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Return values of temperature and snow loadings for 50, 100 and 120-year return periods to support building design standards in Ireland

Carla Mateus[1,2] **and Barry Coonan**[1]

[1]Climate Services, Met Éireann, Dublin, D09 Y921, Ireland
[2]present address: Geography Department, National University of Ireland, Maynooth, Ireland

Correspondence: Carla Mateus (carla.ppmateus@gmail.com)

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Abstract. This research produced gridded datasets and maps for use in building design standards to enhance resilience in support of climate change adaptation in Ireland.

The new isothermal maps of return values of maximum and minimum air temperatures at mean sea level for 50, 100 and 120-year return periods based on the generalised extreme value distribution will be crucial to inform the design of buildings and bridges. 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 new isothermal maps compared to previously published maps for a 50-year return period. Specifically, the new extreme isotherms are 32 °C for the maximum air temperature and −14 °C for the minimum air temperature, whereas the processor maps presented 30 and −16 °C, respectively. The geographical distribution of the isotherms for the 120-year return period range from 28 to 34 °C for the maximum air temperature and from −6 to −18 °C for the minimum air temperature.

For the first time, isothermal maps of return values of the lowest 10 cm soil temperature for 50, 100 and 120-year return periods based on the generalised extreme value distribution have been produced for Ireland. The results presented here will be paramount to supporting the design of building structures. The values of the 120-year return period range from 0 to −2 °C. The produced maps represent the worst-case scenario in the current context of climate warming.

The new maps of return values of snow loading at 100 m above mean sea level for 50, 100 and 120-year return periods based on the generalised Pareto distribution will be indispensable to support the design of buildings and civil engineering works such as roof patterns or bridges. The values of the 50-year return period map present four classes spread North-East to South-West: < 0.3, 0.3–0.4, 0.4–0.5 and 0.5–0.6 $\mathrm{kN\,m^{-2}}$, which is more accurate than the previously published map.

It is expected that the comprehensive explanation of the methods and the rationale for the new maps presented here as being more accurate than the preceding maps will assist regulators in adopting these new maps in their own jurisdictions. Furthermore, these new maps will be of interest to a diversity of sectors, planners and policymakers to make long, lasting and climate-based sensitive decisions.

1 Introduction

Research on air temperature trends and ETCCDI (Expert Team on Climate Change Detection and Indices) daily extreme air temperature indices (Mateus and Potito, 2022) and climate projections (Nolan and Flanagan, 2020) indicate that the climate of Ireland is changing. Met Éireann received funding as part of the Department of Housing, Local Government and Heritage to update and produce new gridded datasets and maps in support of Action 203 of Ireland's Climate Action Plan 2021 – *Develop specific climate maps and data for use in building design to enhance resilience in support of climate change adaptation* and to support the National Adaptation Framework (Mateus and Coonan, 2022a, b, c, 2023; Griffin et al., 2023).

Isothermal maps of return values of extreme high maximum and extreme low minimum air temperatures in degree Celsius for 50, 100 and 120-year return periods are critical to assist the design of buildings and bridges (e.g. Hopkins and Whyte, 1975; CEN, 2003; British Standards Institution, 2007; Rees et al., 2011). The isothermal maps of maximum and minimum air temperatures with a probability of being exceeded of 0.02 (1 in a 50-year return period) have formerly been produced for Ireland and the UK (British Standards Institution, 1978, 2007; National Standards Authority of Ireland, 2008). The methods used for the annual probability of exceedances other than 0.02 were furnished in the National Annex to BS EN 1991-1-5:2003 (British Standards Institution, 2007), EN 1991-1-5: 2003 (CEN, 2003) and National Annex to I.S. EN 1991-1-5-:2003 (National Standards Authority of Ireland, 2008). In this research, isothermal maps of the return values of the highest maximum and lowest minimum air temperatures for 50, 100 and 120-year return periods based on the generalised extreme value distribution (Coles, 2001; Gilleland and Katz, 2016) and adjusted to mean sea level (Hopkins and Whyte, 1975; CEN, 2003) for a dense network of 64 stations for the period from 1961 to 2020 are presented.

The design of building structures requires information on low soil temperatures. For the first time, isothermal maps of return values of the lowest 10 cm soil temperature in degree Celsius for 50, 100 and 120-year return periods based on the generalised extreme value distribution (Coles, 2001; Gilleland and Katz, 2016) have been produced for Ireland.

The maps of return values of snow loading in kilogram-force per square metre ($\mathrm{kN\,m^{-2}}$) for 50, 100 and 120-year return periods are important to inform the structural design of buildings and civil engineering works (National Standards Authority of Ireland, 2015a, b). Examples include the design of different roof patterns (International Organization for Standardization, 2013; National Standards Authority of Ireland, 2015a, b) and bridges (e.g. British Standards Institution, 2007). The previous map of return values of snow loading at 100 m above mean sea level for a 50-year return period for Ireland had assessed the greatest snow depth per year based on daily observations from a small network of 10 stations and without stations from Northern Ireland (Keegan, 2010; Government of Ireland, 2012; National Standards Authority of Ireland, 2015b). Discrepancies were identified in this map produced for Ireland (Keegan, 2010; Government of Ireland, 2012; National Standards Authority of Ireland, 2015b) with the map produced by British Standards Institution (2007) for the United Kingdom and Ireland. Specifically, the discrepancies in the map for Ireland refer to an area of $0.7\,\mathrm{kN\,m^{-2}}$ in the Dublin/Wicklow area, higher snow loadings of $0.6\,\mathrm{kN\,m^{-2}}$ in the Monaghan region and the Southern region represented as $0.4\,\mathrm{kN\,m^{-2}}$ (Keegan, 2010; Government of Ireland, 2012; National Standards Authority of Ireland, 2015b). As Keegan (2010) noted, the results should not be deemed overly accurate due to the small number of stations, the daily resolution of the snow depth observations and the relatively few years with significant snow. The new work presented here does not sustain these issues as a larger network of stations with extra locations in Northern Ireland is employed, including more hourly series, the length of the series is longer and the adjustment added to the daily snow depths to adjust for the discrepancy between daily and hourly values is more precise. Other snow loading map at sea level was produced for the UK and Ireland (National Standards Authority of Ireland, 2015a). In this research, return values of snow loadings at 100 m above mean sea level for 50, 100 and 120-year return periods based on the Generalised Pareto Distribution (Coles, 2001) are presented for Ireland.

The manuscript is structured as follows. Section 2 comprises the methodology, where the data, calculation of return values and the gridding methods are explained. Section 3 details the results and the discussion. The conclusion is provided in Sect. 4.

2 Methodology

2.1 Return values of maximum and minimum air temperatures at mean sea level for 50, 100 and 120-year return periods

2.1.1 Data

A total of 64 stations with quality-controlled and homogenised daily maximum and minimum air temperature observations covering the period from 1961 to 2020 for the island of Ireland were employed in the data analysis (Fig. 1, Table 1). The observations for the 52 stations from Ireland were obtained from the National Climate Archive at Met Éireann and the observations for 12 stations from Northern Ireland were acquired from the Centre for Environmental Data Analysis (CEDA) Archive (Met Office, 2021a). Observations from Northern Ireland are employed in this research to improve the outputs in the border as Met Éireann publishes data for Ireland only.

Table 1. Meteorological stations and respective geographical coordinates, elevation and period covered by the daily maximum and minimum air temperature observations in the period from 1961 to 2020. Stations located in Northern Ireland are marked with an [a]. In case of replacement from manual to automatic station or re-location of the 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 [b].

