Received: 11 October 2019 | Revised: 15 April 2020 | Accepted: 19 April 2020

DOI: 10.1002/gdj3.92

DATA PAPER

Geoscience Data Journal RMetS WILEY

Reconstruction of a long-term historical daily maximum and minimum air temperature network dataset for Ireland (1831-1968)

Carla Mateus[1] | **Aaron Potito**[1] | **Mary Curley**[2]

[1]Discipline of Geography and Ryan Institute, National University of Ireland Galway, Galway, Ireland

[2]Met Éireann, Dublin, Ireland

Correspondence
Carla Mateus. Discipline of Geography, National University of Ireland Galway, Galway, Ireland.
Email: carla.ppmateus@gmail.com

Funding information
Dr Tony Ryan Research Scholarship, Ryan Institute Travel Bursary, Postgraduate Research Travel Bursary and the Discipline of Geography Travel Award from NUI Galway. Geographical Society of Ireland Postgraduate Travel Award from the Geographical Society of Ireland.

Abstract

The extension of spatial and temporal coverage of digital daily maximum and minimum air temperature observations is indispensable for a greater understanding of past climate variability. Long-term series are fundamental for the assessment of frequency, duration, intensity and geographical distribution of past extreme air temperature events at local and regional scales in Ireland. Raw daily observations from 12 long-term and 21 short-term maximum and minimum air temperature series in Ireland, extending from 1831 to 1968, were rescued from multiple archives. Detailed station metadata on instrumentation, site location, observation practices and observer's notes are included in the dataset. Over 970,000 daily maximum and minimum air temperature observations were transcribed from handwritten meteorological registers, publications, newspapers and the *Daily Weather Report*. The data rescue strategies, sources for data and metadata rescue, and methodologies for double keying are discussed. The Ireland Long-term Maximum and Minimum Air Temperature dataset (ILMMT) format for daily air temperature and metadata and organization is reviewed. The ILMMT dataset comprises raw observations and detailed station metadata, so data users can apply their selected quality control and homogenization approaches.

KEYWORDS

climate data rescue, Irish temperature, long-term instrumental series, pre-1850 instrumental series, station metadata

Dataset

Identifier: http://hdl.handle.net/2262/92442

Creator: Mateus, Carla; Potito, Aaron; Curley, Mary.

Title: Ireland Long-term Maximum and Minimum Air Temperature dataset (ILMMT)

Publisher: Met Éireann

Publication Year: 2020

Resource Type: Dataset and metadata

Version: 1.0

1 | INTRODUCTION

Long-term instrumental daily air temperature datasets are crucial to a better assessment of past climate variability and trends, to evaluate extreme air temperature events and to support validation of palaeoclimate reconstructions from proxies or documentary sources (World Meteorological Organization, 2016). Instrumental series are important for the generation of climate products, such as long-term gridded datasets. In addition, long-term series are fundamental for climate monitoring, climate change detection and attribution, climate modelling and to assist climate action and adaption policies. Thus, long-term instrumental series are required to fill key gaps in climate research at a global and national scale. A dataset of geographically well-distributed long-term daily air temperature series dating back to the early 19th century is paramount for understanding Irish climate variability and extreme air temperature events at local and regional scales, as previous research has focused on the period dating back to 1940s (McElwain and Sweeney, 2007).

Climate data and metadata rescue are essential to preserve historical instrumental observations that are in danger of being lost due to the vulnerability of original paper datasources (World Meteorological Organization, 2016). Rescue of instrumental records allows more complete climate datasets and improves data availability for researchers, meteorological institutes, stakeholders and policy-makers. Climate data rescue is necessary in Ireland as instrumental meteorological observations date back to the 17th century (Shields, 1983) and continuous readings of daily maximum and minimum air temperature started in the early to mid-19th century.

Multiple climate data rescue initiatives have been undertaken, such as the International Surface Temperature Initiative (Thorne *et al.*, 2011), I-DARE (International Data Rescue Portal, https://www.idare-portal.org/content/dare) or The International Atmospheric Circulation Reconstructions over the Earth (ACRE) (Allan *et al.*, 2011). On the Island of Ireland, monthly (Noone *et al.*, 2016; Murphy *et al.*, 2018) and daily (Ryan *et al.*, 2018) rainfall series were rescued. Data rescue of climate elements observed at Armagh Observatory were carried out, including daily maximum and minimum air temperature observations (Butler *et al.*, 2005). Historical maximum and minimum air temperature series registered at Markree were previously rescued although not distributed as open access (McKeown *et al.*, 2012). Prior to this project, most of the daily air temperature records in Ireland preceding the 1960s had not been digitized and largely existed as fragile manuscripts and scattered publications stored in various archives across Ireland and abroad. The lack of open access of meteorological observations in a digital format constitutes an obstacle to climate data analysis and research.

This research fulfils data and comprehensive metadata rescue from 12 long-term instrumental daily maximum and minimum air temperature series since the early and mid-19th century to 1968 in Ireland. To facilitate future quality control and homogenization procedures, 21 short-term series recorded in the mid-19th century were also rescued. Early instrumental short-term series are crucial to assess rare weather events (Brönnimann *et al.*, 2019). Despite the existence of other historical observed climate elements in the examined datasources, only the daily maximum and minimum air temperature observations were rescued under a funding-awarded research project for the assessment of past extreme air temperature events in Ireland. A key aim of this research is to make the digital raw series of daily maximum and minimum air temperature observations and related detailed metadata available as open access through the Ireland Long-term Maximum and Minimum Air Temperature dataset (ILMMT) to the wider scientific community, stakeholders and the public. The application of quality control and homogenization procedures on the rescued data is out of the scope of this article.

2 | DATA AND METADATA

2.1 | Long and short-term daily maximum and minimum air temperature series

Early meteorological observations were geographical well-dispersed through Ireland (Figure 1, Tables 1 and 2). Observations were initially undertaken by a variety of observers, such as physicians interested in the relationship between weather and mortality (e.g. John William Moore at Fitzwilliam Square Dublin), scientific societies like the Royal Dublin Society or the Royal Irish Academy, Royal Engineers at the Ordnance Survey Office in Phoenix Park Dublin, Professors at Trinity College Dublin and National University of Ireland Galway (NUI Galway), astronomical observatories, for instance Markree and Birr, and other amateurs. In Ireland and internationally, well-educated amateur observers were responsible for the generation of early instrumental meteorological observations prior the creation of the National Meteorological Services (e.g. Ashcroft *et al.*, 2014; Brönnimann *et al.*, 2019). The 12 long-term series included in the ILMMT dataset comprises a network of telegraphic reporting stations at Malin Head, Blacksod Point, Belmullet, Valentia, Roches Point and Birr, and of climatological stations at Birr, Botanic Gardens Dublin, Fitzwilliam Square Dublin, Killarney, Markree, Phoenix Park Dublin and Trinity College Dublin (Figure 1) which were under the guidance of the British Meteorological Office and since 1936 under the authority of the Irish Meteorological Service. The majority of stations were relocated at times and are currently

