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ISOTHERMAL MAPS OF MAXIMUM AND MINIMUM SHADE AIR TEMPERATURES IN IRELAND

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1. Introduction

The climate of Ireland is changing. Consequently, the Department of Housing, Local Government and Heritage funded this project to update 'Climate maps and data to support building design standards in Ireland'. This research aimed to produce isothermal maps of maximum and minimum shade air temperatures at mean sea level for return periods of 50, 100 and 120 years based on the generalised extreme value distribution for use in building design to enhance resilience in support of climate change adaptation in Ireland.

The outputs of this research will benefit a wide range of stakeholders currently collaborating with Met Éireann, such as the National Standards Authority of Ireland, Transport Infrastructure Ireland, and the Department of Housing, Local Government and Heritage. This report will also inform policy in delivering key national infrastructures such as housing and building renovation and the design of roads and bridges.

1.1. Return periods of maximum and minimum air temperatures

Isothermal maps of extreme high maximum and extreme low minimum shade air temperatures for 50, 100 and 120-year return periods are paramount to inform the design of buildings and bridges (e.g. Hopkins and Whyte, 1975; CEN, 2003; BSI, 2007; Rees *et al*., 2011).

Isothermal maps of maximum and minimum shade air temperatures with a probability of being exceeded of 0.02 (1 in a 50-year return period) have previously been produced for Ireland and the UK (BSI, 1978, 2007; NSAI, 2008). Formulas to determine the maximum and minimum shade air temperatures for an annual probability of exceedances other than 0.02 were furnished in the NA to BS EN 1991-1-5:2003 (BSI, 2007), EN 1991-1-5: 2003 (CEN, 2003) and NA to I.S. EN 1991-1-5-: 2003 (NSAI, 2008).

In this report, Met Éireann produced isothermal maps of maximum and minimum shade air temperatures for 50, 100 and 120-year return periods for Ireland. The calculations are based on the generalised extreme value distribution (Coles, 2001; Gilleland and Katz, 2016) and adjusted for height above mean sea level (Hopkins and Whyte, 1975; CEN, 2003) for a denser network of 64 stations for the period from 1961 to 2020.

1.2. The climate of Ireland

Ireland lies between latitude 51°N and 56°N, longitude 5°W and 11°W in western Europe and at the eastern edge of the north Atlantic Ocean, and has an area of about 84,000 km^2. The elevation is generally less than 150m above sea level in the country's central plain, whereas the main mountains have peaks above 600m. Carrauntoohil in Co. Kerry is the highest mountain at 1041m above sea level. About 240km^2 of the country's area lies above 600m above sea level, and about 4,100km^2 lies between 300 and 600m above sea level (Rohan, 1975, citing Roberts, 1967).

The climate of Ireland is characterised as mild and maritime by the controlling influence of the proximity to the North Atlantic Ocean to the north, west and south and the Irish Sea to the east of the island. The North Atlantic Current subdues the air temperature range in Ireland; therefore, extremes in summer and winter are less intense in comparison to more continental countries at similar latitudes. The westerly atmospheric circulation of the middle latitudes constitutes another major control of Ireland's climate. The geographical and temporal distribution of the pressure systems of the Azores High, the Icelandic Low and the winter Siberian High also control the variation of air temperatures in Ireland.

The maximum and minimum air temperatures in Ireland are affected by oceanic, latitudinal and topographic controls. Despite the small size of Ireland, the difference in the air temperature gradient between inland and coastal areas is evident. The influence of the Irish Sea and the Atlantic Ocean on air temperatures is greater near the coastal areas and decreases with the distance inland. Moreover, mountainous terrain and hills allow shelter from direct oceanic influences and strong winds. The contrast in air temperatures between inland and coastal areas is stronger in the winter, whereas the latitudinal control of air temperatures is more prominent in the summer. Specifically, inland stations are warmer in the summer and colder in the winter in comparison to coastal stations.

Long-term records of daily maximum and minimum air temperature records are necessary to understand past climate variability and to assess the frequency, duration, intensity and geographical distribution of extreme events (e.g. Mateus, 2021; Mateus and Potito, 2022).

Extreme daily maximum air temperatures often occur during heat wave events. A heat wave refers to a period of abnormally hot weather. Heat waves in Ireland are most common in the summer during high pressure dominated periods. The "Azores high" is slow moving and can stall over Ireland for long periods, pushing the north Atlantic jet stream away to the north and blocking low pressure systems from coming over Ireland; therefore, resulting in warm, dry and settled weather conditions for several days. Three types of heat waves may be identified: 1) dry heat waves associated with stable periods of weather with clear skies and large amounts of solar radiation, 2) moist heat waves, which are very warm with humid conditions throughout the day and night, often with night-time cloud cover, which restrain the escape of accumulated heat during the day and preventing relief at night-time, 3) either dry or moist heat waves with the heat island effect as large urban areas undergo heat waves with greater severity.

The highest daily maximum air temperatures surpassing 30°C usually occur during the influence of the hot and dry tropical continental air mass. The tropical continental air mass is most prevalent in summer and originates from over north Africa and tracks northwards over continental Europe when the sub-tropical high pressure moves north.

Socio-economic and environmental impacts during extreme maximum air temperatures include increased heat stress and human mortality associated with underlying medical conditions and the elderly, greater energy demand, higher risk of forest fires, heat stress in cattle, crop failures, greater water consumption and water shortages, which are exacerbated when the extreme heat is linked with drought events (e.g. Pascal *et al*., 2013; Desmond *et al*., 2017; Mateus, 2021).

Extreme daily minimum air temperatures usually occur during cold wave events. A cold wave refers to a period of abnormally cold weather. Cold waves in Ireland are most common and intense in winter. Dry and cold periods of several days can occur with the extension of the continental anticyclone westwards and blocking the progression of depressions towards Ireland. Cold periods also occur during snowfall events when the cold continental air mass from the north or east meets the relatively mild and moist maritime air from the south or west. Persistent and strong negative phases of the Arctic Oscillation and the North Atlantic Oscillation have been linked with extreme low minimum air temperatures (e.g. Mateus, 2021).

Socio-economic and environmental impacts during extreme minimum air temperatures include increased human mortality linked with underlying medical conditions and the elderly, greater energy consumption, and when connected with snowfall events are associated with work closures, disruption of road traffic, rail and air travel, water shortages and damage to overhead power and communication lines (e.g. Desmond *et al*., 2017; Mateus, 2021).

The warmest 5% of the daily maximum air temperatures are projected to increase for the period from 2041 to 2060, ranging from 1.0°C to 1.6°C in the RCP[1]4.5 scenario and from 1.4°C to 2.2°C in the RCP8.5 scenario (Nolan and Flanagan, 2020). The coldest 5% of daily minimum air temperatures are projected to increase in the period from 2041 to 2060, ranging from 0.9°C to 1.8°C in the RCP4.5 scenario and from 1.2°C to 2.4°C in the RCP8.5 scenario (Nolan and Flanagan, 2020).

2. Methodology

This section describes the meteorological data used, the adjustment of maximum and minimum air temperatures to mean sea level, the calculation of return levels of the highest maximum and of the lowest minimum air temperatures for return periods of 50, 100 and 120 years based on the generalised extreme value distribution and the gridding techniques to produce the isothermal maps for Ireland.