Station name	Station number	Latitude (°)	Longitude (°)	Elevation (m)
[a]Aldergrove	9142/9144	54.66400	−6.22500	63
[a]Altnahinch Filters	9147	55.04800	−6.25500	213
Ardee (Boharnamoe)	2638	53.85420	−6.56944	31
[b]Ardfert (Liscahane)	1609	52.31110	−9.77361	30
[a]Armagh	9336	54.35200	−6.65000	62
Ballinamore (Creevy no. 2)	5937	54.04940	−7.83806	72
[a]Ballypatrick Forest	9168/9169	55.18100	−6.15400	156
Ballyshannon (Cathleen's Fall)	2237	54.49833	−8.17583	38
[a]Ballywatticock	9280	54.57200	−5.65700	6
[a]Banagher Caugh Hill	9042	54.88600	−6.96600	214
[b]Belderrig	4535	54.31028	−9.56667	66
Belmullet	1034/2375	54.22750	−10.00690	9
Birr	4919	53.09028	−7.89028	72
Casement	3723	53.30556	−6.43889	91
Claremorris	2727/2175	53.71080	−8.99250	68
Clones	2437	54.18330	−7.23333	89
Cloosh (For. Stn.)	1425	53.35970	−9.33944	101
[b]Cloyne (Lisanley)	6304	51.85611	−8.13611	55
Cork Airport	3904	51.84722	−8.48611	155
[b]Cork (Clover Hill)	4204	51.88472	−8.41944	20
Derrygreenagh	3431	53.39167	−7.25833	90
Dublin (Glasnevin)	1823	53.37000	−6.27028	21
Dublin (Merrion Square)	3923	53.34060	−6.25333	13
Dublin Airport	532	53.42780	−6.24083	71
Dundalk (Annaskeagh W.W.)	538	54.05190	−6.35139	61
[b]Dungarvan (Carriglea)	1407	52.08722	−7.68250	18
Dunsany	3731	53.51580	−6.66000	83
[b]Edenderry Ballinla	6314	53.33111	−7.12500	91
Galway (Univ. Coll.)	3927	53.27640	−9.06389	14
[b]Glencolumbkille (Drimroe)	1741	54.71111	−8.70278	49
[b]Glenealy (Kilmacurragh Park)	2824	52.92917	−6.14972	122
Glenties Hatchery	441	54.79111	−8.28750	44
[a]Helens Bay	9288	54.66900	−5.74800	43
[a]Hillsborough	9238	54.45300	−6.07300	116
John F. Kennedy Park	4514	52.31750	−6.94083	70
Johnstown II	915/1775	52.29778	−6.49667	62
Kilkenny	3613	52.66528	−7.26944	65
Killarney (Muckross House)	3205	52.01670	−9.49861	58
Kinsaley (Agr. Res. Stn.)	1232	53.42222	−6.17222	19
[b]Littleton	6712	52.61167	−7.70000	126
[a]Lough Navar Forest	9215	54.43900	−7.90100	126
[b]Lullymore Nature Centre	2514/4314	53.27889	−6.94222	85
[a]Magherally	9270	54.35900	−6.19600	97
Malin Head	545/1575	55.37194	−7.33917	20
[b]Mallow Spa House	7406	52.13889	−8.63500	61
Markree	636/1275	54.17500	−8.45556	39
[b]Milford Kilmacrennan Road	1444	55.08500	−7.69917	30
Moore Park	575	52.16389	−8.26389	46
[b]Mount Dillon	1975	53.72694	−7.98083	39
Mullingar	2222/2922/875	53.53722	−7.36222	101
[a]Murlough	9260	54.24500	−5.83200	12
[b]Navan (Tara Mines)	4531	53.65833	−6.71833	52
Newport (Furnace)	833	53.92333	−9.57111	14
Oak Park	4814/375	52.86110	−6.91528	61
Phoenix Park	1723/175	53.36361	−6.34972	48
[b]Piltown (Kildalton Agr. Coll.)	5912	52.35139	−7.30000	18
Roches Point	1004/1075	51.79310	−8.24444	43
Rosslare	2615	52.25000	−6.33472	26
Shannon Airport	518	52.69028	−8.91806	15
Sherkin Island	3402/775	51.47639	−9.42833	20
[a]Stormont Castle	9268	54.60300	−5.83000	56
Valentia Observatory	305/2275	51.93830	−10.24080	24
Warrenstown	2931	53.52444	−6.61111	90
Waterford (Tycor)	1812	52.25278	−7.13056	49

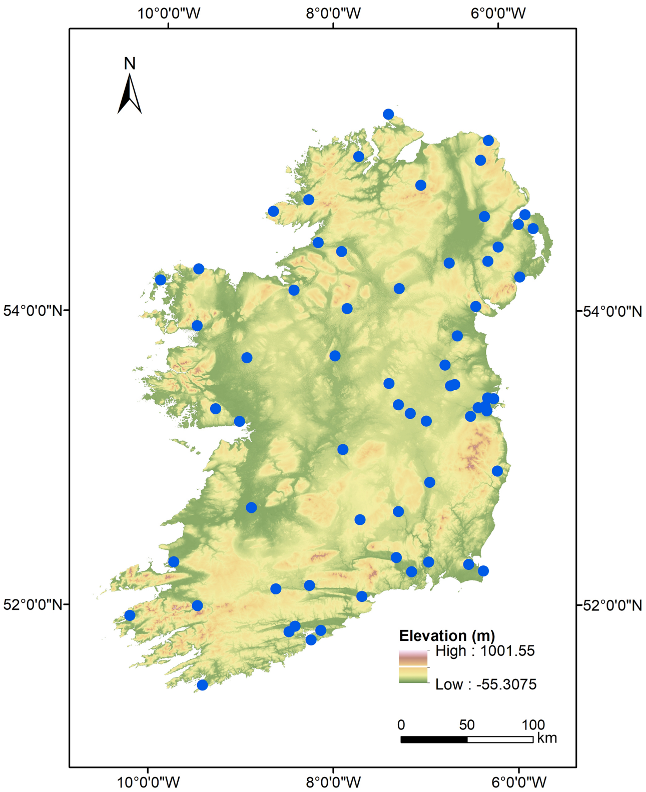

Figure 1. Location of the stations with daily maximum and minimum air temperature observations on the island of Ireland.

The daily maximum air temperature corresponds to the maximum value recorded during the 24 h observation period from 09:00 to 09:00 UTC. Similarly, the daily minimum air temperature represents the minimum value recorded during the 24 h observation period from 09:00 to 09:00 UTC.

The daily maximum and minimum air temperature observations have been quality-controlled according to climate consistency, internal consistency, persistency, day-to-day step change and spatial tests (e.g. Hubbard et al., 2005; Walsh, 2017).

Inhomogeneities in air temperature observations can result from changes in the station's location, thermometers, observation time, station surroundings, observer or the replacement of the manual with automatic stations (e.g. Trewin, 2010). Climate data homogeneity is necessary to minimise artificial effects and ensure that variability, change, and trends arise from weather and climate variations (Conrad and Pollack, 1950). The homogenisation procedures were applied by Met Éireann employing the software MASH (Szentimrey, 2017).

The meteorological instruments, methods of observation, and the quality-control and homogenisation procedures of the maximum and minimum air temperature observations follow the international standards stipulated by the World Meteorological Organization (2018, 2021).

2.1.2 Adjustment of maximum and minimum air temperature for height above sea level

The annual maxima of the maximum air temperature and the annual minima of the minimum air temperature series were adjusted for height above sea level following the methodology described by Hopkins and Whyte (1975) and adopted by CEN (2003) and the National Standards Authority of Ireland (2008). Specifically, the Irish Standard I.S. EN 1991-1-5:2003 + NA Eurocode 1: Actions on structures – Part 1-5: General actions – Thermal actions (National Standards Authority of Ireland, 2008) specifies the recommended method to adjust maximum and minimum air temperatures for height above mean sea level, which must be adopted. Based on the National Standards Authority of Ireland (2008), the minimum air temperature observations were adjusted by subtracting 0.5 °C per 100 m height whereas the maximum air temperatures were adjusted by subtracting 1.0 °C per 100 m height.

2.1.3 Calculation of return values

Extreme values are scarce, and the estimation of return levels for 50, 100 and 120-year return periods entails an extrapolation from instrumental observations to unobserved levels, and extreme value theory enables a class of models to allow such extrapolation (Coles, 2001).

The daily maximum air temperature observations were assessed to calculate the highest value per year from 1961 to 2020 per station and following a block maxima approach (Coles, 2001; Gilleland and Katz, 2016). In parallel, the lowest value of the minimum air temperature was calculated per year from 1961 to 2020 and per station. The generalised extreme value distribution was fitted to the series of the highest maximum air temperature observations reduced to mean sea level to generate the return levels for 50, 100 and 120-year return periods for each station. Similarly, this procedure was applied to the series of the lowest minimum air temperature reduced to mean sea level, except that the values were multiplied by −1 before the extreme value distribution function was fitted (Coles, 2001; Gilleland and Katz, 2016). The generalised extreme value distribution and the block maxima approach algorithms were applied by employing the extreme value analysis R package extRemes 2.0, which has a focal point on climate applications (Gilleland and Katz, 2016).