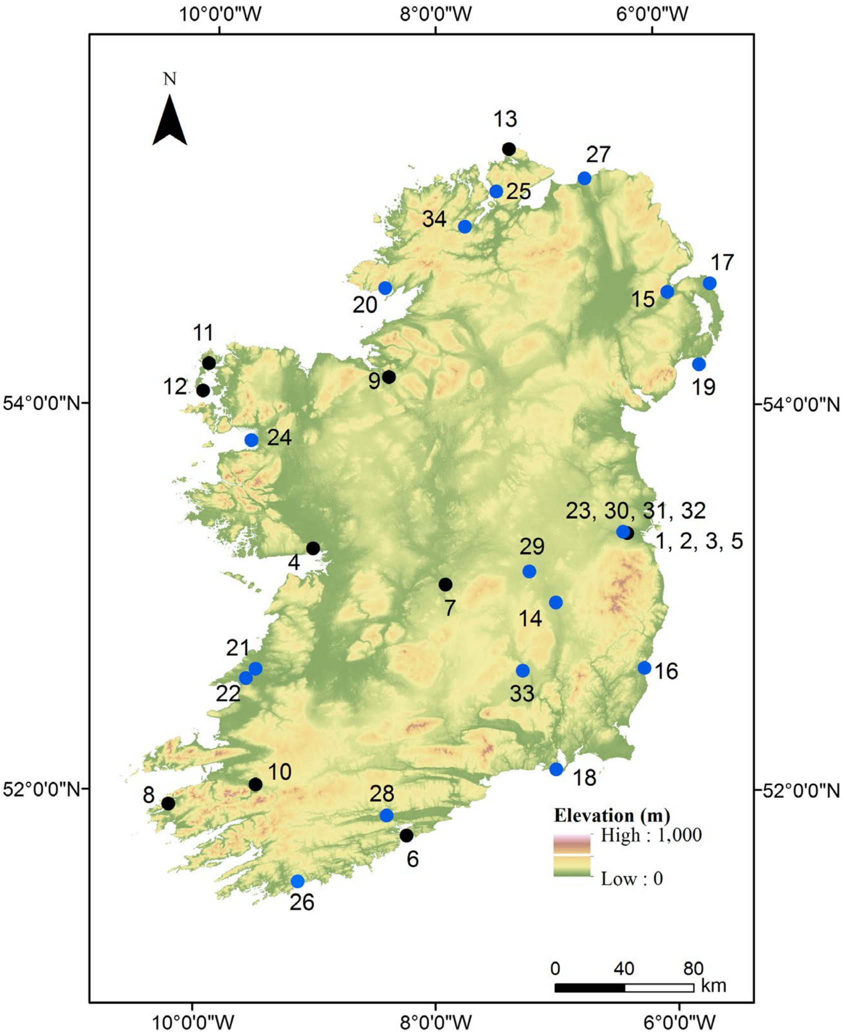

FIGURE 1 Location and length of the rescued daily maximum and minimum air temperature series. Long-term series (black): (1) – Phoenix Park Dublin, (2) – Trinity College Dublin, (3) – Botanic Gardens Dublin, (4) – NUI Galway, (5) – Fitzwilliam Square Dublin, (6) – Roches Point, (7) – Birr, (8) – Valentia, (9) – Markree, (10) – Killarney, (11) – Belmullet, (12) – Blacksod Point, (13) – Malin Head. Short-term series (blue): (14) – Athy, (15) – Belfast, (16) – Courtown, (17) – Donaghadee, (18) – Dunmore, (19) – Killough, (20) – Killybegs, (21) – Kilrush, (22) – Scattery, (23) – Royal Dublin Observatory, (24) – Innisgort Island, (25) – Buncrana, (26) – Castletownsend, (27) – Portrush, (28) – Blackrock, (29) – Portarlington, (30) – Royal College of Surgeons Dublin, (31) – Grafton Street Dublin, (32) – Commercial Buildings Dublin, (33) – Kilkenny, (34) – Glendooen

functioning as part of a network of automatic stations, with a few exceptions: Fitzwilliam Square Dublin where records ceased in 1937; Trinity College Dublin where readings terminated in 1971 and were replaced by Merrion Square Dublin; Killarney which closed in 1933 and re-opened in 1966; NUI Galway which ceased to register in 2011, and Birr which was replaced by Gurteen in 2009. Valentia Observatory was recognized as a Centennial Observing Station by the World Meteorological Organization in May 2017, an acknowledgement for long-term quality instrumental series which are crucial to climate research (https://public.wmo.int/en/our-mandate/what-we-do/observations/centennial-observing-stations).

The majority of short-term series in the mid-19th century (Figure 1, Table 2) were under the authority of the Royal Irish Academy (Lloyd, 1853), while the remaining observations were conducted by volunteers (Kilkenny, Blackrock and Glendooen), instrument makers (Grafton Street Dublin), physicians (Portarlington), professors (Royal College of Surgeons Dublin) or clerks (Dublin Commercial Buildings).

Detailed station histories and metadata on location, instrumental and observing practices are available in each station file which accompanies the dataset.

2.2 | Sources of data rescue

Often long-term observations are available in diverse datasources which are preserved by multiple data-holders. Data included in the ILMMT dataset were rescued from the Met Éireann archives which holds catalogued handwritten meteorological registers containing long-term daily maximum and minimum air temperature series recorded across Ireland dating back to 1855 (Keane *et al.*, 2017). Thermometer observations were also rescued from archives at NUI Galway, National Library of Ireland, Royal Irish Academy, National Botanic Gardens, Met Office, Royal Dublin Society, Trinity College Dublin and online resources (British Newspaper Archive, JSTOR, Hathi Trust Digital Library, Google Books and Digital Library and Archive of the Met Office) to assure completeness of the long-term series (Tables 1 and 2). The majority of instrumental records were rescued from the archive at Met Éireann (75.9%). The remaining observations were rescued from archives at NUI Galway (5.9%), National Library of Ireland (5.2%), online sources (which comprise *Daily Weather Reports*, newspapers, proceedings and transactions, 5.1%), National Botanic Gardens Dublin (3.4%),

TABLE 1 Station data rescue sources for long-term series. Station numbers correspond to the map in Figure 1. Acronyms for data-holders: National Library of Ireland (NLI), Met Éireann (ME), Meteorological Office (MO), National Botanic Gardens of Ireland (NBG), NUI Galway special collections (NUI Galway) and Royal Irish Academy (RIA)

Station	Years	Type of datasource	Data-holder/references
(1) Phoenix Park Dublin	1831-1852	Publication	Cameron (1856)
	1853-1855	Manuscripts	NLI (Larcom Papers, Ms. 7,548, 7,602)
	1855-1959	Manuscripts	MÉ (MÉ/MO/1)
(2) Trinity College Dublin	1840-1843	Publication	Lloyd (1865)
	1844-1850	Publication	Lloyd (1869)
	1851	Manuscripts	RIA (24L42, 24L43, 24L50, 12M16)
	1855-1856	Newspaper	*Allnut's Irish Land Schedule*
	1904-1959	Manuscripts	MÉ (MÉ/MO/16/3- MÉ/MO/16/12)
(3) Botanic Gardens Glasnevin - Dublin	1834	Manuscripts	NLI (Ms. 4,619)
	1848-1855	Publication	Royal Dublin Society (1849, 1850, 1852-1856)
	1856-1867	Publication	Royal Dublin Society (1858, 1860, 1862, 1866, 1870)
	1867-1957	Manuscripts	NBG (not catalogued)
	1911-1958	Manuscripts	MÉ (MÉ/MO/17/2 - MÉ/MO/17/9)
	1882-1952	Manuscripts	NLI (Ms. 4357-4373 and 2,589 – 2,595)
(4) NUI Galway	1851-1852	Manuscripts	RIA (12M16, 24L50)
	1861-1952	Manuscripts	NUI Galway (not catalogued)
(5) Fitzwilliam Square Dublin	1871-1937	Manuscripts	MÉ (MÉ/MO/4)
(6) Roches Point	1872-1956	Manuscripts and *Daily Weather Report* (DWR)	MÉ (MÉ/MO/6) MO
(7) Birr	1872-1954	Manuscripts and DWR	(MÉ) (MÉ/MO/2/1, MÉ/MO/2 MO)
(8) Valentia Observatory	1850-1851	Manuscripts	RIA (24L46, 24L50, 12M16)
	1872-1943	Manuscripts and DWR	MÉ (MÉ/MO/8) MO
(9) Markree	1850-1852	Manuscripts	RIA (12M16, 24L50)
	1855-1856	Newspaper	*Allnut's Irish Land Schedule*
	1874-1968	Manuscripts	MÉ (MÉ/MO/3)
(10) Killarney	1881-1898	Manuscripts	MO (ARCHIVE T22.C1-D4 and ARCHIVE T20.A1-B3)
	1920-1933	Manuscripts	MÉ (MÉ/MO/9/6)
(11) Belmullet	1884-1899	Manuscripts	MÉ (MÉ/MO/5)
	1956	DWR	MO
(12) Blacksod Point	1899-1956	Manuscripts and DWR	MÉ (MÉ/MO/5) MO
(13) Malin Head	1885-1955	Manuscripts and DWR	MÉ (MÉ/MO/7) MO

National Meteorological Archive at the Met Office (2.0%), Royal Irish Academy (1.6%), Trinity College Dublin (0.75%) and Armagh Observatory (0.2%).