[1] A Representative Concentration Pathway (RCP) is a greenhouse gas concentration trajectory used by the Intergovernamental Panel on Climate Change (IPCC).

2.1. Meteorological data

A total of 64 stations with quality-controlled and homogenised daily maximum and minimum air temperature observations for the Island of Ireland and the period from 1961 to 2020 were employed in the data analysis (figure 2, table 1). Of the 64 stations, 12 are located in Northern Ireland and 52 in the Republic of Ireland. The meteorological instruments, methods of observation, and the quality-control and homogenisation procedures of the meteorological observations follow the international standards stipulated by the World Meteorological Organization (World Meteorological Organization, 2018a,b). The observations from the Republic of Ireland were obtained from the National Climate Archive at Met Éireann. Regarding the stations from Northern Ireland, the observations were acquired from the Centre for Environmental Data Analysis (CEDA) Archive (Met Office, 2021).

The daily maximum and minimum air temperature observations have been quality-controlled following internal consistency, climate consistency, day-to-day step change, persistency and spatial tests (e.g. Hubbard *et al*., 2005; Walsh, 2017). Inhomogeneities in air temperature observations can arise from changes in the station's location, thermometers, observer, observation times, station surroundings or the replacement of the manual with automatic stations (e.g. Easterling *et al*., 1995; Trewin, 2010; Venema *et al*., 2018). Climate data homogeneity is required to minimise artificial effects and ensure that variability, change, and trends result from weather and climate variations (Conrad, 1950). The homogenisation procedures were carried out by Met Éireann using the software MASH (Szentimrey, 2017).

The daily observations are defined as follows:

- **Daily maximum air temperature:** maximum air temperature recorded during the 24-hour observation period from 09:00 to 09:00 UTC.
- **Daily minimum air temperature:** minimum air temperature recorded during the 24-hour observation period from 09:00 to 09:00 UTC.

The daily maximum and minimum air temperature observations in Ireland are registered hourly at the synoptic stations. The daily maximum and minimum air temperatures are observed at 09:00 UTC at the manual climate stations. In the case of the minimum air temperature, the observation is assigned to the current day, whereas the maximum air temperature is assigned to the previous day of reading.

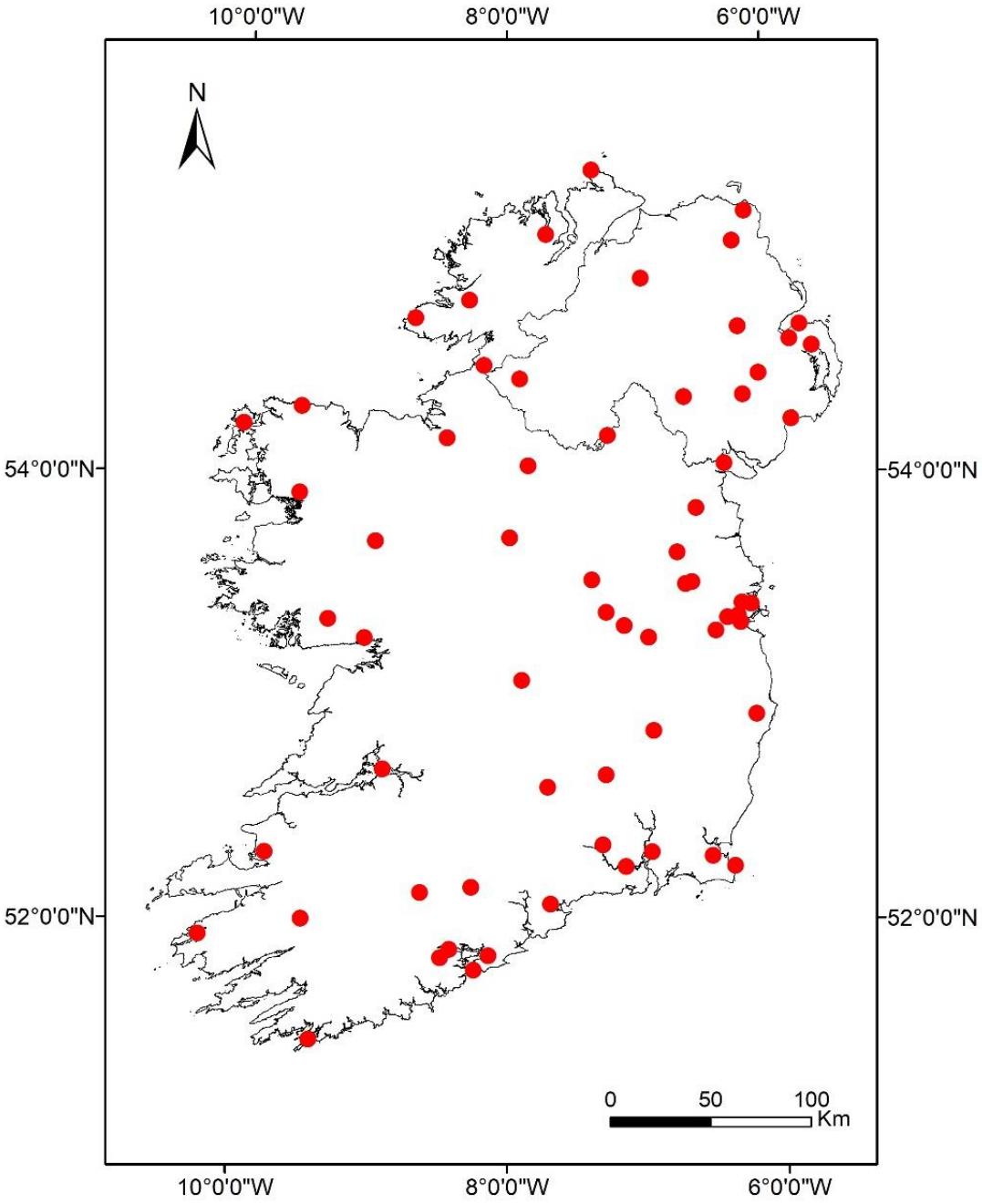

Figure 1: Location of the stations with daily maximum and minimum air temperature observations on the Island of Ireland.

Table 1: Meteorological stations in the Island of Ireland and respective geographical coordinates, elevation and period covered by the daily maximum and minimum air temperature observations. Stations located in Northern Ireland are marked with an asterisk (*). In case of re-location of the station or replacement from manual to automatic station, the geographical coordinates correspond to the most recent location. Some stations were joined and MASH infilled observations in case of gaps; such cases are marked with a cross (ǂ).

