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Climatological Note No. 19

ISOTHERMAL MAPS OF THE LOWEST 10CM SOIL TEMPERATURE IN IRELAND

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Disclaimer

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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'. The aim of this research was to produce maps of isotherms of the lowest 10cm soil temperature for the return periods of 50, 100 and 120-year 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 and the Department of Housing, Local Government and Heritage. This report will also inform policy in delivering key national infrastructure such as housing and building renovation.

1.1. Return periods of the lowest 10cm soil temperature

Maps of isotherms of extreme lowest 10cm soil temperatures for 50, 100 and 120-year return periods are important to inform the design of buildings, namely the structure.

In this report, Met Éireann produced for the first time maps of isotherms of extreme lowest 10cm soil temperatures for 50, 100 and 120-year return periods based on the generalised extreme value distribution (Coles, 2001; Gilleland and Katz, 2016) for Ireland.

1.2. Lowest 10cm soil temperature in Ireland

Soil temperatures below 0°C are often registered at a depth of 5cm and are less frequent at 10cm depth, although negative observations have been registered on some occasions at 20cm depth during more intense cold waves. The lowest 10cm soil temperatures can also be associated with snowfall events. The inland locations in Ireland observe the extreme lowest 10cm soil temperatures.

In the 30 meteorological stations from Ireland analysed in this report (Table 1), the lowest 10cm soil temperature observations (-4.3°C) were registered at Birr, Co. Offaly on the 31st of December 1961 and at Clones, Co. Monaghan on the 23rd January 1963, both at 09:00 (Table 1).

Other major lowest 10cm soil temperatures were recorded at John F. Kennedy Park, Co. Wexford (-4.0°C) on the 7th of January 2010 at 09:00, Claremorris, Co. Mayo (-3.8°C on the 24th of January 1963 at 09:00, Kilkenny, Co. Kilkenny (-3.3°C) on the 31st of December 1961 at 09:00 and at Mullingar, Co. Westmeath (-3.2°C) on the 24th January 1963 at 09:00.

The lowest 10cm soil temperature often occurred during periods of cold weather. Examples include the cold wave of December 2010, when the lowest 10cm soil temperatures were recorded at Ardee (Boharnamoe), Co. Louth, Clonroche (Knoxtown), Co. Wexford, Cork Airport, Co. Cork, Johnstown Castle, Co. Wexford, Straide, Co. Mayo, Valentia Observatory, Co. Kerry and Warrenstown, Co. Meath. During the cold wave of January 1963, the lowest 10cm soil temperature were observed at Belmullet, Co. Mayo, Claremorris, Co. Mayo, Clones, Co. Monaghan, Dublin Airport, Co. Dublin, Mullingar, Co. Westmeath and Shannon Airport, Co. Clare. In January 1982, the lowest 10cm soil temperatures were observed at Casement Aerodrome, Co. Dublin, Glenamoy, Co. Cork and Malin Head, Co. Donegal. During the cold period of January 2010, the lowest 10cm soil temperatures were recorded at Glengarriff (Ilnacullin), Co. Cork, John F. Kennedy Park, Co. Wexford and Moore Park, Co. Cork.

Negative 10cm soil temperatures typically occur in January, February, March, November and December and the number of occurrences peak in January. A total of 56.7% (n=17) of stations observed their lowest temperature in January and 26.7% (n=8) observed their lowest temperature in December (Table 1). Two stations (6.7%) observed their lowest 10cm soil temperature in January and December. The lowest temperature was observed in January, February and December at Roches Point, Co. Cork. Glenamoy, Co. Mayo had the lowest values recorded in January and March. The station at Fethard (Parsonshill), Co. Tipperary, observed its lowest 10cm soil temperature (-1.8°C) in February.

Table 1: Extreme lowest 10cm soil temperature on record and respective date and hour for stations in Ireland.