Despite the desirable data recue from an exclusive datasource such as the original handwritten meteorological logs, sometimes these sources are not traceable. Multiple datasources were utilized to preserve the entire long-term series where possible. The handwritten meteorological registers were the primary datasource selected (Figure 2). When the original manuscripts were missing, the data were rescued from the *Daily Weather Report* (available online at the Digital Library and Archive of the Met Office, https://digital.nmla.metoffice.gov.uk/SO_86058de1-8d55-4bc5-8305-5698d0bd7e13/); newspapers in the British Newspaper Archive (https://www.britishnewspaperarchive.co.uk/), and scientific literature which comprises monographs, transactions and proceedings. Two datasources may be available due to duplicated instruments but with different times of thermometer readings

Station	Years	Datasource	Data-holder/references
(14) Athy	1850-1852	Manuscripts	RIA (12M16)
(15) Belfast	1851-1852	Manuscripts	RIA (12M16)
(16) Courtown	1850-1852	Manuscripts	RIA (12M16)
(17) Donaghadee	1850-1852	Manuscripts	RIA (12M16)
(18) Dunmore	1850-1851	Manuscripts	RIA (12M16)
(19) Killough	1851-1852, 1854	Manuscripts	RIA (12M16)
(20) Killybegs	1850-1851	Manuscripts	RIA (12M16)
(21) Kilrush	1850-1851	Manuscripts	RIA (12M16)
(22) Scattery (Inis Cathaigh)	1850-1852	Manuscripts	RIA (12M16)
(23) Royal Dublin Observatory (Dunsink)	1851	Manuscripts	RIA (12M16)
(24) Innisgort Island	1851-1852	Manuscripts	RIA (24L50, 12M16)
(25) Buncrana	1850-1851	Manuscripts	RIA (24L45, 24L50, 12M16)
(26) Castletownsend	1850-1851	Manuscripts	RIA (12M16)
(27) Portrush	1850-1852	Manuscripts	RIA (24L47, 24L50, 12M16)
(28) Blackrock	1881-1890	Manuscripts	MO (MET/2/1/2/3/489)
(29) Portarlington	1845-1864	Newspaper	*Dublin Medical Press*
	1851-1852	Manuscripts	RIA (12M16)
(30) Royal College of Surgeons Dublin	1841-1857	Newspaper	*Dublin Medical Press*
(31) Grafton Street Dublin	1843-1849	*Transactions of the Royal Irish Academy*	Yeates (1844, 1847a, b, c, 1850a, b, c)
(32) Commercial Buildings Dublin	1850-1858	Newspaper	*Dublin Mercantile Advertiser, and Weekly Price Current*
(33) Kilkenny	1862-1864	Newspaper	*Kilkenny Journal, and Leinster Commercial and Literary Advertiser*
(34) Glendooen	1865-1870	Manuscripts	AO (M 32)

TABLE 2 Station data rescue sources for short-term series. Station numbers correspond to the map in Figure 1. Acronyms for data-holders: Armagh Observatory (AO), Meteorological Office (MO), Royal Irish Academy (RIA)

and re-settings. For instance, there were two sets of manuscripts registered at Birr in the period January 1880–March 1911 at the telegraphic reporting station (morning readings) and at the second-order station (evening readings) which were rescued. Observations taken at different observing times, screen types and locations were rescued. The primary source for data rescue consisted of manuscripts (92.2%), followed by monographs (2.7%), newspapers (2.7%), transactions and proceedings (1.8%) and the *Daily Weather Report* (0.6%).

2.3 | Sources of metadata rescue

Detailed and complete station metadata are crucial to achieve high-quality daily instrumental time-series through quality control and homogenization procedures (Aguilar *et al.*, 2003; Venema *et al.*, 2018) and are thus necessary to data users. Important metadata for air temperature observations include the following: location and relocation of the meteorological station, station surroundings and type of land use and cover, type of thermometer screen, height of thermometer screen above ground, thermometer exposure and position, types of thermometers, time of thermometer setting and observation, number of thermometer observations per day, meteorological observer and instrument maintenance and replacement. Additional metadata comprise observer's comments, explanations on missing observations, thermometer calibration errors, standard time of observation (e.g. Greenwich Mean Time or Local Mean Time) and type of station (e.g. private register, telegraphic or second order).

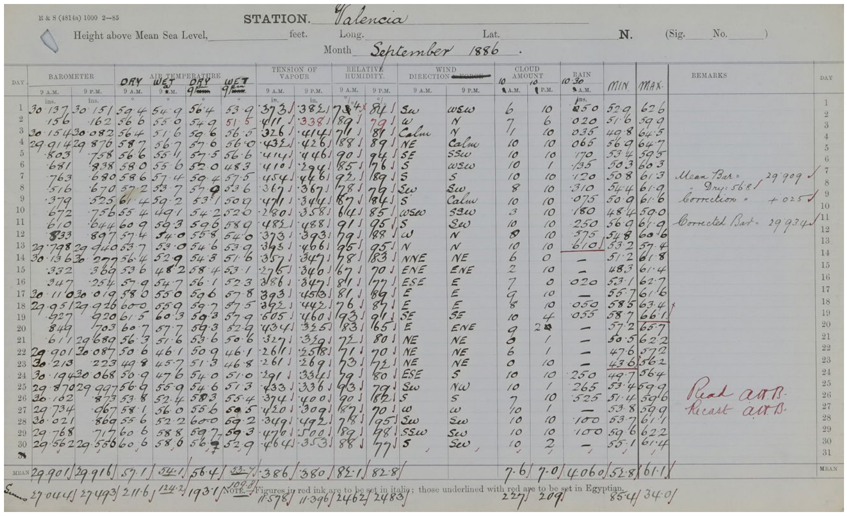

FIGURE 2 Handwritten meteorological record from September 1886 at Valentia Observatory which is preserved in the archive at Met Éireann