Name	Latitude (°)	Longitude (°)	Elevation (m)	Period	Years
*Aldergrove	54.66400	-6.22500	63	1961 – 2020	60
*Altnahinch Filters	55.04800	-6.25500	213	1961 – 2020	60
Ardee (Boharnamoe)	53.85420	-6.56944	31	1961 – 2020	60
ǂArdfert (Liscahane)	52.31110	-9.77361	30	1961 – 2020	60
*Armagh	54.35200	-6.65000	62	1961 – 2020	60
Ballinamore (Creevy no. 2)	54.04940	-7.83806	72	1961 – 2020	60
*Ballypatrick Forest	55.18100	-6.15400	156	1961 – 2020	60
Ballyshannon (Cathleen's Fall)	54.49833	-8.17583	38	1961 – 2020	60
*Ballywatticock	54.57200	-5.65700	6	1961 – 2020	60
*Banagher Caugh Hill	54.88600	-6.96600	214	1961 – 2020	60
ǂBelderrig	54.31028	-9.56667	66	1961 – 2020	60
Belmullet	54.22750	-10.00690	9	1961 – 2020	60
Birr	53.09028	-7.89028	72	1961 – 2020	60
Casement	53.30556	-6.43889	91	1961 – 2020	60
Claremorris	53.71080	-8.99250	68	1961 – 2020	60
Clones	54.18330	-7.23333	89	1961 – 2020	60
Cloosh (For. Stn.)	53.35970	-9.33944	101	1961 – 2020	60
ǂCloyne (Lisanley)	51.85611	-8.13611	55	1961 – 2020	60
Cork Airport	51.84722	-8.48611	155	1961 – 2020	60
ǂCork (Clover Hill)	51.88472	-8.41944	20	1961 – 2020	60
Derrygreenagh	53.39167	-7.25833	90	1961 – 2020	60
Dublin (Glasnevin)	53.37000	-6.27028	21	1961 – 2020	60
Dublin (Merrion Square)	53.34060	-6.25333	13	1961 – 2020	60
Dublin Airport	53.42780	-6.24083	71	1961 – 2020	60
Dundalk (Annaskeagh W.W.)	54.05190	-6.35139	61	1961 – 2020	60
ǂDungarvan (Carriglea)	52.08722	-7.68250	18	1961 – 2020	60
Dunsany	53.51580	-6.66000	83	1961 – 2020	60
ǂEdenderry Ballinla	53.33111	-7.12500	91	1961 – 2020	60
Galway (Univ. Coll.)	53.27640	-9.06389	14	1961 – 2020	60
ǂGlencolumbkille (Drimroe)	54.71111	-8.70278	49	1961 – 2020	60
ǂGlenealy (Kilmacurragh Park)	52.92917	-6.14972	122	1961 – 2020	60
Glenties Hatchery	54.79111	-8.28750	44	1961 – 2020	60
*Helens Bay	54.66900	-5.74800	43	1961 – 2020	60
*Hillsborough	54.45300	-6.07300	116	1961 – 2020	60

Table 1. Continued.

Name	Latitude (°)	Longitude (°)	Elevation (m)	Period	Years
John F. Kennedy Park	52.31750	-6.94083	70	1961 – 2020	60
Johnstown II	52.29778	-6.49667	62	1961 – 2020	60
Kilkenny	52.66528	-7.26944	65	1961 – 2020	60
Killarney (Muckross House)	52.01670	-9.49861	58	1961 – 2020	60
Kinsaley (Agr. Res. Stn.)	53.42222	-6.17222	19	1961 – 2020	60
⸸Littleton	52.61167	-7.70000	126	1961 – 2020	60
*Lough Navar Forest	54.43900	-7.90100	126	1961 – 2020	60
⸸Lullymore Nature Centre	53.27889	-6.94222	85	1961 – 2020	60
*Magherally	54.35900	-6.19600	97	1961 – 2020	60
Malin Head	55.37194	-7.33917	20	1961 – 2020	60
⸸Mallow Spa House	52.13889	-8.63500	61	1961 – 2020	60
Markree	54.17500	-8.45556	39	1961 – 2020	60
⸸Milford Kilmacrennan Road	55.08500	-7.69917	30	1961 – 2020	60
Moore Park	52.16389	-8.26389	46	1961 – 2020	60
⸸Mount Dillon	53.72694	-7.98083	39	1961 – 2020	60
Mullingar	53.53722	-7.36222	101	1961 – 2020	60
*Murlough	54.24500	-5.83200	12	1961 – 2020	60
⸸Navan (Tara Mines)	53.65833	-6.71833	52	1961 – 2020	60
Newport (Furnace)	53.92333	-9.57111	14	1961 – 2020	60
Oak Park	52.86110	-6.91528	61	1961 – 2020	60
Phoenix Park	53.36361	-6.34972	48	1961 – 2020	60
⸸Piltown (Kildalton Agr. Coll.)	52.35139	-7.30000	18	1961 – 2020	60
Roches Point	51.79310	-8.24444	43	1961 – 2020	60
Rosslare	52.25000	-6.33472	26	1961 – 2020	60
Shannon Airport	52.69028	-8.91806	15	1961 – 2020	60
Sherkin Island	51.47639	-9.42833	20	1961 – 2020	60
*Stormont Castle	54.60300	-5.83000	56	1961 – 2020	60
Valentia Observatory	51.93830	-10.24080	24	1961 – 2020	60
Warrenstown	53.52444	-6.61111	90	1961 – 2020	60
Waterford (Tycor)	52.25278	-7.13056	49	1961 – 2020	60

2.2. Adjustment for height above sea level

Maximum and minimum air temperatures decrease with the increase in altitude, although the rate of the decrease of the maximum air temperature is greater than the minimum air temperature. Maximum air temperatures were adjusted for height above sea level by subtracting 1.0 °C per 100m height, whereas the minimum air temperature observations were adjusted by subtracting 0.5 °C per 100m height according to the methodology described in the EN 1991-1-5-: 2003 (CEN, 2003) and Hopkins and Whyte (1975).

2.3. Calculation of return periods

Extreme values are scarce, and the estimation of extremes for levels such as 50, 100 and 120 years implies an extrapolation from instrumental observations to unobserved levels, and extreme value theory allows a class of models to enable such extrapolation (Coles, 2001). The daily maximum air temperature observations were analysed to determine the highest value per year from 1961 to 2020 per station and according to a block maxima approach (Coles, 2001; Gilleland and Katz, 2016). Similarly, the daily minimum air temperature observations were assessed to calculate the lowest value per year from 1961 to 2020 per station and according to a block maxima approach. The generalised extreme value distribution and the block maxima approach algorithms were implemented using the extreme value analysis R package extRemes 2.0, which has a focus on climate applications (Gilleland and Katz, 2016).

The generalised extreme value distribution was fitted to the series of the highest maximum air temperature observations per year to produce the return levels for 50, 100 and 120-year return periods and for each station. A similar procedure was employed for the minimum air temperature, except that the values were multiplied by -1 before the extreme value distribution function was fitted (Coles, 2001; Gilleland and Katz, 2016). Fitting the extreme value distribution requires the data to be distributed such that the 'maximum' of the distribution is the most extreme and equivalent to a longer return period and with more frequently occurring return values at lower return periods.

2.4. Gridding

In order to produce a map based on a limited number of point sources of observation (weather stations), the return period values need to be interpolated across the entirety of the grid to be mapped, a technique which is described as gridding. A 1km^2 grid covering the island of Ireland, which is based on the Irish National Grid (TM75 https://epsg.io/29903-1956), was employed.