Name	Extreme lowest 10cm soil temperature (°C)	Date	Hour	Latitude (°)	Longitude (°)	Period
Ardee (Boharnamoe)	-1.8	25/12/2010	09:00	53.85417	-6.56944	1969 – 2019
Ballinamore	-2.3	13/01/1985	09:00	54.06944	-7.77500	1963 – 2005
Belmullet	-1.0	24/01/1963	09:00	54.22750	-10.00690	1957 – 2021
Carron	-1.4	18/01/1985	09:00	53.03278	-9.07722	1983 – 2019
Casement Aerodrome	-1.8	15/01/1982	03:00	53.30556	-6.43889	1964 – 2021
Claremorris	-3.8	24/01/1963	09:00	53.71083	-8.99250	1954 – 2021
Clones	-4.3	23/01/1963	09:00	54.18330	-7.23333	1954 – 2008
Clonroche (Knoxtown)	-0.5	23/12/2010	09:00	52.44440	-6.78917	1970 – 2019
		25/12/2010	09:00			
Cork Airport	-2.9	25/12/2010	15:00	51.84722	-8.48611	1963 – 2021
Dublin Airport	-1.1	23/01/1963	09:00	53.42778	-6.24083	1954 – 2021
Dunsany	-1.2	31/01/1987	09:00	53.51580	-6.66000	1966 – 2021
Fethard (Parsonshill)	-1.8	27/02/1986	09:00	52.51417	-7.64944	1986 – 2021
Glenamoy	0	01/03/1970	09:00	54.23890	-9.71667	1966 – 1997
		02/03/1970	09:00			
		03/03/1970	09:00			
		04/03/1970	09:00			
		12/01/1982	09:00			
		13/01/1982	09:00			
Glengarriff (Ilnacullin)	-1.6	4/01/2010	09:00	51.73472	-9.54583	1976 – 2021
Gurteen (merged with Birr, 1955 – 2008)	-4.3	31/12/1961	09:00	53.03500	-8.00861	1955 – 2021
John F. Kennedy Park	-4.0	7/01/2010	09:00	52.31750	-6.94083	1966 – 2017
Johnstown Castle	-0.6	6/01/1970	09:00	52.29778	-6.49667	1961 – 2021
		1/01/2002	09:00			
		21/12/2010	09:00			
Kilkenny	-3.3	31/12/1961	09:00	52.66528	-7.26944	1958 – 2007
Killarney (Muckross House)	-2.0	13/01/1987	09:00	52.01667	-9.49861	1969 – 2018
Kinsaley (Agr. Res. Stn.)	-2.1	14/01/1964	09:00	53.42222	-6.17222	1962 – 2004
Malin Head	-0.2	12/01/1982	03:00	55.37194	-7.33917	1956 – 2021
		13/01/1982	03:00, 09:00			
		12/01/1985	09:00			

Table 1. Continued.

Name	Extreme lowest 10cm soil temperature (°C)	Date	Hour	Latitude (°)	Longitude (°)	Period
Moore Park	-0.5	10/01/2010	03:00, 09:00	52.16390	-8.26389	1962 – 2021
Mullingar	-3.2	24/01/1963	09:00	53.53720	-7.36222	1954 – 2021
Oak Park	-1.0	29/12/1985	09:00	52.86111	-6.91528	1967 – 1996
		29/12/1995	09:00			
Roches Point	0	2/02/1963	21:00	51.79306	-8.24444	1956 – 1990
		20/12/1963	03:00			
		5/01/1980	09:00, 15:00			
Rosslare	-0.9	24/01/1958	09:00	52.25000	-6.33472	1957 – 2007
Shannon Airport	-1.9	20/01/1963	03:00	52.69028	-8.91806	1954 – 2021
Straide	-2.3	25/12/2010	09:00	53.92500	-9.12639	1984 – 2019
Valentia Observatory	-1.6	4/01/1962	09:00	51.93833	-10.24083	1953 – 2021
		24/12/2010	09:00, 21:00			
Warrenstown	-1.5	25/12/2010	09:00	53.52444	-6.61111	1984 – 2015

2. Methodology

This section describes the meteorological data employed, the calculation of return levels of the lowest 10cm soil temperature for return periods of 50, 100 and 120-year based on the generalised extreme value distribution and the gridding techniques to produce the isothermal maps for Ireland.