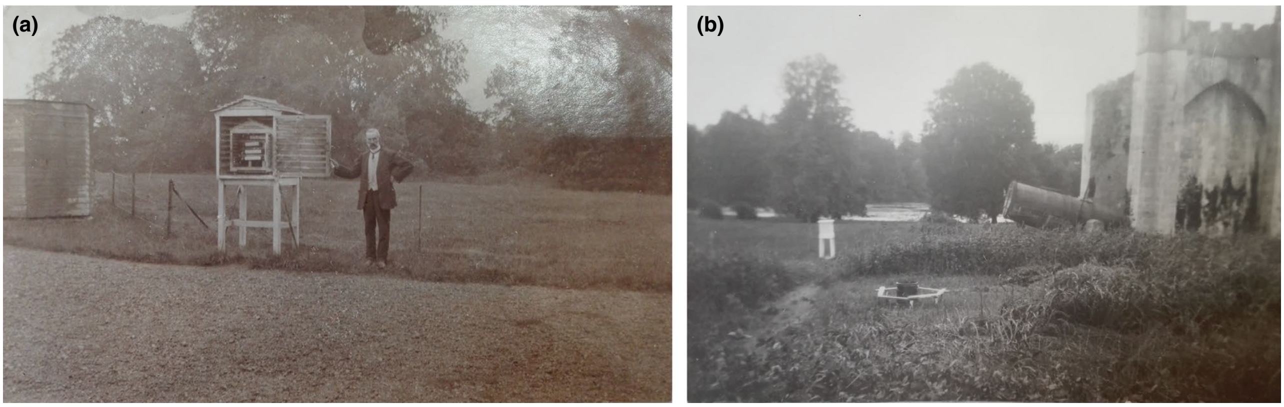

FIGURE 3 Thermometer exposure in 1911 (left) and in 1912 (right) at Birr
Source: National Meteorological Archive Met Office

Diverse sources were exploited to rescue detailed station metadata included in the ILMMT dataset. Notes in the original handwritten meteorological registers, publications, *Daily Weather Report* and newspapers were rescued. In addition, station inspection reports available as original manuscripts or as appendices in meteorological publications such as the annual *Report of the Meteorological Council to the Royal Society* (e.g. Meteorological Council, 1882) were utilized to rescue metadata. Station photographs taken through the time which can show possible changes in the location, type of thermometer screen, land use at station enclosure and surroundings (Figure 3) are furnished in the ILMMT dataset. Drawings when no station photographs are available for the early 19th century, for example Cameron (1856) of the thermometer screen at Phoenix Park Dublin, are furnished. Additionally, the ILMMT dataset comprises rescued metadata from publications by Institutions or Societies responsible for the supervision of the meteorological observations. For example Cameron (1856) furnishes information on location, instrumentation and observing practices by the Royal Engineers at Phoenix Park Dublin. Metadata in observers' publications on their meteorological observations were consulted to appraise early observation practices and instrumentation used such as by Wynne (1886) at Killarney. Observers' correspondences, including query forms from the Meteorological Office to the observers about the meteorological records which are important for assessing any instrumentation or observation errors, were rescued. Publications, for example Morley (1964), which contains a map on the location of the thermometer screen at Trinity College Dublin are also cited in the metadata files. Metadata printed in newspapers as for instance the *Dublin Evening Post* dating of 29th December 1849 on the Rutherford's self-registering minimum thermometer in use at the Commercial Buildings Dublin were also rescued.

3 | METHODOLOGY

3.1 | Data rescue strategy

The data rescue strategy followed the best climate data rescue practices outlined by the World Meteorological Organization (2016). The first step consisted of checking digital climate datasets such as the European Climate Assessment & Dataset

(ECA&D) (https://www.ecad.eu/) and Met Éireann digital database (https://www.met.ie/climate/available-data/historical-data) to determine the availability and completion of the long-term daily maximum and minimum air temperature series. Scanned publications and newspapers containing historical daily maximum and minimum air temperature observations and available in online resources (British Newspaper Archive, JSTOR, Hathi Trust Digital Library, Google Books and Digital Library and Archive of the Met Office) were examined. Contacts were established with diverse Archives holders of catalogued and non-catalogued climate data and metadata. The archives at Met Éireann, National Library of Ireland, National Botanic Gardens Dublin, Royal Irish Academy, Special Collections at NUI Galway, Royal Dublin Society, Trinity College Dublin and the National Archive of the Met Office were consulted for imaging the existing meteorological registers. Images of each page of the handwritten meteorological registers were carefully taken with a digital camera so as to ensure the legibility of the daily observations during manual keying. Station metadata sources were identified for rescue. Station folders comprising meteorological register images for each calendar year and for each station (with instructions and MS Excel templates) were organized for manual data keying. Finally, contacts were established to engage secondary school students as part of a service-learning programme, university students and citizen scientists in climate data keying.

3.2 | Keying procedures

Brönnimann *et al.* (2006) tested diverse methodologies of digitization of manuscript climate data through optical character recognition, speech recognition and manual entry, and concluded that manual key entry was the quickest digitization methodology which led to fewer transcribing errors. Ashcroft *et al.* (2018) also identify manual keying as the best climate digitization methodology after testing speech recognition and optical character recognition technologies. Issues with the legibility of the Irish handwritten meteorological returns included penmanship, faint ink or blurred registers, omission of points as decimal separations, shifts in the registers when the maximum air temperature was recorded in the morning but not entered to previous day, maximum air temperature readings registered by mistake into the minimum air temperature column or vice-versa, reversed values and existence of many corrections over previously written records. Manual key entry into MS Excel templates was the methodology chosen for a faster and low-cost digitization of the historical maximum and minimum thermometer observations.

Observations were keyed as they are written in the datasource following the standard data rescue practice advised by the World Meteorological Organization (2016). This methodology comprises the rescue of obvious errors such as daily maximum air temperature lower than minimum air temperature or outliers which must be examined during quality control procedures.

The daily minimum air temperature readings were keyed to the days on which they were read and registered in the datasource. The daily maximum air temperature observations were rescued to the same calendar day as they were written in the datasource when there was an indication in the manuscript that the observation taken in the morning has been entered to the preceding day on which the readings were made; there is no mention on the observing time or the observations were taken in the morning but there is no indication on the manuscript of the observations having been thrown back to the previous day. However, the daily maximum air temperature values were transcribed and attributed to the previous day if the observations were recorded in the morning and there is an indication in the meteorological return that values were not thrown back. This procedure refers to early instrumental data recorded at the telegraphic reporting stations and it is specified in each station metadata file. Handwritten corrections in the original manuscripts were accepted and digitized. These corrections include marks as red ink or pencil corrections (0.6% of rescued data), which were made to address thermometer index adjustments, observer's errors, comparison of observed air temperature values to neighbouring stations, comparison of the air temperature and dry bulb values, interpolation of non-recorded values or probable values, or reversed minimum and maximum air temperature values.

To reduce keying errors, the monthly air temperature average and sum generated in the MS Excel template were compared after keying the daily air temperature values for a single month with the monthly average and sum supplied in the majority of the datasources. In addition, a visual cross-checking was made between the keyed data and the original data-source to assure that there were no reversed values, any repetition or other observed climate element (e.g. minimum air temperature on grass or dry bulb thermometer). In cases of poor legibility of the handwritten meteorological registers, publications on the readings taken at stations of second order (e.g. Meteorological Office, 1880) and at the telegraphic reporting stations in the *Daily Weather Report* were consulted.

Metadata were keyed once into MS Excel station files by the first author. In situations of poor legibility, the second author was responsible for metadata transcription verification. Each rescued station metadata file was converted to a MS Excel file and included in the ILMMT dataset.