The interpolation of return periods across all grid points is carried out in two steps. First, a linear regression (e.g. Hengl, 2007) of the return period to be interpolated (e.g. the 50-year return period of the highest maximum air temperature) versus geographical variables of the observation points or weather stations is performed. These geographical variables include the stations' position (easting, northing), distance from the sea, exposure to the sea and elevation (Walsh, 2016, 2017). However, only easting, northing and the 25-kilometre exposure to the sea (the proportion of area within a 25-kilometre radius of a grid point which is the sea) were found to be useful predictive variables. The 25-kilometre exposure to the sea had a Pearson R^2 correlation > 0.3, which is greater than that found for other geographical variables. Here the linear regression would look like this:

$$TRP_p = TRP_{mean} + a_1\boldsymbol{easting} + a_2\boldsymbol{northing} + a_3\boldsymbol{25kexp} + \boldsymbol{residual} \quad (\textit{Equation 1})$$

where TRP_p is the predicted temperature return period, TRP_{mean} is the mean of the temperature return period across all stations, *easting* and *northing* are the coordinates of the grid point, *25kexp* is the 25-kilometre exposure to the sea at the grid point and $a_{1,2,3}$ are the values multiplying the geographical variables in order to get the best fit to the observation parameter - the return value of the highest maximum air temperature and the lowest minimum air temperature for the return periods of 50, 100 and 120 years. The regression is unlikely to be a perfect fit, and the residuals quantify the amount of the observation being predicted, which is not captured by the linear regression.

The second step interpolates the linear regression residuals across grid points using a weighted average of the nearest stations to a particular grid point, a technique known as inverse distance weighting (IDW) (e.g.

Hengl, 2007). The R package gstat is used to interpolate the residual values across the grid points (Walsh, 2016).

The final grid point interpolation/prediction is based on equation 2:

$$TRP_p = TRP_{mean} + a_1\boldsymbol{easting} + a_2\boldsymbol{northing} + a_3\boldsymbol{25kexp} + IDW(\boldsymbol{residual}) \quad (\textit{Equation 2})$$

The easting and northing have the purpose of capture spatial trends and the 25-kilometre exposure to the sea aims to model coastal effects (Walsh, 2017). The described gridding methodology has been widely employed by Met Éireann, such as in generating official climate normals (e.g. Walsh, 2016, 2017).

3. Results

The return values of the highest maximum air temperature at mean sea level for return periods of 50, 100 and 120 years and the comparison with the greatest three highest daily maximum air temperature observations per year on record for stations in Ireland are provided in Table 2. The isothermal maps represent lines connecting points of equal temperature and display the return values of the highest maximum air temperature at mean sea level for return periods of 50, 100 and 120 years (Figures 2 – 4).

The geographical distribution of the return values of the 50-year return period of the highest maximum air temperatures at mean sea level presents values from 28°C near coastal areas (Figure 2). The 32°C isotherm covers Co. Laois and parts of the counties of Clare, Carlow, Galway, Kildare, Kilkenny, Limerick, Offaly, Tipperary, Wicklow, and Waterford. A small area of 32°C is also mapped in counties Kerry and Limerick.

The distribution of the return values of the 100-year return period of the highest maximum air temperatures at mean sea level exhibits values from 28°C and 30°C near coastal areas (Figure 3). The isothermal range from 32°C to 34°C includes various counties in the northern, midlands and southern areas. The highest isotherm value of 34°C is shown in a small area in Co. Kilkenny.

The isotherms of the return values of the 120-year return period of the highest maximum air temperatures at mean sea level range from 28°C to 30°C near coastal areas (Figure 4). The isotherm range from 32°C to 34°C covers a wide range of counties. The highest isotherm value of 34°C includes parts of the counties Carlow, Kilkenny, Laois and Tipperary.

The return values of the lowest minimum air temperature at mean sea level for return periods of 50, 100 and 120 years and the comparison with the greatest three lowest daily minimum air temperature observations per year on record for stations in Ireland are provided in Table 3. The isothermal maps represent lines connecting points of equal temperature and display the return values of the extreme lowest minimum air temperature at mean sea level for return periods of 50, 100 and 120 years (Figures 5 – 7).

The isotherms of the return values of the 50-year return period of the lowest minimum air temperatures at mean sea level range from -6°C in the extreme of the southern coastal areas (Figure 5). The isotherms of -10°C and -12°C are distributed among a range of northern, western, southern, midlands and eastern counties. The extreme lowest isotherm of -14°C covers the counties of Cavan, Longford, Westmeath and parts of the counties of Carlow, Donegal, Dublin, Galway, Laois, Leitrim, Louth, Kildare, Meath, Mayo, Monaghan, Sligo, Offaly, Roscommon, Tipperary and Wicklow.

In the case of the geographical distribution of the isotherms of the return values of the 100-year return period of the lowest minimum air temperatures at mean sea level, the highest value of -6°C is displayed in the extreme southwest and southeast coastal areas (Figure 6). The isotherm range from -14°C to -16°C incorporates parts of the counties of Carlow, Clare, Donegal, Dublin, Kilkenny, Galway, Laois, Leitrim, Louth, Mayo, Meath, Monaghan, Offaly, Roscommon, Sligo, Tipperary, Wexford and Wicklow. The extreme lowest isotherm of -16°C is distributed in counties Cavan, Longford and Westmeath and parts of the counties Carlow, Dublin, Kildare, Galway, Laois, Leitrim, Louth, Meath, Monaghan, Offaly, Roscommon, Sligo, Tipperary and Wicklow.

The isotherms of the return values of the 120-year return period of the lowest minimum air temperatures at mean sea level range from -6°C to -18°C (Figure 7). The highest value of -6°C is displayed in the extreme coastal areas of the southern counties. The isotherm range from -14°C to -16°C covers parts of Carlow,

Clare, Donegal, Dublin, Galway, Kilkenny, Laois, Leitrim, Louth, Mayo, Meath, Monaghan, Offaly, Sligo, Tipperary, Wexford and Wicklow. The isotherm range from -16°C to -18°C is distributed in counties Longford and Roscommon and parts of Cavan, Carlow, Donegal, Dublin, Galway, Kildare, Laois, Leitrim, Louth, Mayo, Meath, Monaghan, Offaly, Sligo, Tipperary, Westmeath and Wicklow. The lowest isotherm of -18°C covers parts of Cavan, Meath, Kildare, Offaly and Westmeath.

Table 2: Return values of the highest maximum air temperature for the return periods of 50, 100 and 120-year and the three highest daily maximum air temperature values from 1961 to 2020 per station in Ireland.