2.1. Meteorological data

Soil temperature observations on a standardised and regular basis in Ireland began in late 1953 (Connaughton, 1970). A total of 39 stations with quality-controlled daily 10cm soil temperature observations for the Island of Ireland were employed in the data analysis (figure 2, table 1). The meteorological instruments, methods of observation, and the quality-control procedures of the 10cm soil temperatures follow the international standards stipulated by the World Meteorological Organization (World Meteorological Organization, 2018a,b). The observations from Ireland were obtained from the National Climate Archive at Met Éireann. In the case of stations from Northern Ireland (figure 2, table 1), the observations were downloaded from the Centre for Environmental Data Analysis (CEDA) Archive (Met Office, 2021).

The 10cm soil temperature values from stations in Ireland are instantaneous observations and are defined as follows:

- Climatological stations: registered once daily at 09:00 (Table 2).
- Synoptic stations: registered daily at 03:00, 09:00, 15:00 and 21:00 (Table 2).

The 10cm soil temperature values from stations in Northern Ireland are also instantaneous observations and were registered daily at 09:00 (Table 2). In addition, hourly observations were taken at Ballywatticock, Co. Down from 15th November 2010, Helens Bay, Co. Down from the 1st November 2002 and Murlough, Co. Down from 15th December 2009.

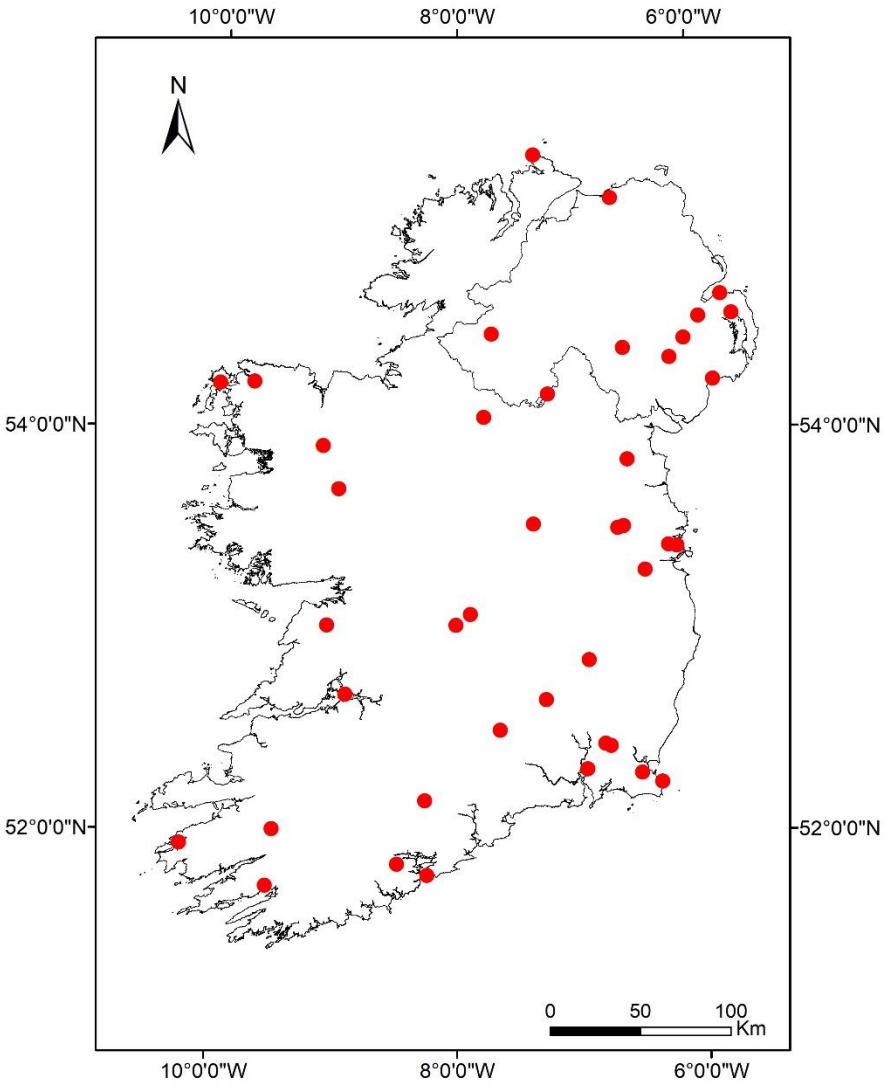

Figure 1: Location of the stations with 10cm soil temperature observations on the Island of Ireland.