3.3 | Data transcription verification

Double keying is a necessary procedure to minimize transcribing errors and to fulfil data accuracy (World Meteorological

	Maximum at 7h	Maximum at 18h	Minimum at 7h	Minimum at 18h
1	46	48	38	39
2	46	47	41	41
3	52	51	43	47
4	48	43	41	39
5	48	49	38	43
6	45	47	41	41
7	44	47	34	35
8	44	46	40	40
9	45	44	38	40
10	43	47	40	41
11	46	47	44	44
12	47	48	45	44
13	45	48	43	45
14	47	47	38	39
15	47	49	40	40
16	49	47	39	38
17	47	47	41	41
18	48	46	40	40
19	45	46	41	44
20	45	42	39	37
21	41	43	35	37
22	42	43	38	40
23	42	46	30	40
24	44	46	39	39
25	42	43	35	37
26	44	46	39	42
27	44	41	38	35
28	43	44	37	41
29	44	44	32	38
30	42	46	33	34
31	45	40	36	36
MEAN	**45.2**	**45.7**	**38.6**	**39.9**
SUM	**1400**	**1418**	**1196**	**1237**

FIGURE 4 MS Excel template used for data keying of air temperature observations registered in Malin Head during the year 1922

Organization, 2016). Thus each daily maximum and minimum air temperature record was rescued by two different persons. The first keying of all daily maximum and minimum air temperature series was accomplished by the first author of this research. The second keying was completed through a variety of methods which description and results are available in Mateus *et al.*, (2020). For the first time, over 140 secondary school students (15-16 years old) from 8 schools achieved climate data rescue under service-learning: 127 students were hosted as research collaborators at NUI Galway and 18 students cooperated at school through the Green School module as part of a student-scientist partnership (Mateus *et al.*, 2020). More than 190 NUI Galway BA Joint Honours (Geography) and BSc Applied Social Science undergraduate students completed data rescue as part of an assignment on climate data rescue and statistical data analysis in the module *Geography in Practice*, analogous to that investigated by Ryan *et al.* (2018). In addition, NUI Galway students through the volunteering programme ALIVE (A Learning Initiative and the Volunteering Experience, https://

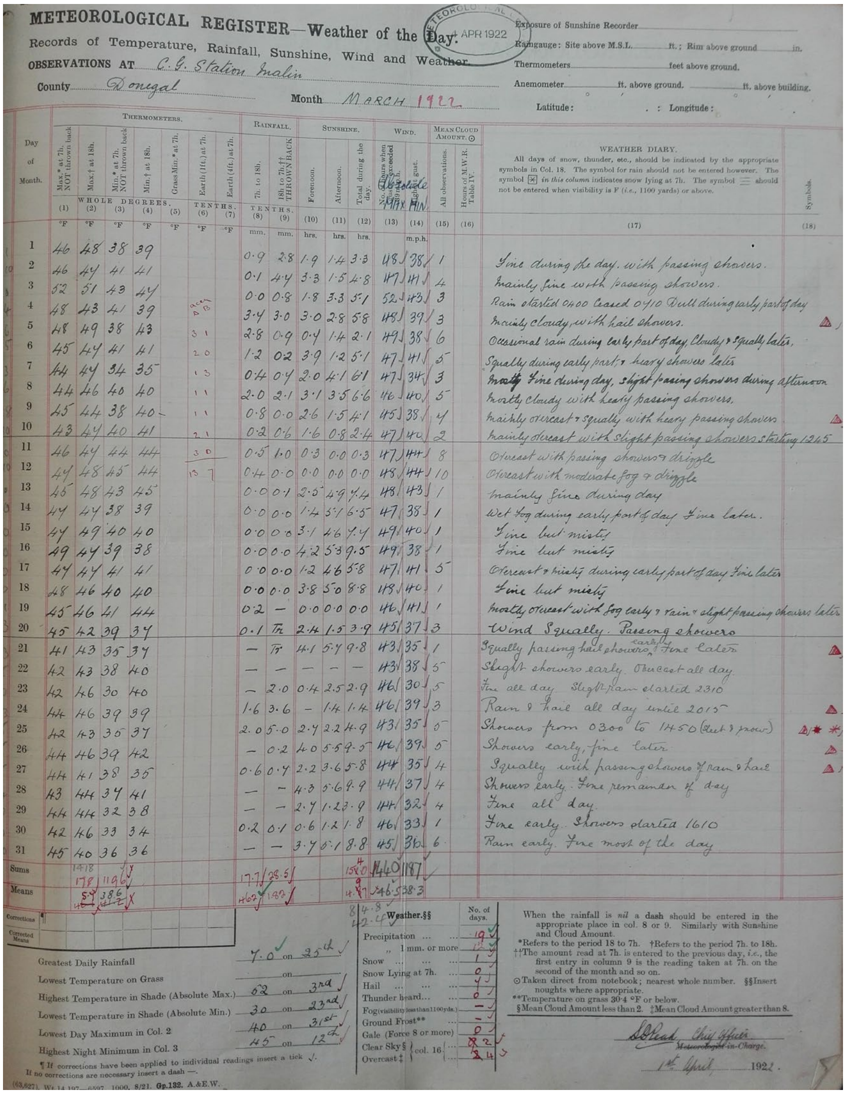

FIGURE 5 Handwritten meteorological record registered in March 1922 at Malin Head and preserved in the archive at Met Éireann

www.studentvolunteer.ie/nuigalway) and volunteers at Met Éireann and Irish Meteorological Society contributed to the second data keying. Students and volunteers enrolled in the second data keying received theoretical and practical training on climate data rescue. Instructions were given on identification of the maximum and minimum air temperature columns in the image of the original datasource and how to perform data input into the MS Excel templates. In order to avoid typing errors, the participants were required to perform a visual cross-checking between the keyed data and the datasource.

MS Excel templates were basic (Figure 4) and similar to the original datasource (Figure 5) to minimize typing errors and to allow a faster keying. Annual MS Excel templates contained a tab for each month, the number of days per each month, columns with the title 'maximum temperature' and 'minimum temperature', and formulas to automatically generate the monthly average and sum after keying of daily values to allow the comparison with the values in the datasource.

MS Excel macros were created to compare the consistency of the first and the second keying. In cases of input differences, the second author of this project was furnished with the information on the date and image of the original station datasource in order to confirm the correct air temperature record. Following cross-checking of keyed data, the first data keying comprised 0.036% errors.

4 | RESULTS AND DATA ACCESS

The ILMMT dataset which comprises 12 long-term and 21 short-term raw daily maximum and minimum air temperature series and related station metadata extending from 1831 to 1968 was rescued, and it is available through edepositIreland (http://hdl.handle.net/2262/92442) and the Met Éireann website (https://www.met.ie/climate/available-data/long-term-data-sets). The ILMMT dataset comprises each station file available as CSV format, which contains the original raw Fahrenheit and the converted Celsius daily maximum and minimum air temperature series (°C = (°F−32)/1.8). Supplemental observations such as values not corrected for