Name	**Three highest daily maximum air temperatures values from 1961 to 2020 (°C)**			**Return period**		
	1st	**2nd**	**3rd**	**50-year (°C)**	**100-year (°C)**	**120-year (°C)**
Ardee (Boharnamoe)	30.7	29.4	29.3	30.6	31.3	31.5
Ardfert (Liscahane)	31.6	30.8	30.8	31.4	32.1	32.3
Ballinamore (Creevy no. 2)	30.4	30.0	29.7	31.2	32.0	32.2
Ballyshannon (Cathleen's Fall)	30.3	29.8	29.7	31.0	32.0	32.3
Belderrig	30.3	28.6	28.2	29.8	30.4	30.6
Belmullet	29.9	28.7	28.3	29.3	29.9	30.1
Birr	31.0	30.7	30.1	31.8	32.8	33.0
Casement	30.9	30.3	29.6	31.8	32.9	33.2
Claremorris	30.2	30.2	29.5	31.0	31.8	32.0
Clones	30.5	29.8	29.3	31.6	32.7	33.0
Cloosh (For. Stn.)	29.8	29.4	28.4	30.3	30.8	31.0
Cloyne (Lisanley)	29.1	29.0	28.7	29.7	30.3	30.5
Cork Airport	28.5	27.9	27.8	29.6	30.3	30.5
Cork (Clover Hill)	31.9	31.3	30.1	31.3	32.1	32.4
Derrygreenagh	31.1	30.9	30.0	32.0	32.9	33.1
Dublin (Glasnevin)	31.2	28.5	28.2	29.7	30.3	30.5
Dublin (Merrion Square)	29.8	28.8	28.7	29.1	29.7	29.9
Dublin Airport	28.6	27.6	27.5	28.7	29.2	29.3
Dundalk (Annaskeagh W.W.)	30.1	29.6	29.2	30.4	31.3	31.6
Dungarvan (Carriglea)	30.9	29.2	29.1	30.4	31.5	31.8
Dunsany	29.8	29.6	28.7	31.0	32.1	32.4
Edenderry Ballinla	30.8	30.5	30.4	31.9	32.8	33.0
Galway (Univ. Coll.)	31.3	31.1	30.0	31.0	31.6	31.8
Glencolumbkille (Drimroe)	29.5	28.3	28.0	29.5	30.1	30.3

Table 2. Continued.

Name	Three highest daily maximum air temperatures from 1961 to 2020 (°C)			Return period		
	1st	2nd	3rd	50-year (°C)	100-year (°C)	120-year (°C)
Glenealy (Kilmacurragh Park)	28.1	27.8	27.7	29.4	30.0	30.2
Glenties Hatchery	31.0	30.1	30.0	31.3	32.3	32.6
John F. Kennedy Park	29.2	28.8	28.4	30.6	31.7	32.0
Johnstown II	28.0	27.1	26.8	27.9	28.6	28.8
Kilkenny	31.5	31.6	30.8	32.9	34.3	34.7
Killarney (Muckross House)	31.4	30.8	30.6	31.7	32.5	32.8
Kinsaley (Agr. Res. Stn.)	27.9	27.5	26.8	27.5	27.9	28.0
Littleton	30.5	30.4	30.2	32.8	33.8	34.1
Lullymore Nature Centre	31.0	30.9	30.2	32.8	33.8	34.1
Malin Head	27.0	25.9	25.9	26.6	26.9	27.0
Mallow Spa House	30.9	30.8	30.8	31.4	32.2	32.4
Markree	29.9	29.6	28.9	30.2	31.1	31.4
Milford Kilmacrennan Road	30.0	29.3	29.0	30.2	31.0	31.2
Moore Park	30.1	30.1	29.8	30.9	31.9	32.2
Mount Dillon	30.8	30.7	30.5	31.4	32.2	32.4
Mullingar	29.7	29.4	29.2	31.2	32.1	32.4
Navan (Tara Mines)	30.0	29.3	29.0	31.1	32.2	32.5
Newport (Furnace)	31.2	29.9	29.7	30.4	30.9	31.1
Oak Park	32.3	31.0	30.8	32.5	33.7	34.0
Phoenix Park	30.3	29.4	28.6	30.2	31.0	31.2
Piltown (Kildalton Agr. Coll.)	30.1	30.1	29.6	31.4	32.5	32.8
Roches Point	27.3	27.1	26.9	27.5	28.2	28.3
Rosslare	26.5	25.9	25.7	26.2	26.6	26.7
Shannon Airport	32.0	31.3	30.2	31.6	32.6	32.8
Sherkin Island	28.5	26.5	26.3	27.6	28.4	28.6
Valentia Observatory	29.2	28.4	28.0	29.0	29.5	29.6
Warrenstown	30.7	30.5	30.1	32.2	33.3	33.6
Waterford (Tycor)	30.3	30.0	29.6	31.4	32.5	32.9

Table 3: Table 2: Return values of the lowest minimum air temperature for the return periods of 50, 100 and 120-year and the three lowest daily minimum air temperature values from 1961 to 2020 per station in Ireland.

Name	Three lowest daily minimum air temperatures from 1961 to 2020 (°C)			Return period		
	1st	2nd	3rd	50-year (°C)	100-year (°C)	120-year (°C)
Ardee (Boharnamoe)	-15.3	-12.8	-12.7	-15.4	-17.7	-18.4
Ardfert (Liscahane)	-12.0	-11.8	-11.1	-11.6	-13.2	-13.6
Ballinamore (Creevy no. 2)	-14.5	-13.7	-12.1	-14.4	-16.0	-16.4
Ballyshannon (Cathleen's Fall)	-11.9	-8.9	-8.8	-10.9	-12.3	-12.7
Belderrig	-10.7	-10.1	-9.0	-10.1	-11.2	-11.4
Belmullet	-8.0	-7.8	-6.7	-7.9	-8.6	-8.8
Birr	-14.7	-13.0	-11.8	-13.5	-14.9	-15.3
Casement	-15.7	-13.9	-13.3	-15.0	-17.1	-17.7
Claremorris	-17.3	-15.1	-13.0	-14.4	-16.4	-17.0
Clones	-13.1	-12.3	-11.3	-14.0	-15.9	-16.4
Cloosh (For. Stn.)	-10.4	-10.4	-10.3	-12.7	-14.7	-15.2
Cloyne (Lisanley)	-7.5	-7.2	-6.9	-7.7	-8.2	-8.3
Cork Airport	-8.6	-8.6	-8.1	-9.2	-10.0	-10.2
Cork (Clover Hill)	-8.9	-8.8	-8.0	-8.4	-9.0	-9.2
Derrygreenagh	-14.9	-12.7	-11.1	-13.3	-14.7	-15.1
Dublin (Glasnevin)	-11.4	-11.3	-11.2	-12.0	-13.4	-13.8
Dublin (Merrion Square)	-10.6	-9.4	-9.0	-10.6	-12.4	-13.0
Dublin Airport	-12.2	-11.5	-10.7	-11.6	-12.6	-12.9
Dundalk (Annaskeagh W.W.)	-13.0	-10.9	-10.9	-12.6	-13.9	-14.3
Dungarvan (Carriglea)	-9.8	-9.2	-8.2	-9.0	-9.6	-9.8
Dunsany	-15.7	-13.8	-13.8	-17.1	-20.0	-20.8
Edenderry Ballinla	-15.1	-15.1	-14.1	-18.0	-21.4	-22.4
Galway (Univ. Coll.)	-14.3	-10.5	-9.5	-12.4	-14.7	-15.4
Glencolumbkille (Drimroe)	-9.8	-9.6	-7.7	-9.6	-10.7	-11.0
Glenealy (Kilmacurragh Park)	-11.6	-11.6	-8.6	-11.2	-13.2	-13.7
Glenties Hatchery	-11.8	-11.5	-10.2	-11.9	-12.9	-13.2
John F. Kennedy Park	-8.7	-7.9	-7.6	-10.8	-12.9	-13.5
Johnstown II	-8.9	-6.7	-6.6	-8.1	-9.2	-9.4
Kilkenny	-14.1	-13.4	-11.8	-13.3	-14.7	-15.1
Killarney (Muckross House)	-11.3	-9.6	-9.2	-10.0	-10.9	-11.1
Kinsaley (Agr. Res. Stn.)	-12.2	-11.8	-11.6	-12.1	-13.8	-14.3

Table 3. Continued.