2.2 Return values of the lowest 10 cm soil temperature for 50, 100 and 120-year return periods

2.2.1 Data

A total of 39 stations with quality-controlled daily 10 cm soil temperature observations registered in the period from 1953 to 2021 and with lengths ranging from 30 to 69 years were used in the data analysis (Fig. 2, Table 2). The observations from the 30 stations in Ireland were acquired from the Na-

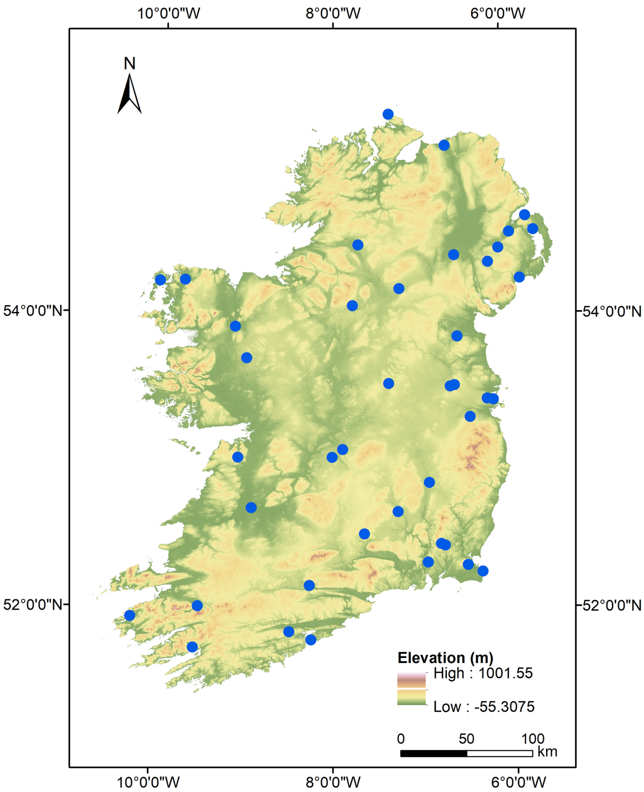

Figure 2. Location of the stations with 10 cm soil temperature observations on the island of Ireland.

tional Climate Archive at Met Éireann. For the 9 stations from Northern Ireland, the observations were obtained from the CEDA Archive (Met Office, 2021b).

The 10 cm soil temperature observations from stations in Ireland are instantaneous records registered once daily at 09:00 UTC at the climatological stations and at 03:00, 09:00, 15:00 and 21:00 UTC daily at synoptic stations. In the case of the 10 cm soil temperature observations from stations in Northern Ireland, the records are instantaneous and were registered daily at 09:00 UTC. Additionally, hourly observations were registered at Ballywatticock, Co. Down from 15 November 2010, Helens Bay, Co. Down from the 1 November 2002 and Murlough, Co. Down from 15 December 2009.

The meteorological instruments, methods of observation, and the quality-control procedures of the 10 cm soil temperature observations follow the international standards recommended by the World Meteorological Organization (2018, 2021).

2.2.2 Calculation of return values

The 10 cm soil temperature observations were analysed to calculate the lowest observation per year and station according to a block maxima approach (Coles, 2001; Gilleland and Katz, 2016). The generalised extreme value distribution was fitted to the lowest 10 cm soil temperature series to produce the return levels for 50, 100 and 120-year return periods for each station. The negative 10 cm soil temperature values were multiplied by -1 before the extreme value distribution function was fitted using the extreme value analysis R package extRemes 2.0 (Gilleland and Katz, 2016).

2.3 Return period of snow loadings at 100 m above mean sea level

2.3.1 Data

A total of 33 stations with quality-controlled daily snow depth observations were employed in the data analysis (Fig. 3, Table 3). The daily snow depth observations from 19 stations in Ireland cover the period from 1940 to 2022 and have lengths between 33 and 80 years of data, which was obtained from the National Climate Archive at Met Éireann. A total of 14 stations from Northern Ireland have daily snow depth observations covering the period from 1959 to 2022 and with lengths between 16 to 64 years of data, which were accessed from the CEDA Archive (Met Office, 2021c). Hourly snow depth observations for 13 stations with a record length generally from 1990, which have an overlapping with daily data, were also employed in the data analysis. The hourly observations were obtained from the National Climate Archive at Met Éireann and from the CEDA Archive (Met Office, 2021d).

The daily snow depth data for locations in Ireland correspond to observations in centimetres taken at synoptic and climate stations. In the case of the synoptic stations, the snow depths were recorded at the main hours of 06:00 and 09:00 UTC and also reported on hourly synoptic observations if snow depths were present, whereas the snow depths were only taken at 09:00 UTC in the climate stations. For Northern Ireland stations, the snow depth observations in centimetres were registered once-daily at 09:00 UTC. The hourly snow depths at stations from Ireland and Northern Ireland were registered in centimetres observed in the 24 h from 00:00 to 23:00 UTC hours.

The meteorological instruments, methods of observation, and quality-control procedures of the snow depth observations follow the international standards published by the World Meteorological Organization (2018, 2021).

2.3.2 Calculation of return values

The daily snow depth observations were examined to ascertain the highest snow depth per year with a zero-value returned when there was no snow recorded at the station in that year. Furthermore, when both daily and hourly observations were obtainable for the same period, the hourly observations were examined to determine the highest snow depth per year. A Generalised Pareto distribution was fitted to the series of the greatest snow depths per year to calculate the return levels for 50, 100 and 120-year return periods for each station

Table 2. Meteorological stations and respective elevation, geographical coordinates, period and observation time covered by the 10 cm soil temperature observations. Stations in Northern Ireland are marked with an asterisk (*). In case of replacement from manual to automatic station or re-location of the station, the geographical coordinates correspond to the most recent location.

Station name	Station number	Latitude (°)	Longitude (°)	Elevation (m)	Period	Years
Ardee (Boharnamoe)	2638	53.85417	−6.56944	31	1969–2019	51
Ballinamore	3337	54.06944	−7.77500	82	1963–2005	43
*Ballywatticock	9280	54.57200	−5.65700	6	1978–2020	43
*Belfast Newforge	9178	54.56000	−5.94100	36	1982–2017	36
Belmullet	1034/2375	54.22750	−10.00690	9	1957–2021	65
Carlow (Oak Park)	4814/375	52.86111	−6.91528	61	1967–1996	61
Carron	1718	53.03278	−9.07722	145	1983–2019	37
Casement	3723	53.30556	−6.43889	91	1964–2021	58
*Castle Archdale Forest	9547	54.48200	−7.70900	66	1963–1994	32
Claremorris	2727/2175	53.71083	−8.99250	68	1954–2021	68
Clones	2437	54.18330	−7.23333	89	1954–2008	55
Clonroche (Knoxtown)	5415	52.44440	−6.78917	117	1970–2019	50
*Coleraine University	9077	55.15400	−6.67800	23	1973–2003	31
Cork Airport	3904	51.84722	−8.48611	155	1963–2021	59
Dublin Airport	532	53.42778	−6.24083	71	1954–2021	68
Dunsany	3731/1375	53.51580	−6.66000	83	1966–2021	56
Fethard (Parsonshill)	7112	52.51417	−7.64944	165	1986–2021	36
Glenamoy	1134	54.23890	−9.71667	25	1966–1997	32
Glengarriff (Ilnacullin)	201	51.73472	−9.54583	7	1976–2021	46
Gurteen (merged with Birr, 1955–2008)	1475/4919	53.03500	−8.00861	75	1955–2021	67
*Helens Bay	9288	54.66900	−5.74800	43	1989–2018	30
*Hillsborough	9238	54.45300	−6.07300	116	1968–2018	51
John F. Kennedy Park	4514	52.31750	−6.94083	70	1966–2017	52
Johnstown Castle	915/475	52.29778	−6.49667	62	1961–2021	61
Kilkenny	3613	52.66528	−7.26944	65	1958–2007	50
Killarney (Muckross House)	3205	52.01667	−9.49861	58	1969–2018	50
Kinsaley (Agr. Res. Stn.)	1232	53.42222	−6.17222	19	1962–2004	43
*Loughgall nos. 1 and 2	9347/9346	54.40800	−6.59200	37	1973–2005	33
*Magherally	9270	54.35900	−6.19600	97	1981–2019	39
Malin Head	545/1575	55.37194	−7.33917	20	1956–2021	66
Moore Park	3606/575	52.16390	−8.26389	46	1962–2021	60
Mullingar	2222/875	53.53720	−7.36222	101	1954–2021	68
*Murlough	9260	54.24500	−5.83200	12	1973–2018	46
Roches Point	1004/1075	51.79306	−8.24444	43	1956–1990	35
Rosslare	2615	52.25000	−6.33472	26	1957–2007	51
Shannon Airport	518	52.69028	−8.91806	15	1954–2021	68
Straide	3335	53.92500	−9.12639	21	1984–2019	36
Valentia Observatory	305/2275	51.93833	−10.24083	24	1953–2021	69
Warrenstown	2931	53.52444	−6.61111	90	1984–2015	32

by implementing the R package extRemes 2.0 (Gilleland and Katz, 2016). The Generalised Pareto distribution, also known as the Peaks-Over-Threshold method, has been employed to calculate the return period of snow loads (e.g. O'Donnell et al., 2020).

A Generalised Pareto distribution is used as it can accommodate extreme value datasets where there are zero values (years without snowfall events). Precisely, major snowfall events across Ireland are rare, with numerous annual maximum snow depth observations from lower-lying and southerly located stations, in specific, exhibiting a high proportion of no snow years. As an example, over the 72-year (1940–2011) snow record of Valentia Observatory, only 20 years had snow depth observations, with most of the values being light snow depths.

