12 km) for biogeographic regions in Europe where Norway spruce stands occur. Three regions have no NFI surveyed Norway spruce stands: Arctic, Anatolian and Steppic. Lines indicate the median frequency of RCM1 that is considered the middle of the ensemble range

coupled with highly variable values from year to year suggesting the risk of frost to Norway spruce will remain high. The slight changes in the frost buffer suggest a similar risk of frost in a warmer world, particularly in regions with a less predictable switch from winter to spring temperatures as for example in the Atlantic region, whereas in the Continental region the risk of frost damage may decline slightly.

We calculated late spring frost affected areas of Norway spruce, centred on the PGWT threshold year (Table 1b) using UKCP Regional RCM member 1 to demonstrate changes. There were no frost occurrences at PGWT + 1 °C in the Boreal region, and the area affected across the PGWT points remained low in the Boreal and Alpine regions. The Atlantic and Continental regions show an increase in the frost affected area increasing with PGWT temperatures. In the Mediterranean and Pannonian regions the frost affected area remains higher and more constant through increasing PGWT temperatures. To examine the risk of frost we looked at the frequency of occurrence for each of the PGWT points using frost buffer data from all the pixels in the six biogeographic regions for years in which 5% or more of the Norway spruce stands are affected (Fig. 7). Data in these pixels are defined as having a negative frost buffer and comprise the data in the left-hand tail of the distribution of probability shown in Figs. 5 and 6. Changes in the frequency of occurrence stay fairly constant over the PGWT temperature points 1–3 °C, tending to decrease at PGWT + 4 °C but show a large range of values among RCM members for the Atlantic, Continental, Mediterranean, and Pannonian regions.

4 Discussion

Our approach removes some of the uncertainty associated with unknown future greenhouse gas emissions scenario trajectories to judge changes in extreme climate events, and by inference the effect on trees (Passos et al. 2024). Instead, it assumes that climate model outcomes are scaled to global temperature thresholds. This reasoning is to ensure that forest policy and forestry practitioners in Europe are aware of the potential impacts of extreme climate events in magnitude and frequency, associated with global warming (Fuchs et al 2024), and to prepare the forest industry to the potential damage of extreme events linked to global warming points compared to the pre-industrial period.

4.1 Drought and heat

Our results show that in the drought distribution of the Alpine, Atlantic, and Mediterranean regions, the critical period of change in the shape of the frequency and magnitude of drought distribution is between PGWT + 1 °C and + 2 °C. These results suggest a rapid shift from the high likelihood of moderate drought events under PGWT + 1 °C to a corresponding broadening of the extreme tail of the distribution with a higher range of likelihood at PGWT 2 °C and beyond. Our study shows more frequent and intense hot drought events as the global mean temperature increases above pre-industrial levels such that it is likely there will be an increasing risk of stress damage to trees including Norway spruce, from extreme annual climatic events across European biogeographic regions.

The analysis indicates that for three of the four main regions of Norway spruce (Alpine, Atlantic, and Continental), an increase in the frequency and extent of hot and dry summers has affected Norway spruce stands since the reference period (1981–2010). This is supported by increasing mortality (George et al. 2021; Senf et al. 2020), reduced growth (Bhuyan et al. 2017), increasing drought stress (Rakovec et al. 2022), and driving *Ips typographus* bark beetle damage (Hlásny et al. 2021) in the recent literature. The projections of extreme hot and dry summers into future higher PGWT temperatures will further affect areas of Norway spruce and more frequently from year to year. This tree species is native to boreal and montane climates across Europe, although it has been widely planted outside its native range in Atlantic (oceanic) and Continental temperate forest regions of central Europe and Scandinavia for commercial timber production (Mauri et al. 2017). Even so, we found that approximately 10% of the area of the Boreal region heartlands of Norway spruce are likely to be affected by hot and dry summers.

4.2 Frost

The study shows changes in the phenology of leafing and how this date interacts with late spring frosts using the growing degree days (GDD) calculated by accumulating temperature to drive leafing in Norway spruce (200-degree days above + 5 °C) using published data (Svystun et al. 2021). The 200 GDD value might be changed for other species. For example, Lin et al. (2024) gives a 170 GDD value for hornbeam (Carpinus betulus), 200 GDD for sweet chestnut (Castanea sativa), and 220 GDD for sessile oak (Quercus petraea). Our value is used as an illustration of the method and our results indicate the frost buffer period that separates late spring frost and leafing date will adjust slightly differently in European biogeographic regions. It will shorten leading to an increased frost likelihood in the Anatolian, Atlantic, Pannonian, Steppic and Mediterranean regions and lengthen leading to increased frost avoidance likelihood in the Arctic, Boreal and Continental regions, and remain constant in the Alpine region.

Frost damage affects various conifer and broadleaved species of tree. Zohner et al. (2020) showed that frost damage is increasing in Europe, and they estimated that frost will affect and damage approximately 35% of the forest area of Europe in the future. Our analysis calculated using daily bias corrected data from all twelve members of the UKCP Regional projections shows frost damage will continue to cause damage in areas of Europe. Our thorough treatment across all pixels within biogeographic zones provides a foundation for examining the trends in the frost damage buffer into the future.