Name	Three lowest daily minimum air temperatures from 1961 to 2020 (°C)			Return period		
	1st	2nd	3rd	50-year (°C)	100-year (°C)	120-year (°C)
Littleton	-11.5	-11.4	-10.5	-11.5	-12.5	-12.8
Lullymore Nature Centre	-18.8	-12.8	-12.7	-16.4	-19.5	-20.4
Malin Head	-6.4	-6.3	-5.8	-6.6	-7.3	-7.4
Mallow Spa House	-12.6	-10.4	-10.0	-11.0	-12.0	-12.2
Markree	-16.0	-13.3	-11.7	-13.7	-15.2	-15.6
Milford Kilmacrennan Road	-13.5	-12.0	-10.7	-13.0	-14.4	-14.8
Moore Park	-12.3	-11.0	-10.1	-11.3	-12.3	-12.6
Mount Dillon	-16.7	-13.	-12.6	-15.9	-18.9	-19.8
Mullingar	-15.2	-14.1	-12.6	-14.1	-15.8	-16.3
Navan (Tara Mines)	-14.7	-12.5	-12.2	-13.8	-15.5	-16.0
Newport (Furnace)	-9.9	-8.0	-7.4	-8.3	-9.3	-9.6
Oak Park	-15.6	-13.4	-12.9	-14.3	-16.5	-17.1
Phoenix Park	-14.2	-13.0	-11.5	-13.9	-16.0	-16.6
Piltown (Kildalton Agr. Coll.)	-11.7	-10.0	-8.8	-10.8	-12.1	-12.4
Roches Point	-7.3	-5.4	-5.4	-6.2	-7.1	-7.3
Rosslare	-5.6	-4.4	-4.1	-5.0	-5.6	-5.7
Shannon Airport	-11.4	-10.6	-9.9	-10.9	-12.2	-12.6
Sherkin Island	-6.2	-5.8	-5.6	-6.6	-7.6	-7.9
Valentia Observatory	-7.7	-6.5	-6.5	-6.9	-7.5	-7.7
Warrenstown	-14.6	-14.6	-14.3	-16.1	-18.6	-19.3
Waterford (Tycor)	-8.3	-8.1	-7.1	-8.6	-9.5	-9.8

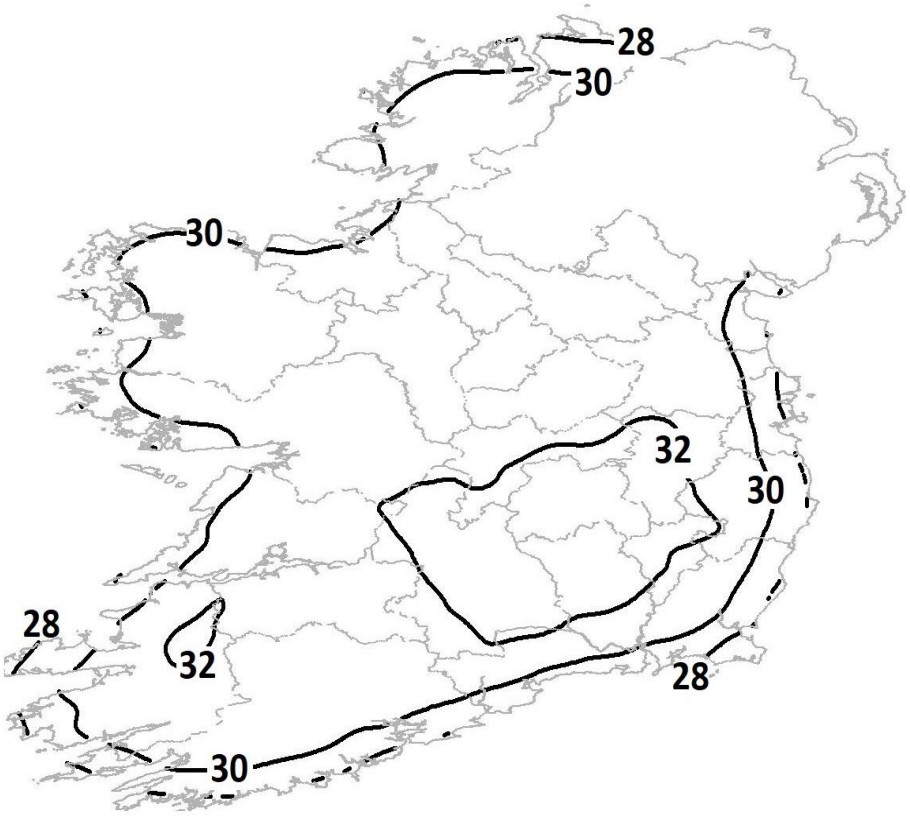

Figure 2: Isotherms of highest maximum shade air temperature (°C) at mean sea level in Ireland for a 50-year return period.

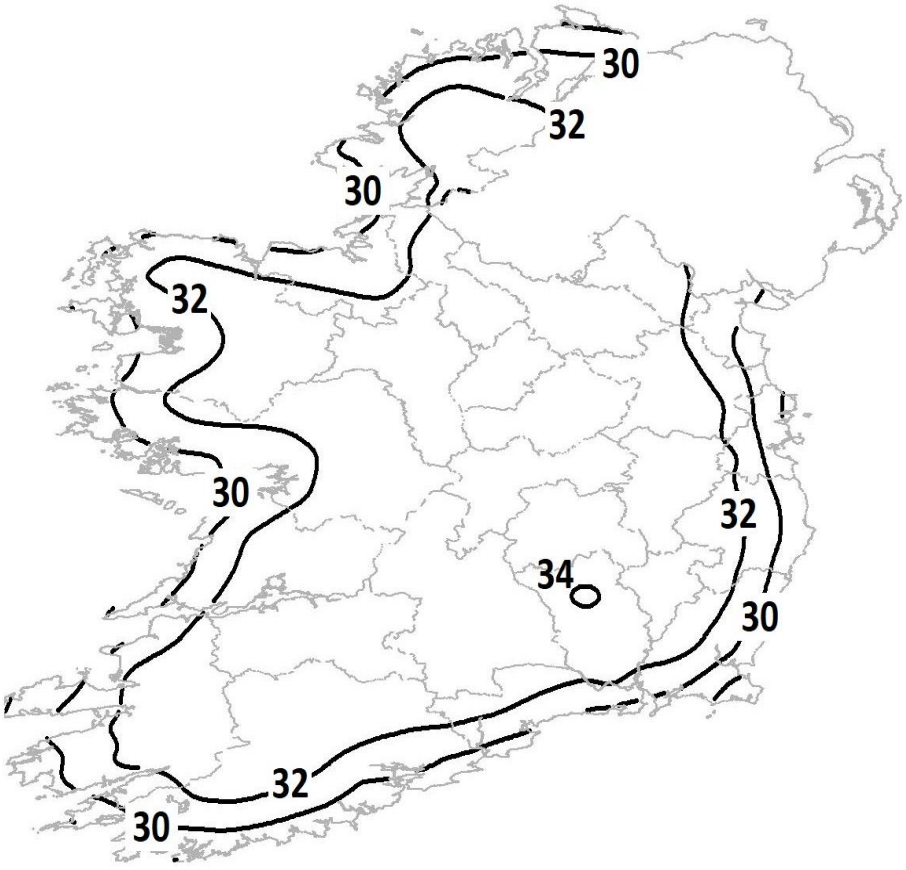

Figure 3: Isotherms of highest maximum shade air temperature (°C) at mean sea level in Ireland for a 100-year return period.