The Generalised Pareto distribution characterises an instrumental observation as extreme if it exceeds a specific threshold (Coles, 2001). Accordingly, the threshold selection entails an equilibrium between bias and variance: a threshold too low is likely to violate the asymptotic basis of the model, emanating in bias, whereas a threshold too high will generate few excesses with which the model can be estimated,

Table 3. Meteorological stations and respective elevation, geographical coordinates, data resolution and period covered by the snow depth observations. Stations located in Northern Ireland are marked with an asterisk (*). In case of replacement from manual to automatic station or re-location of the station, the geographical coordinates correspond to the most recent location.

Name	Station number	Latitude (°)	Longitude (°)	Elevation (m)	Data	Period	Years
*Armagh	9336	54.35200	−6.65000	62	Daily	1959–2022	64
Ballyshannon (Cathleen's Fall)	2237	54.49833	−8.17583	38	Daily	1966–2022	57
*Ballywatticock	9280	54.57200	−5.65700	6	Daily	1974–2010	37
*Belfast Newforge	9178	54.56000	−5.94100	36	Daily	1982–2020	39
*Belfast Ravenhill Road	9259	54.58400	−5.91000	10	Daily	1986–2020	35
Belmullet	1034	54.22780	−10.00690	9	Daily	1957–1989	55
					Hourly	1990–2011	
Birr (merged with Gurteen)	4919	53.09030	−7.89028	72	Daily	1955–1989	67
					Hourly	1990–2009	
Gurteen	1475	53.03500	−8.00861	75	Daily	2010–2021	
Casement	3723	53.30556	−6.43889	91	Daily	1962–1989	60
					Hourly	1990–2021	
*Castlederg	9420	54.70700	−7.57700	49	Daily	2006–2007 2012	15
					Hourly	2008–2011, 2013–2020	
*Castlereagh	9269	54.56500	−5.87100	122	Daily	1990–2020	31
Claremorris	2727	53.71111	−8.99139	69	Daily	1950–1989	63
					Hourly	1990–2012	
Clones	2437	54.18330	−7.23330	89	Daily	1951–1989	60
					Hourly	1990–2010	
Cork Airport	3904	51.84722	−8.48611	155	Daily	1962–1989	60
					Hourly	1990–2021	
*Derrygonnelly	9516	54.41800	−7.82100	65	Daily	2002–2017	16
Dublin Airport	532	53.42778	−6.24083	71	Daily	1942–1989	80
					Hourly	1990–2021	
Dundalk (Annaskeagh W.W.)	538	54.05190	−6.35139	61	Daily	1974–2016	43
*Edenfel	9437	54.59400	−7.28300	89	Daily	1981–2016	36
Glenealy (Kilmacurragh Park)	2824	52.92917	−6.14972	122	Daily	1982–2019	38
*Hillsborough	9238	54.45300	−6.07300	116	Daily	1959–2020	62
Kilkenny	3613	52.66530	−7.26944	65	Daily	1958–1989	51
					Hourly	1990–2008	
*Loughgall no 1	9347	54.40800	−6.60400	25	Daily	1959–1995	53
*Loughgall no 2	9346	54.40800	−6.59200	37	Daily	1995–2011	
*Lough Navar Forest	9515	54.43900	−7.90100	126	Daily	1961–2020	60
*Magherally	9270	54.35900	−6.19600	97	Daily	1977–2020	44
Malin Head	545	55.37222	−7.33889	22	Daily	1956–1989	66
		55.37222	−7.33889		Hourly	1990–2010	
	1575	55.37194	−7.33917	20	Daily	2011–2021	
Mount Russell	5306	52.32970	−8.56917	195	Daily	1990–2022	33
Mullingar	2222	53.53720	−7.36222	111	Daily	1950–1989	72
					Hourly	1990–2008	
	875			101	Daily	2009–2021	
Roches Point	1075	51.79306	−8.24444	40	Daily	2005–2021	17
Shannon Airport	518	52.69028	−8.91806	15	Daily	1946–1990	76
					Hourly	1991–2021	
*Silent Valley	9240	54.12700	−6.00200	129	Daily	1977–2020	44
Straide	3335	53.92500	−9.12639	21	Daily	1984–2019	36
*Trassey Slievenaman	9245	54.20600	−6.00600	220	Daily	1985–2020	36
Valentia Observatory	305	51.93806	−10.24330	24	Daily	1940–1989	72
					Hourly	1990–2011	
Warrenstown	2931	53.52440	−6.61111	90	Daily	1961–2015	55

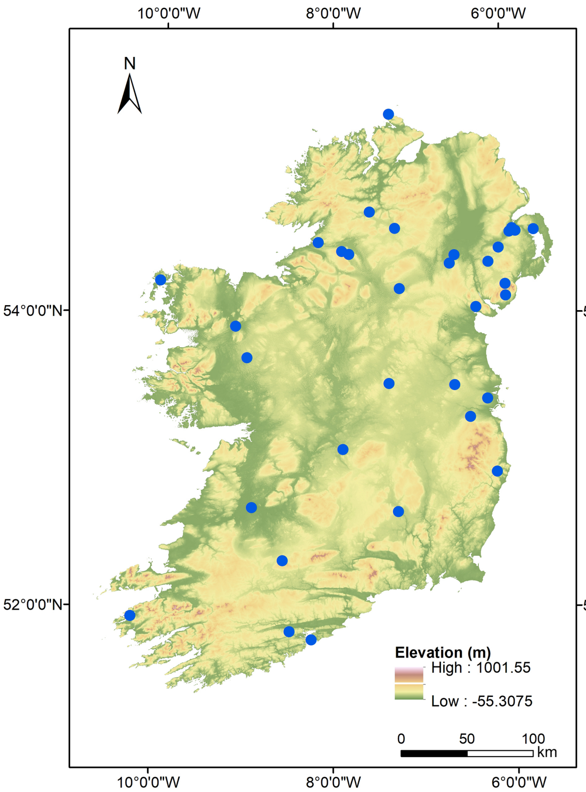

Figure 3. Location of the stations with snow depth observations on the island of Ireland.

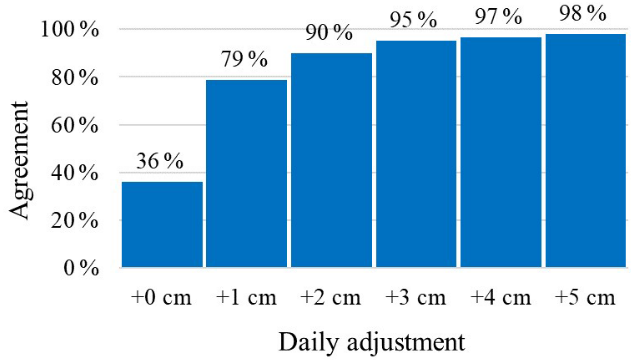

Figure 4. Agreement between hourly and daily snow depth observations.

resulting in high variance (Coles, 2001). Consequently, the typical practice is to select a low threshold as feasible and subject to the limit model proving a reasonable approximation (Coles, 2001). Therefore, mean residual life plots were interpreted, and the Generalised Pareto distribution was fitted to a range of thresholds to evaluate the stability of parameter estimates (Coles, 2001). This process was cross-referenced with the three greatest snow depth observations registered on the instrumental record for each station. In this respect, the Generalised Pareto distribution sets a threshold below which data are ignored, removing years when no snow or very little snow is recorded and fitting to the remaining dataset. This threshold can be set to optimise the fit between the instrumental data and the model and thus improve the confidence in the estimated return values.

2.3.3 Adjustment for the once-daily versus hourly observations

A once-daily snow depth observation will likely occasionally omit the highest snow depth due to melting compared to hourly observations taken over the equivalent 24 h period. This discrepancy was quantified after analysing the available overlapping once-daily and hourly snow depths observations for the 13 stations where both observations were available. In just 36 % of cases where the snow depth was greater than zero (Fig. 4), the daily and hourly highest snow depth observations were the same. However, if an adjustment of +3 cm was made to the daily values, then in 95 % of cases, the daily value matched or exceeded the hourly value. Therefore, a +3 cm adjustment was made to the daily snow depths to adjust for the discrepancy between daily and hourly values, where no hourly data was available. Effectively, this adjustment minimises the chance that daily snow observations underestimate the highest snowfall depth in each 24 h period.

2.3.4 Adjustment of return values of snow depths to 100 m elevation above mean sea level

Snow depths generally increase with altitude. Rather than including topography in the snow load maps, an adjustment was applied to the return levels of snow depths to generate equivalent values at a standardised elevation of 100 m above mean sea level, making the generated maps easier to read. The adjustment of return values of snow depths to 100 m elevation above mean sea level is required by the National Annex plus Amendment NA+A2:2020 to I.S. EN 1991-1-3:2003&A1:2015 (National Standards Authority of Ireland, 2015b).