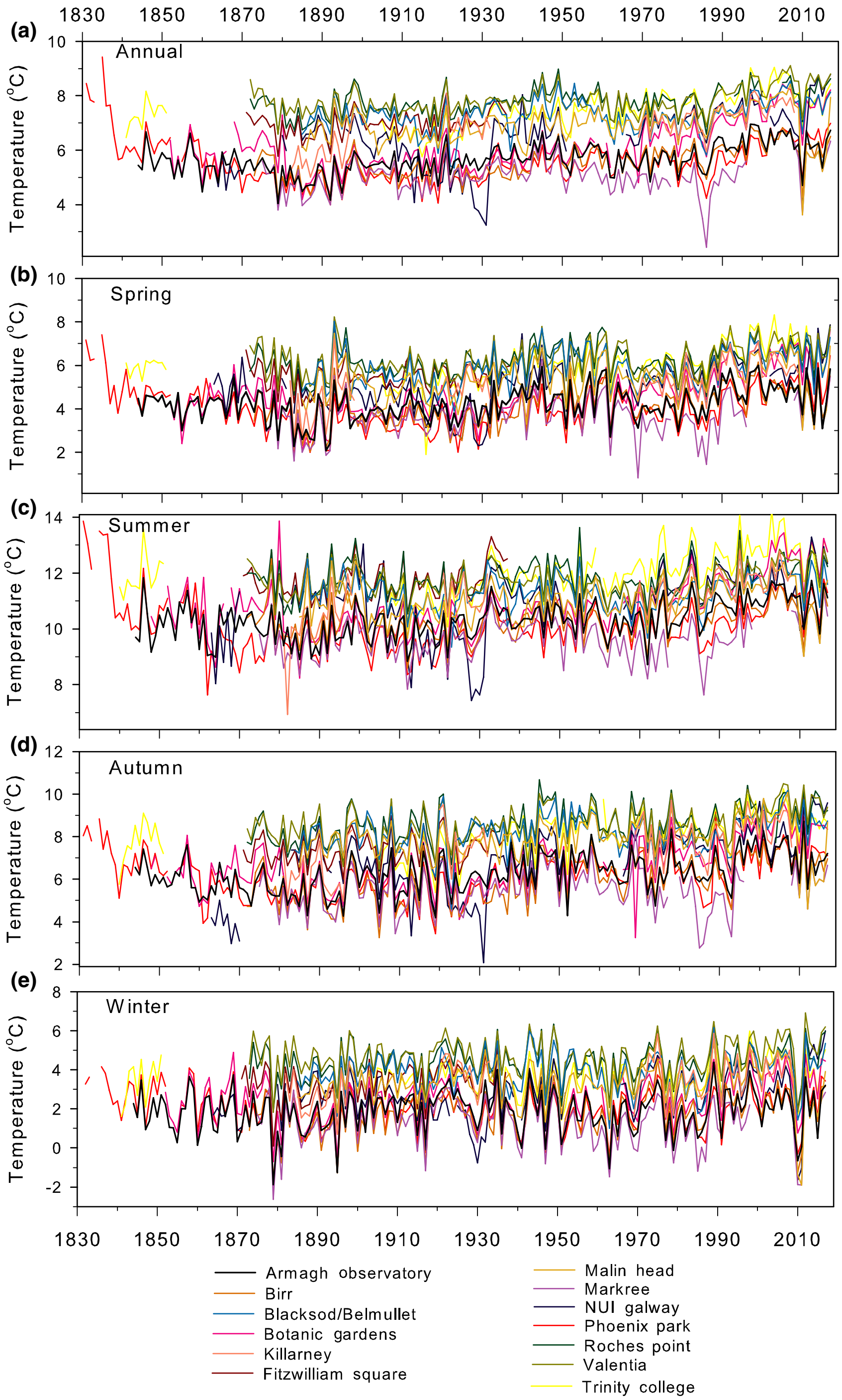

FIGURE 6 Long-term rescued raw annual (a), spring (b), summer (c), autumn (d) and winter (e) minimum air temperature series merged with the modern digital Met Éireann and Armagh Observatory series (Butler *et al.*, 2005; http://www.climate.armagh.ac.uk/)

thermometer index error, observations in different thermometer exposures which are crucial to determine instrumental bias, or readings at different setting and observing times which are necessary to check observing time bias, are provided. Missing data is represented as NA (not available).

Detailed and traceable station metadata rescued from multiple sources include references on the data and metadata sources and early inspection of station summaries which are presented chronologically in each station folder as MS Excel files. The metadata tables are organized in columns (date, metadata and description). Keywords such as 'thermometers', 'inspection of station' or 'location' characterize the type of metadata to aid the users' navigation. Station photographs and drawings are provided in the metadata files. Diverse thermometer exposures were in use prior to the introduction of the Stevenson thermometer screen in the late 1870s and early 1880s such as: indoors in a window recess, a large closed shed, thermometer stands, attached to an external wall or window typically facing northwards or non-standard screens which comprised double screens or a pyramidal roof screen painted green. Different types of thermometer exposures led to distinct

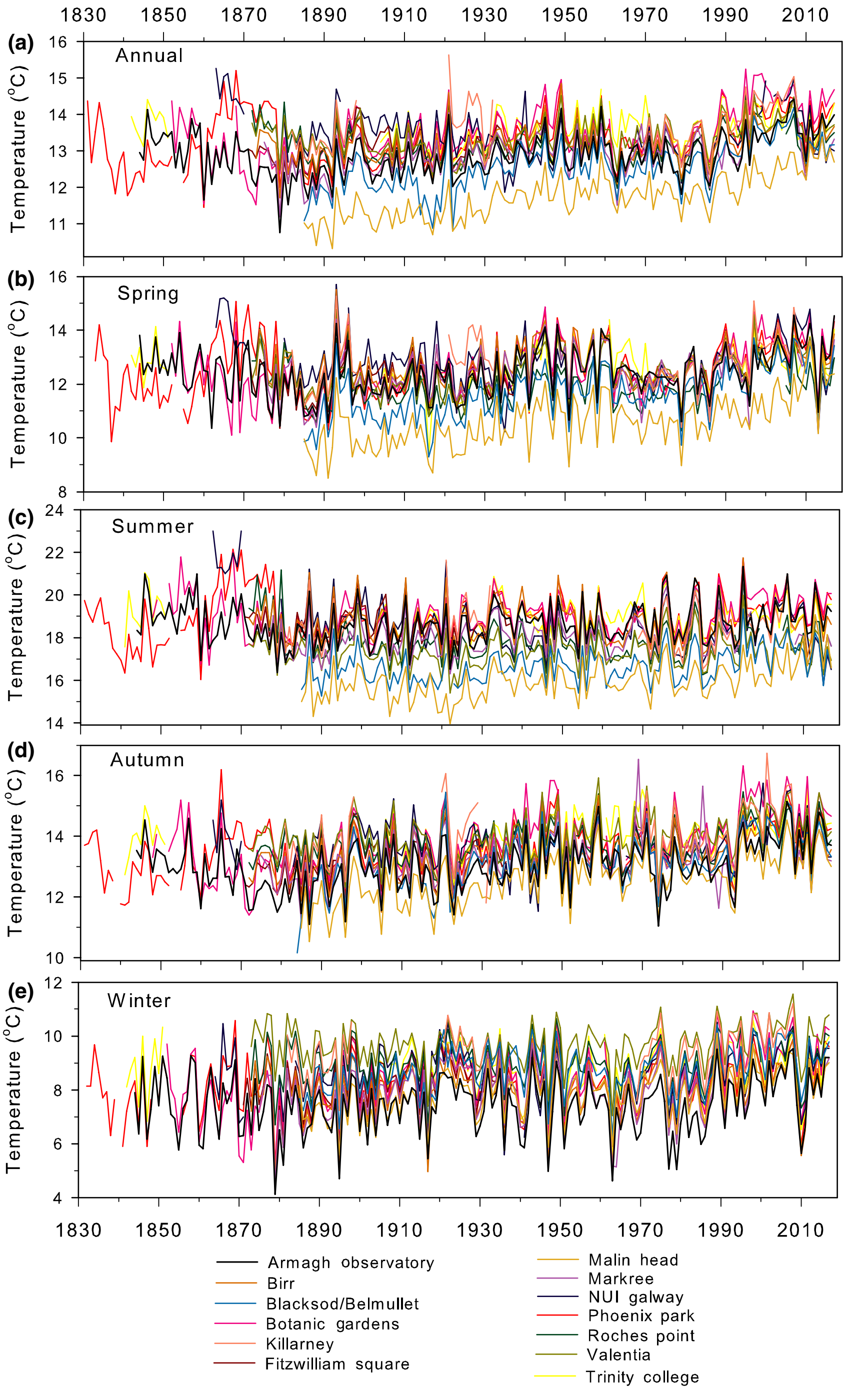

FIGURE 7 Long-term rescued raw annual (a), spring (b), summer (c), autumn (d) and winter (e) maximum air temperature series merged with the modern digital Met Éireann and Armagh Observatory series (Butler *et al.*, 2005; http://www.climate.armagh.ac.uk/)

height of thermometers above the ground. Thermometers were initially protected against radiation by wood or metal shade. Particular observing practices were undertaken in case of indoor thermometer observations: it was routine to open a window for a few minutes prior the thermometer readings when the thermometers were placed at a window recess. The rooms adjacent to these indoor thermometers could have had fires in the autumn and winter (Cameron, 1856).