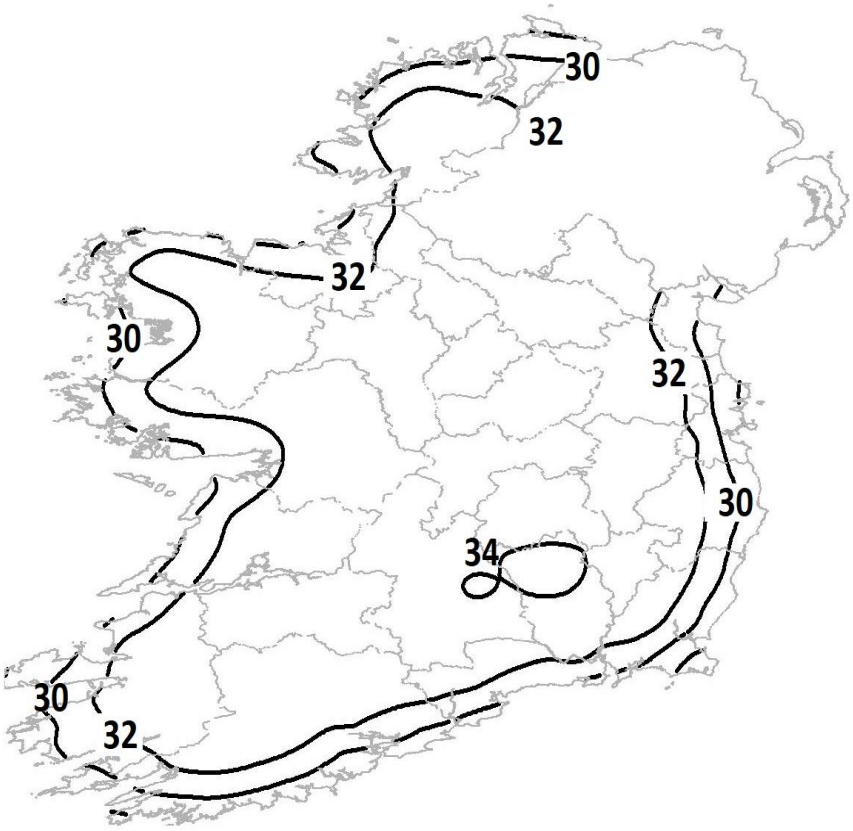

Figure 4: Isotherms of highest maximum shade air temperature (°C) at mean sea level in Ireland for a 120-year return period.

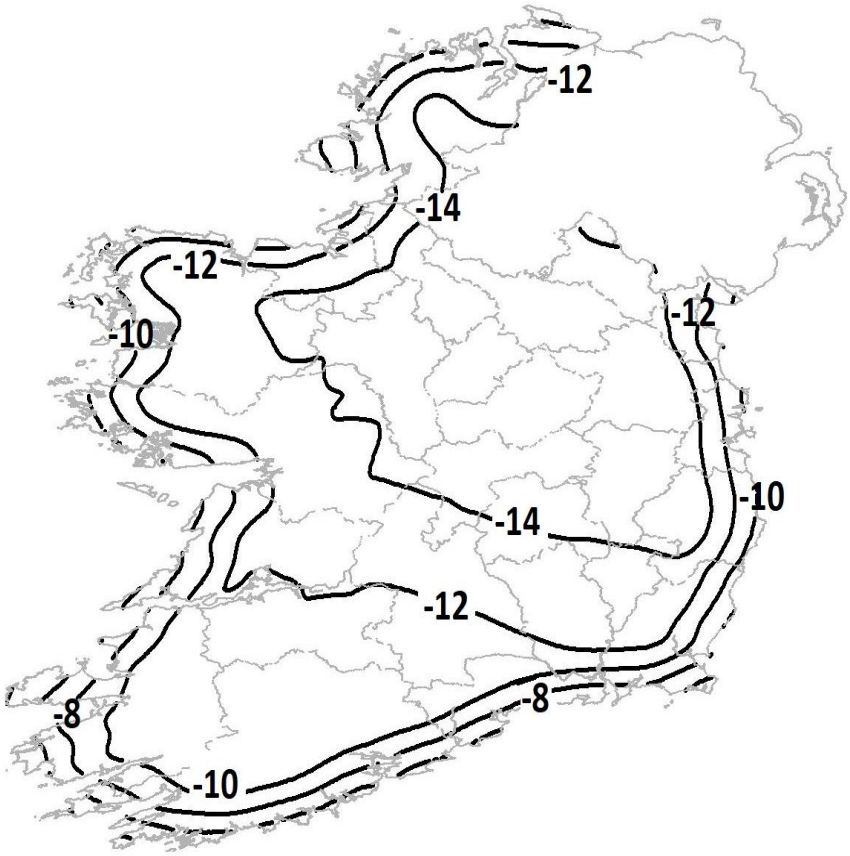

Figure 5: Isotherms of lowest minimum shade air temperature (°C) at mean sea level in Ireland for a 50-year return period.

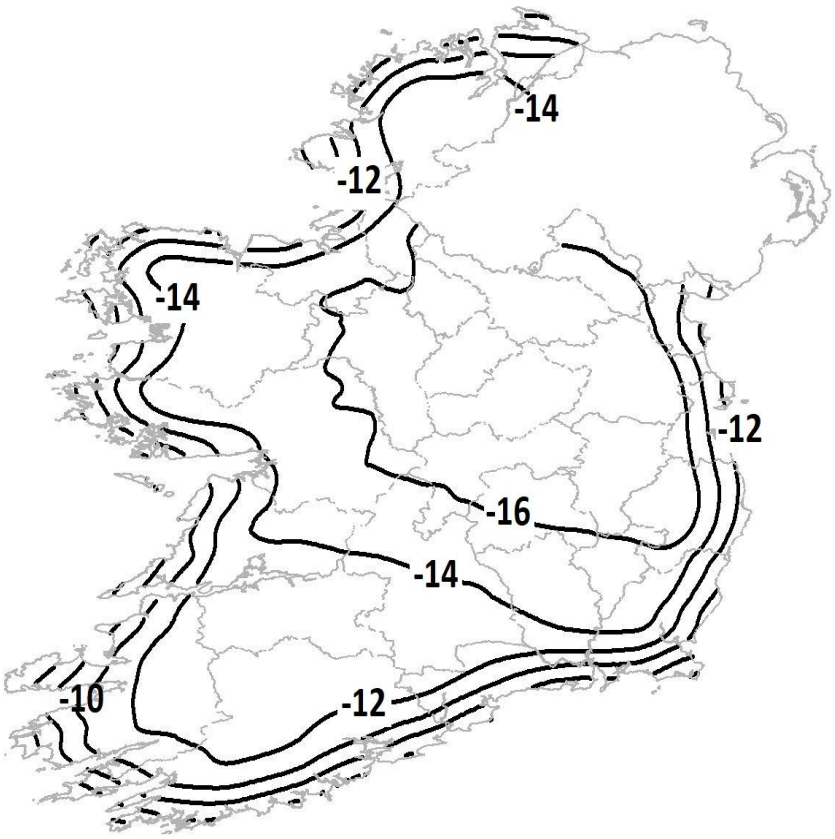

Figure 6: Isotherms of lowest minimum shade air temperature (°C) at mean sea level in Ireland for a 100-year return period.