This adjustment was established on the distribution of station altitudes and the return values of snow depths for each return period by employing a linear regression fit of the snow depth versus elevation. The correction applied to the return values of snow depths was 9.4 cm per 100 m for the 50-year return period, 11 cm per 100 m for the 100-year return period and 11.4 cm per 100 m for the 120-year return period. For instance, the return value of a snow depth for a 100-year return period for a station at 50 m elevation will be adjusted up by 5.5 cm, whereas a station at an elevation of 200 m will have its return value for a 100-year return period reduced by 11 cm. For context, British Standards Institution (2007) suggests a variation of 0.2 $\mathrm{kN\,m^{-2}}$ in snow load for every 100 m of height for use in the UK and Ireland, which is equivalent to a 10 cm snow depth adjustment.

Clearly, elevation does not fully describe the return period snow depths as snowfall events can be localised, depending on the direction of the incoming snow front and location north to south and east to west in the country. The RMSE error in snow depth of the 100 m adjustment was found to be 7.9, 9.4 and 9.9 cm at return periods of 50, 100 and 120 years, respectively (Fig. 5).

2.3.5 Adjustment for snow loadings at 100 m above mean sea level

The density of snow must be known to convert the return values of snow depths for 50, 100 and 120-year return periods to a snow loading. The $2.0\,\mathrm{kN\,m^{-3}}$ value is applicable for snow which is settled after several hours or days after its fall (Keegan, 2010). Therefore, 1 cm of snow depth corresponds to $0.02\,\mathrm{kN\,m^{-2}}$ of snow loading. The adjustment of snow loads to 100 m elevation above mean sea level is required by the Irish Standard *I.S. EN 1991-1-3:2003&AC:2009&A1:2015 Eurocode 1 – Actions on structures – Part 1-3: General actions – Snow loads* (National Standards Authority of Ireland, 2015a) and the *National Annex plus Amendment NA+A2:2020 to I.S. EN 1991-1-3:2003&A1:2015. Irish National Annex (Informative) to Eurocode 1 – Actions on structures – Part 1-3: General actions – Snow loads* (National Standards Authority of Ireland, 2015b).

2.4 Gridding

In order to produce a map based on a limited number of point sources of observation (weather stations), the return values for each 50, 100 and 120-year return period of the highest maximum air temperature, lowest minimum air temperature, lowest 10 cm soil temperature and snow depths needed to be interpolated across the entirety of the grid to be mapped, a technique which is described as gridding. A $1\,\mathrm{km}^2$ grid covering the island of Ireland, which is based on the Irish National Grid (TM75, https://epsg.io/29903-1956, last access: 21 September 2022), was employed in the mapping.

The interpolation of return values across all grid points is executed in two steps. First, a linear regression of the return values to be interpolated (e.g. the return values of the 50-year return period of the highest maximum air temperature) versus geographical variables of the weather stations is performed. These geographical variables include the stations' position (easting, northing), 25 km exposure to the sea (the proportion of land within a 25 km radius of a grid point which is the sea), distance from the sea, and elevation for soil temperature where it has not previously been accounted for (Walsh, 2017). The radius from the sea is employed to model coastal effects and the 25 km is the best fitting value to model the station's observations.

In the case of the highest maximum air temperature, lowest minimum air temperature and lowest 10 cm soil temperature, only easting, northing and the 25 km exposure to the sea were found to be useful predictive variables. The 25 km exposure to the sea had a Pearson R^2 correlation > 0.3 for the highest maximum air temperature and the lowest minimum air temperature and of ≥ 0.25 for the lowest 10 cm soil temperature, which is greater than that found for other geographical variables. The linear regression for the highest maximum air temperature, lowest minimum air temperature and lowest 10 cm soil temperature is presented in Eq. (1):

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

where $\mathrm{TRP_p}$ is the predicted return value for temperature, $\mathrm{TRP_{mean}}$ is the mean of the return value for temperature across all stations, easting and northing are the coordinates of the grid point, 25kexp is the 25 km 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 50, 100 and 120-year 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.

For the snow loading, only easting and northing were found to have useful predictive power, Pearson R^2 correlation > 0.2, so they were the only geographical variables used to fit the snow loads data. The linear regression is represented in Eq. (2):

$$\mathrm{SLRP_p} = \mathrm{SLRP_{mean}} + a_1\mathrm{easting} + a_2\mathrm{northing} + \mathrm{residual} \quad (2)$$

where $\mathrm{SLRP_p}$ is the predicted return value for snow loading, $\mathrm{SLRP_{mean}}$ is the mean of the return value for snow loading across all stations, easting and northing are the coordinates of the grid point and $a_{1,2}$ are the values multiplying the geographical variables in order to get the best fit for the observation parameter – the return value of the snow loading for the 50, 100 and 120-year return period.

The second step interpolated 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 was applied to interpolate the residual values across the grid points.

The final grid point interpolation/prediction for the highest maximum air temperature, lowest minimum air temperature and the lowest 10 cm soil temperature is based on Eq. (3):

$$\mathrm{TRP_p} = \mathrm{TRP_{mean}} + a_1\mathrm{easting} + a_2\mathrm{northing} + a_3\mathrm{25kexp} + \mathrm{IDW(residual)} \quad (3)$$

For the snow loadings, the final grid point interpolation/prediction is presented in Eq. (4):

$$\mathrm{SLRP}_p = \mathrm{SLRP_{mean}} + a_1\mathrm{easting} + a_2\mathrm{northing} + \mathrm{IDW(residual)} \quad (4)$$

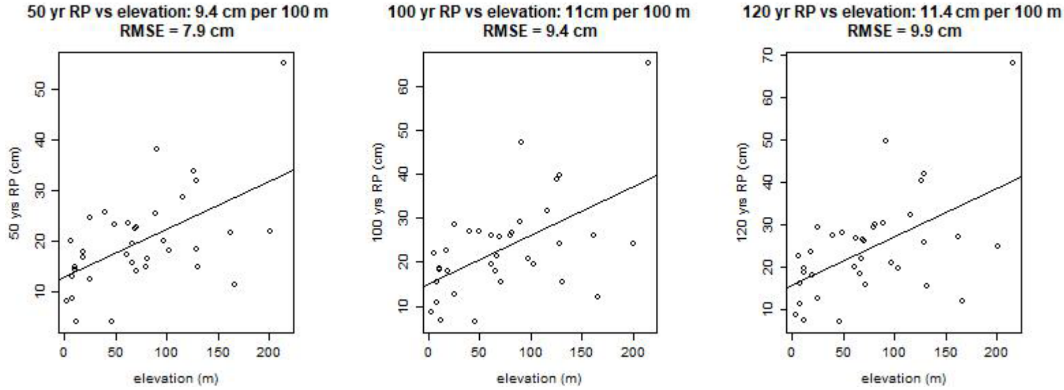

Figure 5. The root mean square error (RMSE) of the 100 m elevation adjustment of the snow depth values for the 50, 100 and 120-year return periods.

The easting and northing aim to capture spatial trends and the 25 km exposure to the sea has the purpose to model coastal effects (Walsh, 2017).

The outlined gridding methodology has been broadly implemented by Met Éireann, such as in producing official climate normals (e.g. Walsh, 2017).

3 Results and discussion

3.1 Return values of maximum and minimum air temperatures at mean sea level for 50, 100 and 120-year return periods

The new isothermal maps of return values of the highest maximum air temperature at mean sea level for 50, 100 and 120-year return periods are presented in Figs. 6–8. The isotherms of the return values of the 50-year return period range from 28 °C near coastal areas to 32 °C (Fig. 6). The geographical distribution of the return values of the 100-year return period exhibits values from 28 and 30 °C near coastal areas and the isothermal range from 32 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 (Fig. 7). The isotherms of the return values of the 120-year return period range from 28 to 30 °C near coastal areas and the range from 32 to 34 °C covers several counties. The highest isotherm value of 34 °C includes parts of the midlands (Fig. 8).

The new isothermal maps of return values of the lowest minimum air temperature at mean sea level for 50, 100 and 120-year return periods are shown in Figs. 9–11. The geographical distribution of the isotherms of the return values of the 50-year return period ranges from −6 °C in the extreme of the southern coastal areas to −14 °C. The isotherms of −10 and −12 °C are spread among a range of northern, western, southern, midlands and eastern counties (Fig. 9). The isotherms of the return values of the 100-year return period range from the highest value of −6 °C displayed in

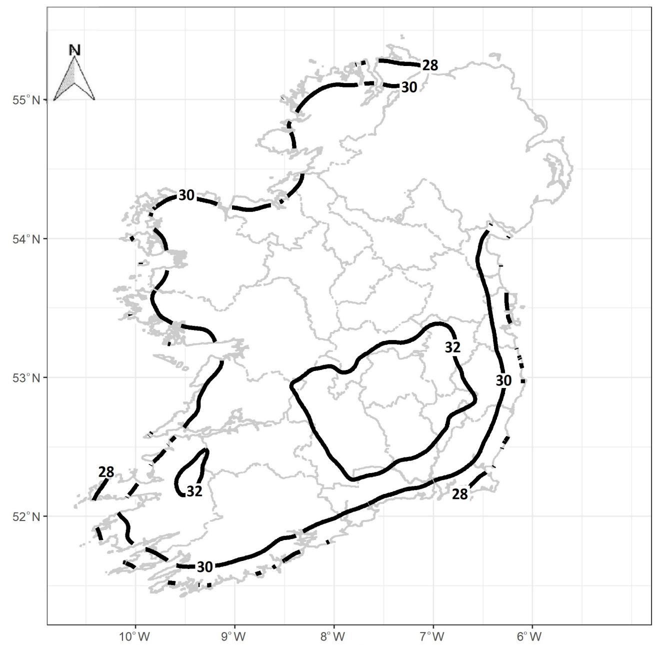

Figure 6. Isotherms of highest maximum air temperature (°C) at mean sea level in Ireland for a 50-year return period.

the extreme southwest and southeast coastal areas to the extreme lowest isotherm of −16 °C is distributed across various counties (Fig. 10). The distribution of the isotherms of the return values of the 120-year return period ranges range from −6 °C in the extreme coastal areas of the southern counties to −18 °C, which covers parts of the midlands (Fig. 11).