Table 2: Meteorological stations and respective elevation, geographical coordinates, period and observation time covered by the 10cm soil temperature observations. Stations 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.

Name	Elevation (m)	Latitude (°)	Longitude (°)	Period	Time	Years
Ardee (Boharnamoe)	31	53.85417	-6.56944	1969 – 2019	09:00	51
Ballinamore	82	54.06944	-7.77500	1963 – 2005	09:00	43
*Ballywatticock	6	54.57200	-5.65700	1978 – 2020	09:00 (1978 – 2010), hourly (from 15/11/2010)	43
*Belfast Newforge	36	54.56000	-5.94100	1982 – 2017	09:00	36
Belmullet	9	54.22750	-10.00690	1957 – 2021	03:00, 09:00, 15:00, 21:00	65
Carlow (Oak Park)	61	52.86111	-6.91528	1967 – 1996	09:00	61
Carron	145	53.03278	-9.07722	1983 – 2019	09:00	37
Casement	91	53.30556	-6.43889	1964 – 2021	03:00, 09:00, 15:00, 21:00	58
*Castle Archdale Forest	66	54.48200	-7.70900	1963 – 1994	09:00	32
Claremorris	68	53.71083	-8.99250	1954 – 2021	03:00, 09:00, 15:00, 21:00	68
Clones	89	54.18330	-7.23333	1954 – 2008	03:00, 09:00, 15:00, 21:00	55
Clonroche (Knoxtown)	117	52.44440	-6.78917	1970 – 2019	09:00	50
*Coleraine University	23	55.15400	-6.67800	1973 – 2003	09:00	31
Cork Airport	155	51.84722	-8.48611	1963 – 2021	03:00, 09:00, 15:00, 21:00	59
Dublin Airport	71	53.42778	-6.24083	1954 – 2021	03:00, 09:00, 15:00, 21:00	68
Dunsany	83	53.51580	-6.66000	1966 – 2021	09:00 (1963 – 2006), 03:00, 09:00, 15:00, 21:00 (2006 – 2021)	56
Fethard (Parsonshill)	165	52.51417	-7.64944	1986 – 2021	09:00	36
Glenamoy	25	54.23890	-9.71667	1966 – 1997	09:00, 15:00, 21:00 (1966 – 1974), 09:00 (1974 – 1997)	32
Glengarriff (Ilnacullin)	7	51.73472	-9.54583	1976 – 2021	09:00	46
Gurteen (merged with Birr, 1955 – 2008)	75	53.03500	-8.00861	1955 – 2021	03:00, 09:00, 15:00, 21:00	67

Table 2. Continued.

Name	Elevation (m)	Latitude (°)	Longitude (°)	Period	Time	Years
*Helens Bay	43	54.66900	-5.74800	1989 – 2018	09:00 (1989 – 2002), hourly (from 1/11/2002)	30
*Hillsborough	116	54.45300	-6.07300	1968 – 2018	09:00	51
John F. Kennedy Park	70	52.31750	-6.94083	1966 – 2017	09:00	52
Johnstown Castle	62	52.29778	-6.49667	1961 – 2021	09:00 (1961 – 2008), 03:00, 09:00, 15:00, 21:00 (2009 – 2021)	61
Kilkenny	65	52.66528	-7.26944	1958 – 2007	03:00, 09:00, 15:00, 21:00	50
Killarney (Muckross House)	58	52.01667	-9.49861	1969 – 2018	09:00	50
Kinsaley (Agr. Res. Stn.)	19	53.42222	-6.17222	1962 – 2004	09:00	43
*Loughgall-no-2	37	54.40800	-6.59200	1973 – 2005	09:00	33
*Magherally	97	54.35900	-6.19600	1981 – 2019	09:00	39
Malin Head	20	55.37194	-7.33917	1956 – 2021	03:00, 09:00, 15:00, 21:00	66
Moore Park	46	52.16390	-8.26389	1962 – 2021	09:00 (1962 – 2009), 10:00 (1963 – 1968), 03:00, 09:00, 15:00, 21:00 (2009 – 2021)	60
Mullingar	101	53.53720	-7.36222	1954 – 2021	03:00, 09:00, 15:00, 21:00	68
*Murlough	12	54.24500	-5.83200	1973 – 2018	09:00 (1973 – 2009), hourly (from 15/12/2009)	46
Roches Point	43	51.79306	-8.24444	1956 – 1990	03:00, 09:00, 15:00, 21:00	35
Rosslare	26	52.25000	-6.33472	1957 – 2007	03:00, 09:00, 15:00, 21:00	51
Shannon Airport	15	52.69028	-8.91806	1954 – 2021	03:00, 09:00, 15:00, 21:00	68
Straide	21	53.92500	-9.12639	1984 – 2019	09:00	36
Valentia Observatory	24	51.93833	-10.24083	1953 – 2021	03:00, 09:00, 15:00, 21:00	69
Warrenstown	90	53.52444	-6.61111	1984 – 2015	09:00	32