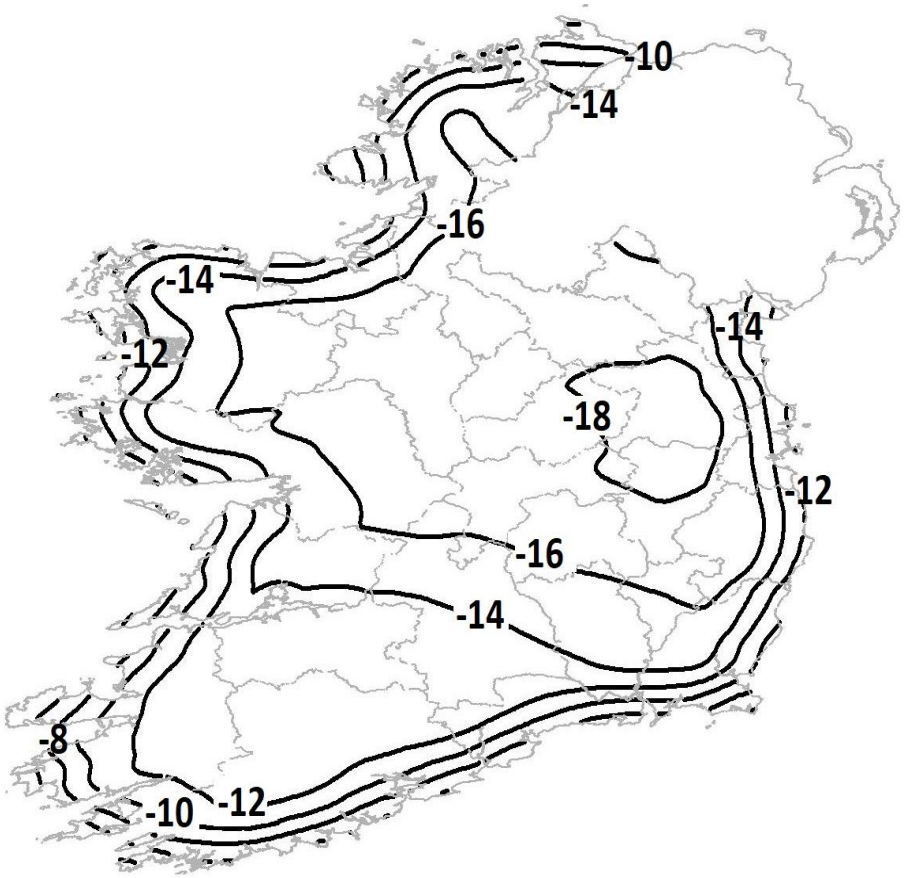

Figure 7: Isotherms of lowest minimum shade air temperature (°C) at mean sea level in Ireland for a 120-year return period.

4. Discussion

The warming of the maximum and minimum air temperatures due to climate change has increased the intensity of the highest maximum air temperature while decreasing the intensity of the lowest extreme minimum air temperature of the isothermal maps produced in this research compared to previously published maps (BSI, 1978, 2007; NSAI, 2008). Isothermal maps of maximum and minimum shade air temperatures in Ireland with a probability of being exceeded of 0.02 (1 in a 50-year return period) have been formerly published (BSI, 1978, 2007; NSAI, 2008), and formulas to determine the maximum and minimum shade air temperatures for an annual probability of exceedances other than 0.02 were furnished in the NA to BS EN 1991-1-5:2003 (BSI, 2007), EN 1991-1-5: 2003 (CEN, 2003) and NA to I.S. EN 1991-1-5-: 2003 (NSAI, 2008). In this report, Met Éireann produced isothermal maps of maximum and minimum shade air temperatures for 50, 100 and 120-year return periods for Ireland. The calculations are based on the generalised extreme value distribution (Coles, 2001; Gilleland and Katz, 2016) and adjusted for height above mean sea level (Hopkins and Whyte, 1975; CEN, 2003) for a denser network of stations and a more recent period from 1961 to 2020.

5. Future climate change

The isotherm maps of return values of the lowest minimum air temperature for return periods of 50, 100 and 120 years produced here for Ireland represent the likely worst-case scenario. The sixth assessment report of the Intergovernmental Panel on Climate Change projects an increase in frequency and intensity of hot temperature extremes, which are defined as daily maximum air temperatures over land that were exceeded on average as a 10-year or 50-year events during the 1850 – 1900 reference period (IPCC, 2021). In Ireland, the warmest 5% of the daily maximum air temperatures are projected to increase for the period from 2041 to 2060, ranging from 1.0°C to 1.6°C in the RCP4.5 scenario and from 1.4°C to 2.2°C in the RCP8.5 scenario (Nolan and Flanagan, 2020). The coldest 5% of daily minimum air temperatures are projected to increase in the period from 2041 to 2060 in Ireland, ranging from 0.9°C to 1.8°C in the RCP4.5 scenario and from 1.2°C to 2.4°C in the RCP8.5 scenario (Nolan and Flanagan, 2020). Therefore, in the current context of climate warming, it is expected to see extreme high temperatures occurring more frequently and extreme low temperatures occurring less frequently. Hence, the lowest minimum air temperature return periods maps presented here are likely to represent conservative, safe estimates of future Irish minimum temperatures.

6. Conclusion

Isothermal maps of return values of the highest maximum and lowest minimum air temperature for return periods of 50, 100 and 120-year have been produced for Ireland and based on the generalised extreme value distribution (Coles, 2001; Gilleland and Katz, 2016) and adjusted for height above mean sea level (Hopkins and Whyte, 1975; CEN, 2003). The new maps will assist in the design of buildings and bridges to enhance resilience in support of climate change adaptation in Ireland.

The new isothermal maps of return values of the highest maximum air temperature and the lowest minimum air temperature adjusted to mean sea level for a 50-year return period are more accurate and supersede the previous maps (BSI, 2007; NSAI, 2008) and stakeholders should adopt them.

It is hoped that the detailed explanation of the methodology and the rationale for the new maps being more accurate than the preceding maps provided here will assist regulators in adopting these new maps in their own jurisdictions.

The results will also be of interest to a diversity of sectors, planners and policy makers to make long, lasting and climate sensitive decisions.

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