Early historical self-registering thermometers include for instance Rutherford, Six, Negretti and Casella. According to the metadata observational gaps in the early instrumental series were due to the entanglement of mercury on the maximum thermometer index, the distillation of alcohol into the top of the minimum thermometer tube, thermometer breakages, absence of observers, inexistence of observations on Sundays or historical political events such as the Easter Rising in April 1916.

The rescued raw series merged with modern Met Éireann digital observations and with the calibrated series recorded at Armagh Observatory (Butler *et al.*, 2005; http://www.climate.armagh.ac.uk/) allows the spatial and temporal expansion of the long-term maximum and minimum air temperature records in Ireland back to 1831 (Figures 6 and 7). Twice daily readings of the self-registering thermometers were made at 7 and 18 hr at Malin Head, Blacksod Point, Birr Castle, Valentia Observatory and Roches Point since 1921. Later, the observing time changed as 9 and 21 hr. Thus, for these stations the extreme air temperatures were calculated in the 24 hr period 07-07 hr and at 09-09 hr for Figures 6 and 7. Met Éireann observations from 1960s onwards refer to 09-09 hr period. Since raw data is presented, deviations are displayed such as in the minimum air temperature at NUI Galway in the early 1930s (Figure 6). The application of quality control and homogenization techniques is essential to generate high-quality data prior to any climate data analysis. However, the main goal of this article is the provision of raw observations and detailed station metadata so users can apply their selected procedure according to their aims.

Despite the provision of raw data, well known extreme air temperature events in Britain are also evident in the rescued Irish air temperature series such as the cold periods (Figure 6) of December 1879 (Marriott, 1880), January 1881 (Marriott, 1881), January 1891 (Harding, 1891), January and February 1895 (Bayard and Marriott, 1895), January and February 1917 (Bonacina, 1917) or March 1947 (Booth, 2007), and the warm periods (Figure 7) of July 1868 (Symons, 1868), July 1876 (Symons, 1876), July 1885 (Symons, 1885), August 1893 (Symons, 1893), September 1898 (Symons, 1898) and summer 1911 (Harding, 1912).

5 | CONCLUSIONS AND FURTHER WORK

The examination of diverse data-holders and datasources of historical meteorological observations allowed the rescue of detailed station metadata and the generation of a long-term air temperature dataset. Open access to unexplored and geographically well-distributed daily maximum and minimum air temperature series and related comprehensive metadata dating back to the early and mid-19th century through the ILMNT dataset will fill key gaps in climate research for Ireland, Europe and worldwide. The authors have fulfilled quality control and homogenization procedures on the rescued data, the results of which will be available to users in a forthcoming publication. These series will contribute to the generation of climate products, to assist climate change and attribution studies and to support climate modelling research. The long-term daily maximum and minimum air temperature series will offer a better understanding of past climate variability, trends and assessment of frequency, duration, intensity and distribution of extreme air temperature events and calculation of return period of rare events. The authors are assessing past extreme air temperature events in Ireland using quality controlled and homogenized daily air temperature data, and findings will be available in a forthcoming publication. Due to the rich heritage and importance of early instrumental observations in Ireland, the authors are undertaking further data rescue and continuing the search for missing manuscripts.

ACKNOWLEDGEMENTS

This research has been funded by the Dr Tony Ryan Research Scholarship, Ryan Institute Travel Bursary, Postgraduate Research Travel Bursary, and the Discipline of Geography Travel Award from NUI Galway, and the Geographical Society of Ireland Postgraduate Travel Award from the Geographical Society of Ireland. The authors wish to thank Met Éireann, Early Printed Books and Special Collections at Trinity College Dublin, National Botanical Gardens of Ireland, National Library of Ireland, Special Collections at NUI Galway, Royal Dublin Society, Royal Irish Academy, Armagh Observatory and Dr John Butler, and National Meteorological Archive at Met Office for permission to access their meteorological records. The authors acknowledge the second data keying by: secondary school students (Transition Year) from Calasanctius College Oranmore, Galway Community College, Presentation College Athenry, Claregalway College, Salerno Secondary School, Dominican College Taylor's Hill and Our Lady's College in Galway and Holy Child Community School in Sallynoggin; NUI Galway first-year BA Joint Honours (Geography) and BSc Applied Social Science undergraduates; members of the Irish Meteorological Society Paul Halton, Sonia Lall, Graeme Morrison, Patricia McGrath and Ciara O'Hara; Met Éireann volunteers Tom Murphy and Viviene O'Keeffe and NUI Galway students Michelle Temple-Moore, and Amrina Aljeffri, Cailín McGoldrick, Christopher Fox, Corinne McGillicuddy, Darragh Gilmartin, Eoghan Moylan, Emily Warner, Gillian Wilson, Nicolás Contador, Preston Turner and Victoria Petruk through the volunteering programme ALIVE in the academic year 2017/2018. The authors are grateful to the editor and reviewers for their insightful suggestions.

OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at http://hdl.handle.net/2262/92442 Learn more about the Open Practices badges from the Center for OpenScience: https://osf.io/tvyxz/wiki

ORCID

Carla Mateus https://orcid.org/0000-0002-4640-1614
Aaron Potito https://orcid.org/0000-0003-0194-9552
Mary Curley https://orcid.org/0000-0002-6209-8221

ENDNOTE

[1] Last accessed on 21/05/2019.

[2] Despite the availability of daily maximum and minimum air temperature observations dating back to 1861 at NUI Galway and to 1880 at Phoenix Park Dublin at ECA&D, there was no indication on the

double keying practices. Thus, these series were double-keyed. The comparison of the double-keyed series with the available series at ECA&D revealed a few keying errors on those series namely on the NUI Galway series (not shown).

REFERENCES

Aguilar, E., Auer, I., Brunet, M., Peterson, T.C. and Wieringa, J. (2003) *Guidelines on climate metadata and homogenization*. WMO/TD-No. 1186. Geneva, Switzerland: World Meteorological Organization.

Allan, R., Brohan, P., Compo, G.P., Stone, R., Luterbacher, J. and Brönnimann, S. (2011) The international atmospheric circulation reconstructions over the Earth (ACRE) initiative. *Bulletin of the American Meteorological Society*, 92(11), 1421–1425.

Ashcroft, L., Gergis, J. and Karoly, D.J. (2014) A historical climate dataset for southeastern Australia, 1788–1859. *Geoscience Data Journal*, 1(2), 158–178.

Ashcroft, L., Coll, J.R., Gilabert, A., Domonkos, P., Brunet, M., Aguilar, E. *et al*. (2018) A rescued dataset of sub-daily meteorological observations for Europe and the southern Mediterranean region, 1877–2012. *Earth System Science Data*, 10, 1613–1635.

Bayard, F.C. and Marriott, W. (1895) The frost of January and February 1895 over the British Isles. *Quarterly Journal of the Royal Meteorological Society*, 21(95), 141–160.

Bonacina, L.C.W. (1917) *The frost of January and February, 1917*. Symons's Monthly Meteorological Magazine, 52(614), 13–15. London, UK: Edward Stanford.

Booth, B.G. (2007) Winter 1947 in the British Isles. *Weather*, 62(3), 61–68.