4.3 Extreme weather events in future forest management

Our use of 12 dynamically downscaled climatically coherent Regional Climate Models with data for twenty-one years surrounding the predicted year in which the global mean temperature reaches a specific warming threshold above the pre-industrial period provides a thorough analysis for examining changes in the frequency and magnitude of hot droughts. The IPCC (2023) tests the exceedance of global warming above pre-industrial periods by calculating the mean global temperature over 20 years to determine if and when the global warming threshold was exceeded. This same approach could be used in other regions to assess the extreme climate that tree species or provenances may experience under climate change. An advantage of the approach is allowing forest policy and management stakeholders to plan adaptation management based on the amount of warming that is likely above the pre-industrial period. It is quite difficult for forest managers to understand the degree of risk and uncertainty for long term forest plans. Our method reduces the problem to studying the occurrence of extreme climate events associated with global warming thresholds, or in this case for the European continent, therefore termed pseudo-global warming threshold temperatures. Managing productive forests is a long-term investment and by having information about the amount of warming that is likely during a full stand rotation helps managers formulate decisions about species choice and silviculture before planting. Such information can be more clearly defined and used than a range of emissions scenarios, in which the uncertainty posed by the range of trajectories can cloud decisions (Keenan 2015).

A second benefit of our approach is the incorporation of all ensemble members in the results to provide an improved climate extremes analysis. Studies of the impacts of climate change on forests have largely focused on average climate change futures (Passos et al. 2024). Gradually, it has become increasingly evident that extreme events are as important, if not more important, than a mean change in climate conditions (Gould et al. 2024). Hot drought events and late spring frosts commonly weaken tree defences leading to pathogen, parasite or herbivore attack from which a tree may decline (Hlásny et al. 2021, Holuša et al. 2018, Seidl et al. 2017).

Additionally, an analysis of extreme impacts using our approach is less dependent on new climate projections from GCMs or RCMs and adjustments to green-house gas emission scenarios. This is because changes in the projections from climate models tend to make adjustments to the temporal dimension of climatic events, e.g., changing the rate at which climate changes occur in the future. Since the method removes the time constraint of change, focusing only on the threshold global temperature increases above the pre-industrial climate period, the findings from an analysis performed this way are robust.

We are aware that our models have not introduced any genetic variation or plasticity response of Norway spruce to avoid frost damage or to resist hot drought stress (Svystun et al. 2021; Klisz et al. 2019). However, the method described in this study could assist tree breeders. If tailored to specific provenances or genotypes of tree species, the method could help in assessing and selecting suitable forest reproductive material (FRM) under climate change (Ray et al. 2022). The methodology of this study provides a visualisation of potential changes in drought and frost risk and the accompanying uncertainty. From provenance trials, tree breeders may derive empirical evidence of adaptive variation, or acclimation through plasticity, that imparts drought tolerance (Ramírez-Valiente et al. 2022). They frequently calculate temperature sum thresholds driving bud burst from provenances and species in common garden trials (Salmela et al. 2013). Using our approach, such information could set drought exposure limits or GDD requirements for the deployment of material from breeding programmes. Using higher resolution spatial climate data downscaled statistically from dynamical RCM projections, the method would allow investigation of the risk of damage from increasing drought frequency and exposure, or the risk of damage to trees from a late spring frost, across smaller forest regions.

5 Conclusions

The assessment of extreme events of hot drought and frost from European climate projections associated with areas of Norway spruce forest show a continuing risk of more frequent hot droughts varying by biogeographic region. Our analysis using the UKCP Regional (12 km) ensemble shows that the drought index (SPEI) will become more extreme with increasingly wet and drier growing seasons as pseudo-global warming thresholds (PGWT) are reached. This suggests more extreme variation in year-to-year climatic conditions. Moreover, between PGWT of + 1 °C and + 2 °C above the pre-industrial period substantial changes to more severe and higher likelihood drought events are projected in the Alpine, Atlantic, and Mediterranean biogeographic regions. In addition, the frequency of hot droughts and their spatial extent will increase with PGWT across all areas within Norway spruce stands in each of the six biogeographical regions of Europe where the species currently occurs. The UKCP Regional ensemble reveals that the likelihood of late spring frost in the Anatolian, Atlantic, Pannonian, Steppic and Mediterranean regions will increase, whereas in the Arctic, Boreal, Alpine and Continental regions frost likelihood will remain constant or decline.

Our methods are applicable to a wide range of tree species, we chose Norway spruce as an example study species of the Horizon project B4EST (https://b4est.eu/). It has a wide natural distribution in Europe that has been extended in 20 th century plantations on sites that have become unsuitable under drier summer conditions. This method might be applied to other tree species, provenances and genotypes and could be achieved using an ensemble of climate projections at a resolution suited to the scale of the enquiry. The SPEI drought index can be calculated in the SPEI R package using monthly temperature projections; a set of daily temperature climate projections are needed to calculate the frost buffer based on the phenology of leaf flushing from literature or from phenology surveys of tree provenances in a common garden trial, often available to tree breeders.

Such a study showing trends and shifts in extreme events applied to trees will help tree breeders set targets for selecting forest reproductive material for resistance, or resilience, or avoidance of extreme events. Studies of this kind will provide evidence for policy makers and practitioners to understand safe deployment regions to plan and maintain resilient forests into the future.

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Author contributions All authors contributed an equal part in the study.

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Data availability 1. Data used in this study is all in the public domain.
2. UKCP Regional (12 km) ensemble climate data is from the CEDA data catalogue.
3. Monthly SPEI drought and bias corrected daily temperature data were calculated using Python and R packages.
4. The Norway spruce distribution data is available from JRC see:
Mauri A, Strona G, San-Miguel-Ayanz J (2017) EU-Forest, a high-resolution tree occurrence dataset for Europe. Scientific Data 4:1–8. https://doi.org/10.1038/sdata.2016.123
5. The pseudo-global warming threshold matrix is available in Hanlon et al. 2021 (supplementary data):
Hanlon HM, Bernie D, Carigi G, Lowe JA (2021) Future changes to high impact weather in the UK. Climatic Change 166:1–23. https://doi.org/10.1007/s10584-021-03100-5

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