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 new isothermal maps compared to previously published maps (British Standards Institution, 1978, 2007; National Standards Authority of Ireland, 2008). Specifically, the new

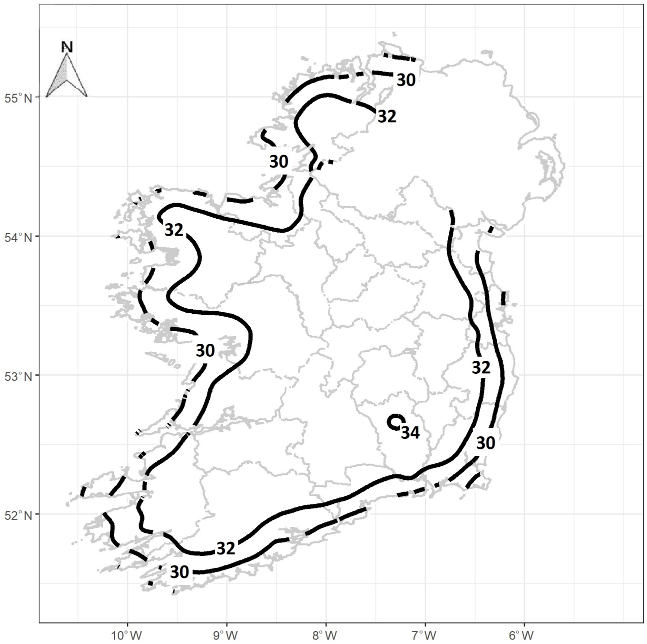

Figure 7. Isotherms of highest maximum air temperature (°C) at mean sea level in Ireland for a 100-year return period.

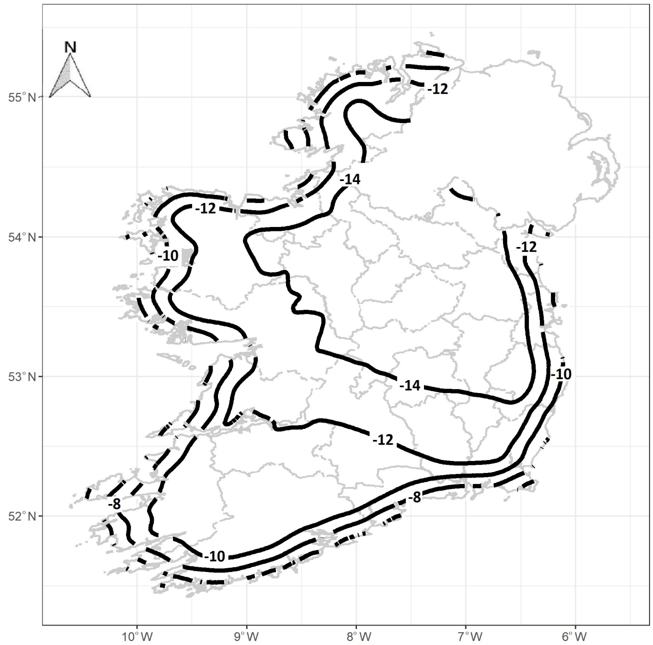

Figure 9. Isotherms of lowest minimum air temperature (°C) at mean sea level in Ireland for a 50-year return period.

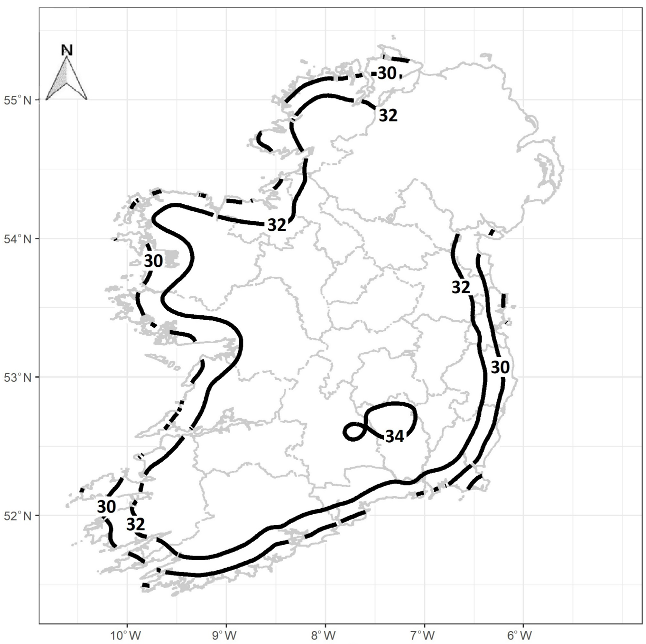

Figure 8. Isotherms of highest maximum air temperature (°C) at mean sea level in Ireland for a 120-year return period.

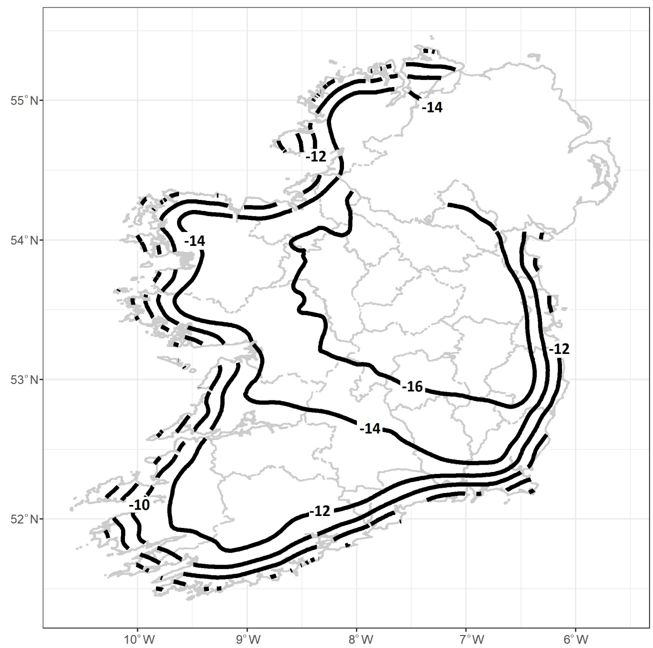

Figure 10. Isotherms of lowest minimum air temperature (°C) at mean sea level in Ireland for a 100-year return period.

extreme isotherms are 32 °C for the maximum air temperature and −14 °C for the minimum air temperature, whereas the processor maps presented 30 °C and −16 °C, respectively (National Standards Authority of Ireland, 2008). These results agree with the IPCC (2021) and the climate projections for Ireland (Nolan and Flanagan, 2020). The sixth assessment report of the Intergovernmental Panel on Climate Change projects an increase in intensity and frequency of hot temperature extremes, which are defined as daily maximum air temperatures over land that were exceeded on average as

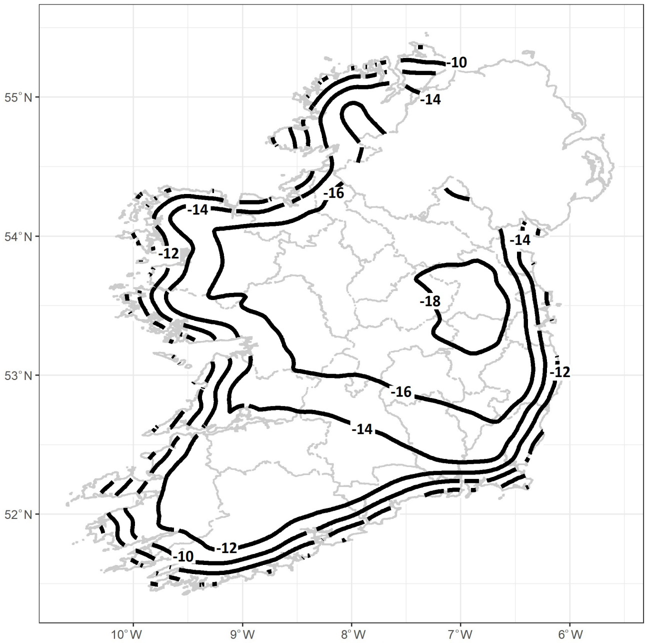

Figure 11. Isotherms of lowest minimum air temperature (°C) at mean sea level in Ireland for a 120-year return period.