2.2. 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 10cm soil temperature observations were assessed to determine the lowest observation per year and station according to a block maxima approach (Coles, 2001; Gilleland and Katz, 2016). 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 lowest 10cm soil temperature observations per year to produce the return levels for 50, 100 and 120-year return periods and for each station. The negative 10cm soil temperature 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.

2.3. Gridding

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

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 lowest 10cm soil temperature) versus the 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 sea) were found to be useful predictive variables - the 25-kilometre exposure to the sea had a Pearson R^2 correlation ≥ 0.25 which is greater than that found for other geographical variables. Here the linear regression would look like:

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

where TRP_p is the predicted lowest 10cm soil temperature return period, TRP_{mean} is the mean of the lowest 10cm soil 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 lowest 10cm soil temperature return period. 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 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 the publication of official climate normals (e.g. Walsh, 2016, 2017).

3. Results

The return values of the lowest 10cm soil temperature for return periods of 50, 100 and 120-year and the comparison with the lowest 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 lowest 10cm soil temperature 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 lowest 10cm soil temperature presents values from 0°C in areas in Cork, Kerry and Wexford to -2°C in more inland locations in counties Mayo and Monaghan (Figure 2).

The isothermal map of the return values of the 100-year return period of the lowest 10cm soil temperature displays a range from 0°C in the southwest and southeast to -2°C (Figure 3). The isotherms representing the interval from -1°C to -2°C comprise Carlow and parts of Clare, Cork, Donegal, Dublin, Galway, Kerry, Kildare, Laois, Leitrim, Limerick, Louth, Mayo, Meath, Monaghan, Sligo, Tipperary, Waterford, Wexford and Wicklow. The isotherm displaying the area equal to and below -2°C comprises the counties of Cavan, Longford, Offaly, Roscommon and Westmeath and parts of Clare, Cork, Donegal, Dublin, Galway, Kerry, Kildare, Kilkenny, Laois, Leitrim, Limerick, Louth, Meath, Mayo, Monaghan, Sligo, Tipperary, and Wicklow.

The distribution of the return values of the 120-year return period of the lowest 10cm soil temperature exhibits values from 0°C to -2°C (Figure 4). The isotherms representing the interval from -1°C to -2°C comprise parts of the counties of Carlow, Clare, Cork, Donegal, Dublin, Galway, Kerry, Kilkenny, Laois, Leitrim, Louth, Mayo, Meath, Sligo, Tipperary, Waterford, Wexford and Wicklow. The isotherm representing the area equal to and below -2°C includes the counties of Cavan, Kildare, Longford, Monaghan, Offaly, Roscommon and Westmeath and parts of Carlow, Clare, Cork, Donegal, Dublin, Galway, Kerry, Kildare, Laois, Leitrim, Louth, Mayo, Meath, Sligo and Tipperary.

Table 3: Return periods of the 10cm soil temperature observations per station in Ireland.