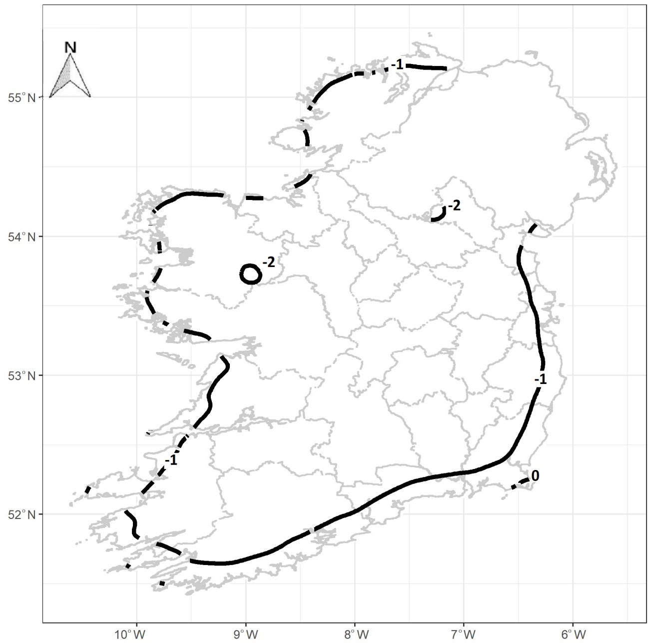

Figure 12. Isotherms of the lowest 10 cm soil temperature (°C) for a 50-year return period in Ireland.

10 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 to 1.6 °C in the RCP4.5 scenario and from 1.4 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 to 1.8 °C in the RCP4.5 scenario and from 1.2 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 isothermal maps of return values of the lowest minimum air temperature for 50, 100 and 120-year return periods produced here for Ireland represent the likely worst-case scenario, conservative and safe estimates of future Irish minimum temperatures. Yet higher maximum air temperatures may occur.

3.2 Return values of the lowest 10 cm soil temperature for 50, 100 and 120-year return periods

The isothermal maps of return values of the lowest 10 cm soil temperature for 50, 100 and 120-year return periods are provided in Figs. 12–14. The distribution of the return values of the 50-year return period exhibits values from 0 °C in areas in Cork, Kerry and Wexford to −2 °C in Mayo and Monaghan (Fig. 12). The isothermal map of the return values of the 100-year return period presents a range from 0 °C in the southwest and southeast to −2 °C, which comprises various counties (Fig. 13). The geographical distribution of the return values of the 120-year return period also displays values ranging from 0 to -2 °C, although the −2 °C isotherm covers a wider area (Fig. 14). In the current context of climate warming (Nolan and Flanagan, 2020; IPCC, 2021), the produced maps represent the worst-case scenario. There are no previous maps for Ireland available to compare results.

3.3 Return values of snow loadings at 100 m above mean sea level for 50, 100 and 120-year return periods

The maps of return values of snow depth loadings at 100 m above mean sea level for 50, 100 and 120-year return periods are presented in Figs. 15–17. The geographical distribution of the return values of the 50-year return period presents four classes spread North-East to South-West: < 0.3, 0.3–0.4, 0.4–0.5 and 0.5–0.6 kN m^{-2} (Fig. 15). The lowest class, < 0.3 kN m^{-2}, is displayed in a small area in the southwest. The highest class of 0.5–0.6 kN m^{-2} is distributed in parts of Cavan, Donegal, Dublin, Louth, Meath and Monaghan. The return values of the 100-year return period are spread across four classes ranging from the lowest at 0.3–0.4 kN m^{-2} to the highest at 0.6–0.7 kN m^{-2} (Fig. 16). The 0.3–0.4 kN m^{-2} class covers parts of the southwest. The highest class of 0.6–0.7 kN m^{-2} is distributed in parts of Donegal in the northwest and in the east in Louth and parts of Cavan, Meath and Monaghan in the midlands and Dublin. The geographical distribution of the return values of the 120-year return period

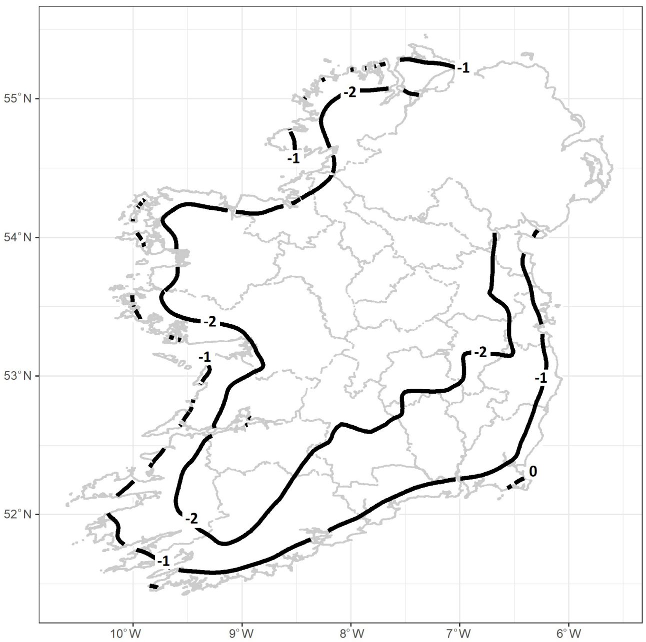

Figure 13. Isotherms of the lowest 10 cm soil temperature (°C) for a 100-year return period in Ireland.

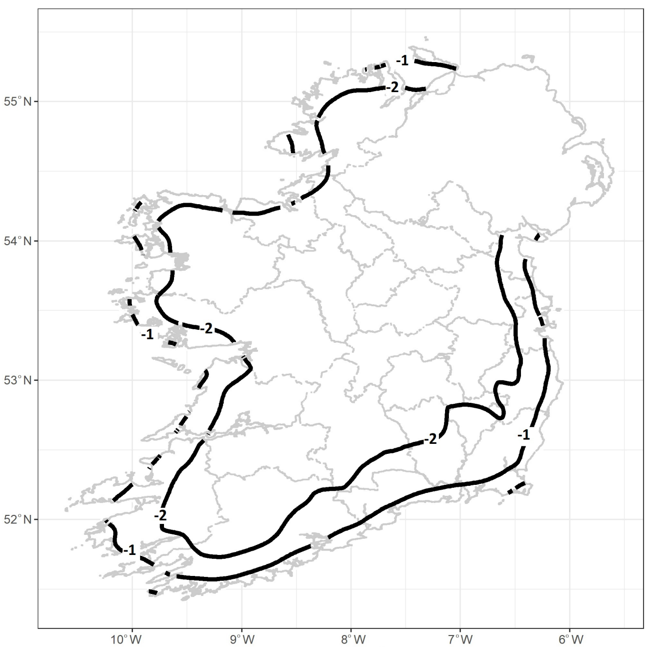

Figure 14. Isotherms of the lowest 10 cm soil temperature (°C) for a 120-year return period in Ireland.

has five classes ranging from the lowest at 0.3–0.4 $kN\,m^{-2}$ to the highest at 0.7–0.8 $kN\,m^{-2}$ (Fig. 17). The 0.3–0.4 $kN\,m^{-2}$ class covers parts in the southwest, whereas the highest class of 0.7–0.8 $kN\,m^{-2}$ only spans parts of Donegal in the northwest and Louth in the east.

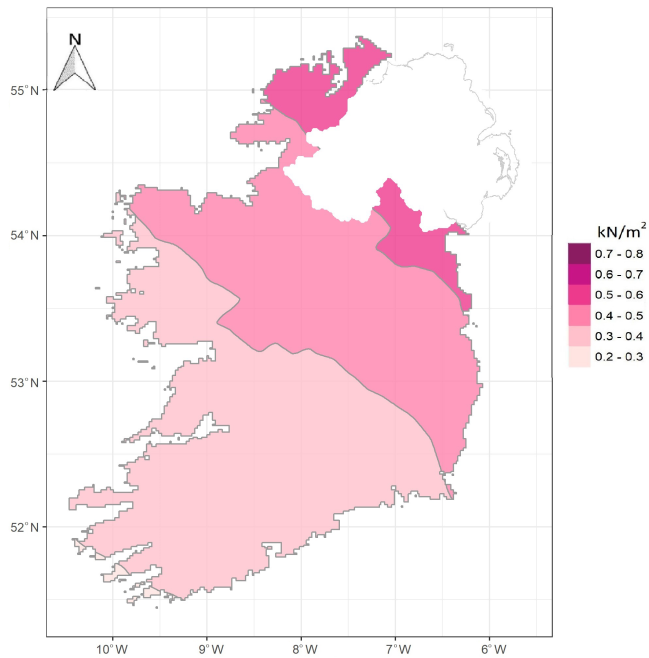

Figure 15. Return values of snow loadings at 100 m above mean sea level in Ireland for a 50-year return period.

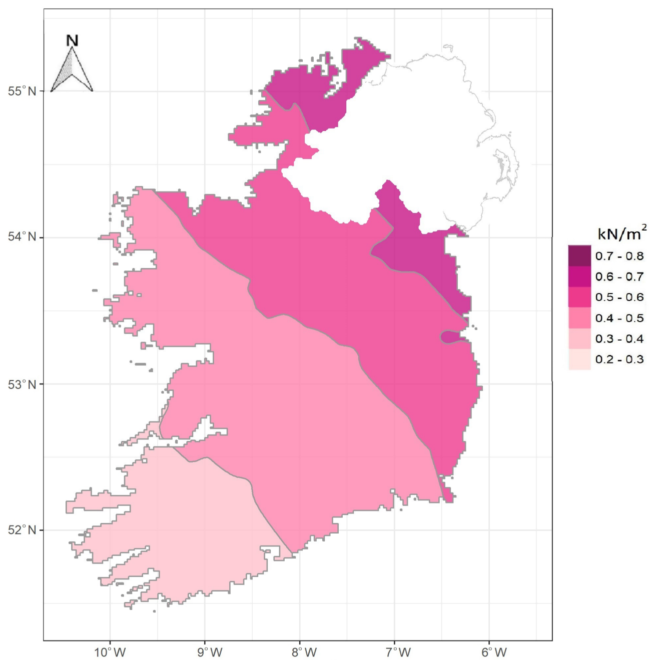

Figure 16. Return values of snow loadings at 100 m above mean sea level in Ireland for a 100-year return period.

The classes of return values of snow loadings for the 50, 100 and 120-year return periods have a decreasing geographical distribution from the North-East to South-West. Specifically, the occurrence of snow tends to increase with distance from the west and south coasts, and snow lying is more often

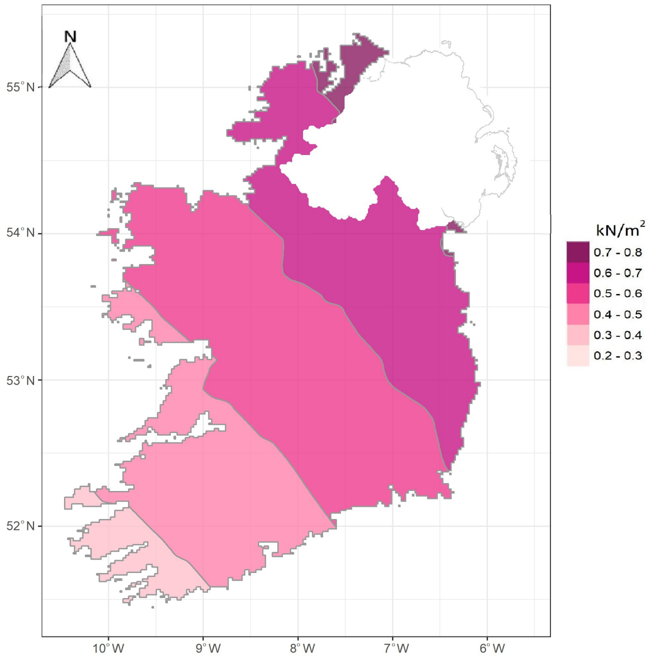

Figure 17. Return values of snow loadings at 100 m above mean sea level in Ireland for a 120-years return period.

recorded in the midlands, eastern and northern areas than in the western part of the country due to an easterly polar continental airflow, where the jet stream has been pushed south.

Discrepancies were identified in the previous 50-year return period map produced for Ireland (Keegan, 2010; Government of Ireland, 2012; National Standards Authority of Ireland, 2015b) with the map produced by the British Standards Institution (2007) for the United Kingdom and Ireland. Discrepancies in the map for Ireland refer to an area of 0.7 kN m^{-2} in the Dublin/Wicklow area, higher snow loadings of 0.6 kN m^{-2} in the Monaghan region and the Southern region represented as 0.4 kN m^{-2} (Keegan, 2010; Government of Ireland, 2012; National Standards Authority of Ireland, 2015b). The values of the 50-year return period map present four classes spread North-East to South-West: < 0.3, 0.3–0.4, 0.4–0.5 and 0.5–0.6 kN m^{-2}, whereas the previous map had four classes distributed as follows: 0.4, 0.5, 0.6 and 0.7 kN m^{-2} (Keegan, 2010; Government of Ireland, 2012; National Standards Authority of Ireland, 2015b). The map of return values of the 50-year return period produced in this research has a more representative geographical distribution of snow loads than the preceding map (Keegan, 2010; Government of Ireland, 2012; National Standards Authority of Ireland, 2015b) and presents more agreement with the previous map published for the UK and Ireland (British Standards Institution, 2007). The rationale for the new map presented here being more accurate than the preceding map (Keegan, 2010; Government of Ireland, 2012; National Standards Authority of Ireland, 2015b) is outlined as follows:

– Employment of a denser network of stations, including locations in Northern Ireland, to avoid discrepancies of outputs in the border, with longer lengths and comprising a few stations with hourly data in addition to the daily snow depths.

– The application of a more accurate correction of +3 cm to account for a possible discrepancy between the once-daily recorded snow depth and the actual maximum snow depth over that particular day which can occur at any time over 24 h.

– The gridding methodology employed in R software to produce the maps is more robust than the spline interpolation employed in ArcGIS software to generate the previous map of snow loads.

There is a discussion in the scientific literature about contrasting responses between mean and extreme snowfall to climate change (Räisänen, 2008; O'Gorman, 2014; Fontrodona Bach et al., 2018). The new maps of return values of snow loadings for 50, 100 and 120-year return periods presented here represent the worst-case scenario in the current context of climate warming. The IPCC (2021) projects a decrease in snowfall events, which would be larger at 2.0 °C warming or above in comparison to a warming of 1.5 °C in the global mean air temperature. In addition, the annual snowfall in Ireland is projected to decrease by the middle of the 21st century when considering the RCP4.5 (mean value 52 %) and RCP8.5 (mean value 63 %) scenarios, with the largest decrease in the low-lying regions (Nolan and Flanagan, 2020). Averaged over Ireland, the decreases in snowfall are 51 % (RCP4.5) and 60 % (RCP8.5) (Nolan and Flanagan, 2020).

4 Conclusion

Isothermal maps of return values of the highest maximum and lowest minimum air temperatures for return periods of 50, 100 and 120-year, 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) have been produced for Ireland. These maps supersede the previous maps published for a 50-year return period (British Standards Institution, 2007; National Standards Authority of Ireland, 2008) and regulators should adopt them.

For the first time, isothermal maps of return values of the lowest 10 cm soil temperature for 50, 100 and 120-year return periods based on the generalised extreme value distribution (Coles, 2001; Gilleland and Katz, 2016) have been produced for Ireland.

Maps of return values of snow loadings at 100 m above mean sea level for 50, 100, and 120-year return periods based on the Generalised Pareto distribution (e.g. Coles, 2001) and National Standards Authority of Ireland (2015a) have been published for Ireland. These new maps are more representative and supersede the previous map of return values of snow loadings at 100 m above mean sea level for a 50-year return period (Keegan, 2010; Government of Ireland, 2012; National Standards Authority of Ireland, 2015b).

It is expected that the comprehensive explanation of the methodology and the rationale for the new maps being more accurate than the preceding maps will assist regulators in adopting these new maps in their own jurisdictions. The new maps will support the structural design of buildings and civil engineering works to enhance resilience in support of climate change adaptation and will also be of interest to a diversity of sectors and planners in Ireland.

The methodology employed here can be applied by other countries in Europe that must employ the same Eurocodes (CEN, 2003; British Standards Institution, 2007; International Organization for Standardization, 2013).

The motivation of this research was to renew existing return value estimates. Future work shall employ climate projections in the assessment of the effects of climate change on the estimates.

Data availability. The csv files with information on gridded data for 1 km and the shapefiles of all maps will be available open-access via the National Framework for Climate Services and the Met Éireann website (https://www.met.ie/, Met Éireann, 2023). Further enquiries to data access can be made to Met Éireann's Climate Enquiries at enquiries@met.ie.

Author contributions. CM calculated the return values for maximum, minimum and soil temperatures and BC for snow loadings. CM produced the location station maps. BC wrote the code and produced the gridded maps. CM wrote the manuscript, which was revised by BC.

Competing interests. The contact author has declared that neither of the authors has any competing interests.

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