Name	Period	Years	Three lowest daily 10 cm soil temperature per year on record (°C)			Return periods		
			1st	2nd	3rd	50-year (°C)	100-year (°C)	120-year (°C)
Ardee (Boharnamoe)	1969 – 2019	51	-1.8	-0.4	-0.3	-1.1	-1.3	-1.4
Ballinamore	1963 – 2005	43	-2.3	-2.1	-1.4	-1.8	-2.1	-2.2
Belmullet	1957 – 2021	65	-1.0	0.2	0.2	-0.2	-0.5	-0.6
Carlow (Oak Park)	1967 – 1996	61	-1.0	-1.0	0.9	-1.0	-1.1	-1.1
Carron	1983 – 2019	37	-1.4	-0.4	0.0	-1.1	-1.4	-1.4
Casement	1964 – 2021	58	-1.8	-1.6	-0.9	-1.2	-1.5	-1.6
Claremorris	1954 – 2021	68	-3.8	-2.8	-2.2	-2.6	-3.3	-3.5
Clones	1954 – 2010	57	-4.3	-3.2	-2.1	-3.6	-4.9	-5.3
Clonroche (Knoxtown) (merged with Clonroche, 1970 – 2003)	1970 – 2019	50	-0.5	0.0	0.2	-0.2	-0.4	-0.4
Cork Airport	1963 – 2021	59	-2.9	-0.7	-0.2	-1.2	-1.7	-1.8
Dublin Airport	1954 – 2021	68	-1.1	-0.6	-0.6	-0.8	-1.0	-1.0
Dunsany	1966 – 2021	56	-2.2	-1.2	-1.0	-1.7	-2.2	-2.3
Fethard (Parsonshill)	1986 – 2021	36	-1.8	-1.5	-1.4	-1.1	-1.7	-1.9
Glenamoy	1966 – 1997	32	0.0	0.0	0.4	0.1	-0.1	-0.1
Glengarriff (Ilnacullin)	1976 – 2021	46	-1.6	0.1	0.3	-0.7	-1.0	-1.1
Gurteen (merged with Birr, 1955 – 2008)	1955 – 2021	67	-4.3	-2.8	-2.3	-2.8	-3.7	-3.9
John F. Kennedy Park	1966 – 2017	52	-4.0	-0.8	-0.2	-1.5	-2.0	-2.2
Johnsown Castle	1961 – 2021	61	-0.6	-0.6	-0.6	-0.6	-0.8	-0.8
Kilkenny	1958 – 2007	50	-3.3	-3.2	-3.1	-2.9	-3.6	-3.8
Killarney (Muckross House)	1969 – 2018	50	-2.0	-1.8	-0.5	-1.3	-1.7	-1.8
Kinsaley (Agr. Res. Stn.)	1962 – 2004	43	-2.1	-0.4	-0.2	-1.1	-1.4	-1.5
Malin Head	1956 – 2021	66	-0.2	-0.2	0.0	-0.1	-0.2	-0.2
Moore Park	1962 – 2021	60	-0.5	-0.1	-0.1	-0.3	-0.4	-0.4
Mullingar	1954 – 2021	68	-3.2	-2.1	-1.7	-2.0	-2.5	-2.6
Roches Point	1956 – 1990	35	0.0	0.0	0.1	0.0	-0.1	-0.2
Rosslare	1957 – 2007	51	-0.9	-0.4	0.0	-0.5	-0.7	-0.7
Shannon Airport	1954 – 2021	68	-1.9	-1.7	-1.2	-1.4	-1.7	-1.8
Straide	1984 – 2019	36	-2.3	-2.1	-0.4	-2.1	-3.0	-3.2
Valentia Observatory	1953 – 2021	69	1.8	2.1	2.4	-1.1	-1.4	-1.5
Warrenstown	1984 – 2015	32	-1.5	-0.7	-0.5	-1.1	-1.3	-1.4

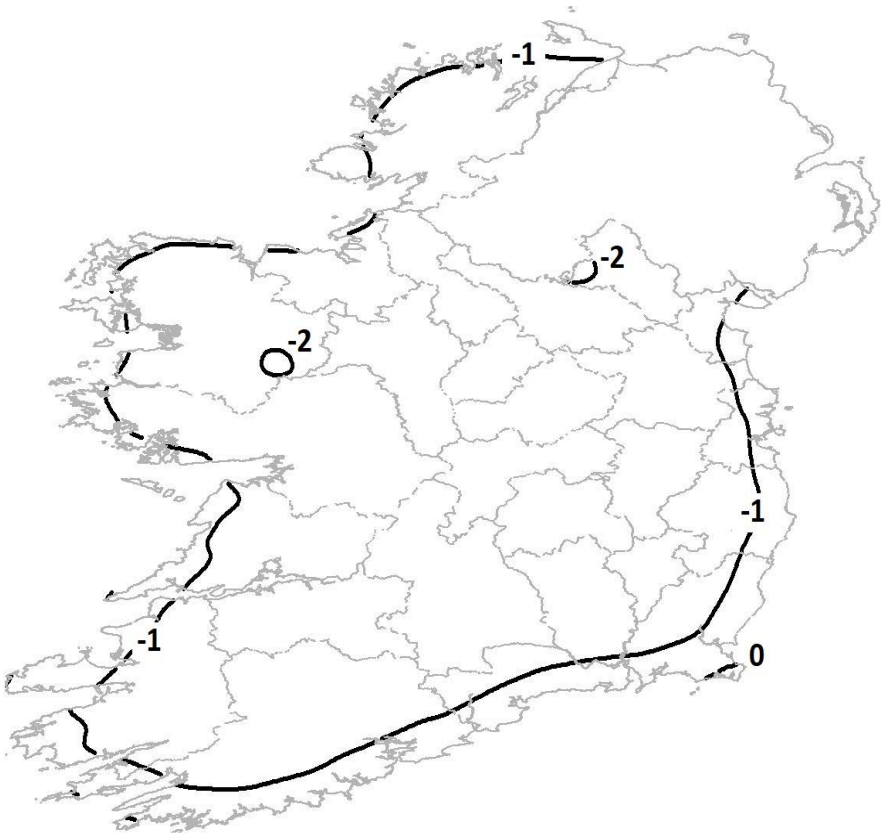

Figure 2: Isotherms of the lowest 10cm soil temperature (°C) for a 50-year return period in Ireland.

Figure 3: Isotherms of the lowest 10cm soil temperature (°C) for a 100-year return period in Ireland.

Figure 4: Isotherms of the lowest 10cm soil temperature (°C) for a 120-year return period in Ireland.

4. Discussion

Met Éireann produced, in this report, the first isothermal maps of return values of the lowest 10cm soil temperature for return periods of 50, 100 and 120 years for Ireland. These maps will assist the design of buildings to enhance resilience in support of climate change adaptation in Ireland and stakeholders should adopt them.

It would be desirable to produce the isothermal maps of the return values of the lowest 10cm soil minimum temperature observations in a 24h period for return periods of 50, 100 and 120 years for Ireland to represent the worst-case scenario. However, the length of the minimum thermometer in the soil at a 10cm depth range from 13 to 21 years for a current network of 21 automated synoptic stations. A minimum of 30 or more years of data is necessary to calculate longer return periods. Specifically, the calculation of rare extremes such as 100 or 120-year return period require a long-term observational dataset (Klein Tank *et al*., 2009). Therefore, the lowest 10cm soil temperature observations were analysed in this research. Future work should calculate the return values of the hourly 10cm soil minimum temperature observations for return periods of 50, 100 and 120 years when a minimum of 30 or more years of data for a denser network become available from the automatic stations.

5. Conclusion

Isothermal maps of return values of the lowest 10cm soil temperature for return periods of 50, 100 and 120 years have been produced based on the generalised extreme value distribution (Coles, 2001; Gilleland and Katz, 2016). Met Éireann produced, in this report, the first isothermal maps of return values of the lowest 10cm soil temperature for return periods of 50, 100 and 120 years for Ireland. These maps will assist the design of buildings to enhance resilience in support of climate change adaptation in Ireland and stakeholders should adopt them.

It is hoped that the detailed explanation of the methodology provided here will assist regulators in adopting these new maps in their own jurisdictions.

In the current context of climate warming, it is expected that these return values will increase. The sixth assessment report of the Intergovernmental Panel on Climate Change projects an increase in the global mean air temperature (IPCC, 2021). 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). The isothermal maps of return values of the lowest 10cm soil temperature for return periods of 50, 100 and 120 years produced here for Ireland represent the worst-case scenario.

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