Brönnimann, S., Annis, J., Dann, W., Ewen, T., Grant, A.N., Griesser, T. *et al*. (2006) A guide for digitising manuscript climate data. *Climate of the Past*, 2, 137–144.

Brönnimann, S., Allan, R., Ashcroft, L., Baer, S., Barriendos, M., Brázdil, R. *et al*. (2019) Unlocking pre-1850 instrumental meteorological records: A global inventory. *Bulletin of the American Meteorological Society*, 100, ES389–ES413.

Butler, C.J., García-Suárez, A.M., Coughin, A.D.S. and Cardwell, D. (2005) *Meteorological data recorded at Armagh Observatory: Vol. II – Daily, Mean Monthly, Seasonal and Annual, Maximum and Minimum Temperatures, 1844–2004*. Armagh Observatory Climate Series. http://www.climate.armagh.ac.uk/calibrated/airtemp/yellow-textD.pdf. Data available at: http://www.climate.armagh.ac.uk/calibrated.html and http://www.climate.armagh.ac.uk/scan.html (Last accessed on 20/05/2019).

Cameron, H.J. (1856) *Meteorological observations taken during the year 1829 to 1852 at the Ordnance Survey Office, Phoenix Park Dublin: to which is added a series of similar observations made at the principal trigonometrical stations, and at other places, in Ireland*. Dublin, Ireland: Alexander Thom and Sons.

Harding, C. (1891) The great frost of 1890–1891. *Quarterly Journal of the Royal Meteorological Society*, 17(78), 93–117.

Harding, C. (1912) The abnormal summer of 1911. *Quarterly Journal of the Royal Meteorological Society*, 38(161), 1–32.

Keane, A., Lonergan, T. and Treanor, M. (2017) *Meteorological observations in Ireland 1855-1976: an archival finding aid* (p. 39). Historical Note No. 6. Dublin, Ireland: Met Éireann. Retrieved from http://hdl.handle.net/2262/74613

Lloyd, H. (1853) Notes on the meteorology of Ireland, deduced from the Observations made in the year 1851, under the direction of the Royal Irish Academy. *The Transactions of the Royal Irish Academy*, 22, 411–498.

Lloyd, H. (1865) *Observations made at the magnetical and meteorological observatory at trinity college, Dublin*. Vol. I. (pp. 1840–1843). Dublin, Ireland: Hodges, Smith and Co.

Lloyd, H. (1869) *Observations made at the magnetical and meteorological observatory at trinity college, Dublin: Under the direction of Humphrey Lloyd*. Vol. II. (pp. 1844–1850). Dublin, Ireland: Hodges, Foster and Co.

Marriott, W. (1880) On the frost of December, 1879, over the British Isles. *Quarterly Journal of the Royal Meteorological Society*, 6(34), 102–114.

Marriott, W. (1881) The frost of January 1881 over the British Isles. *Quarterly Journal of the Royal Meteorological Society*, 7(38), 138–155.

Mateus, C., Potito, A. and Curley, M. (2020) Engaging secondary school students in climate data rescue through service-learning partnerships. *Weather*. (Under review).

McElwain, L. and Sweeney, J. (2007) *Key meteorological indicators of climate change in Ireland. Environment research centre report*. Johnstown Castle, Wexford, Ireland: Environment Protection Agency.

McKeown, M., Potito, A. and Hickey, K. (2012) The long-term temperature record from Markree Observatory, County Sligo, from 1842 to 2011. *Irish Geography*, 45(3), 257–282.

Meteorological Council (1882) *Report of the meteorological council to the royal society, for the year ending 31st of March 1881*. London, UK: George E. Eyre and William Spottiswoode.

Meteorological Office (1880) *Meteorological observations at stations of the second order for the year 1878*. London, UK: Her Majesty's Stationery Office.

Morley, T. (1964) *The climate of Dublin II. Temperature at Trinity College 1904–1963. Geophysical Bulletin No. 23. School of Cosmic Physics*. Dublin, Ireland: Dublin Institute for Advanced Studies.

Murphy, C., Broderick, C., Burt, T.P., Curley, M., Duffy, C., Hall, J. *et al*. (2018) A 305-year continuous monthly rainfall series for the island of Ireland (1711–2016). *Climate of the Past*, 14, 413–440.

Noone, S., Murphy, C., Coll, J., Matthews, T., Mullan, D., Wilby, R.L. *et al*. (2016) Homogenisation and analysis of an expanded long-term monthly rainfall network for the Island of Ireland (1850–2010). *International Journal of Climatology*, 36(8), 2837–2853.

Royal Dublin Society (1849) *The proceedings of the Royal Dublin Society, from November 2, 1848, to June 19, 1849* 85. Dublin, Ireland: University Press.

Royal Dublin Society (1850) *The proceedings of the Royal Dublin Society, from November 1, 1849, to June 27, 1850*. 86. Dublin, Ireland: University Press.

Royal Dublin Society (1852) *The proceedings of the Royal Dublin Society, from November 6, 1851, to June 24, 1852*. 88. Dublin, Ireland: University Press.

Royal Dublin Society (1853) *The proceedings of the Royal Dublin Society, from November 4, 1852, to September 8, 1853*. 89. Dublin, Ireland: University Press.

Royal Dublin Society (1854) *The proceedings of the Royal Dublin Society, from July 1, 1853, to June 30, 1854*. 90. Dublin, Ireland: University Press.

Royal Dublin Society (1855) *The proceedings of the Royal Dublin Society, from July 1, 1854, to June 30, 1855*. 91. Dublin, Ireland: University Press.

Royal Dublin Society (1856) *The proceedings of the Royal Dublin Society, from July 1, 1855, to June 30, 1856*. 92. Dublin, Ireland: University Press.

Royal Dublin Society (1858) *The Journal of the Royal Dublin Society*. 1856–57. 1. Dublin, Ireland: Hodges, Smith, & Co., 104, Grafton-Street.

Royal Dublin Society (1860) *The Journal of the Royal Dublin Society*. 1858–59. 2. Dublin, Ireland: Hodges, Smith, & Co., 104, Grafton-Street.

Royal Dublin Society (1862) *The Journal of the Royal Dublin Society*. 1860–1861. 3. Dublin, Ireland: Hodges, Smith, & Co., 104, Grafton-Street.

Royal Dublin Society (1866) *The Journal of the Royal Dublin Society*. 1863–1865. 4. Dublin, Ireland: Hodges, Smith, & Co., 104, Grafton-Street.

Royal Dublin Society (1870) *The Journal of the Royal Dublin Society*. 5. Dublin, Ireland: Hodges, Foster, & Co., 104, Grafton-Street.

Ryan, C., Duffy, C., Broderick, C., Thorne, P.W., Curley, M., Walsh, S. *et al*. (2018) Integrating data rescue into the classroom. *Bulletin of the American Meteorological Society*, 99, 1757–1764.

Shields, L. (1983) The beginnings of scientific weather observation in Ireland (1684–1708). *Weather*, 38(10), 304–311.

Symons, G.J. (1868) *The heat in July, 1868*. Symons's Monthly Meteorological Magazine, 3(31), 107–108. London, UK: Edward Stanford.

Symons, G.J. (1876) *The temperature in July*. Symons's Monthly Meteorological Magazine, 11(128), 94–97. London, UK: Edward Stanford.

Symons, G.J. (1885) *July, 1885*. Symons's Monthly Meteorological Magazine, 20(235): 110. London, UK: Edward Stanford.

Symons, G.J. (1893) *The maximum temperatures, Aug. 13th – 19th, 1893*. Symons's Monthly Meteorological Magazine, 28(332), 113–115. London, UK: Edward Stanford.

Symons, G.J. (1898) *Heat and drought in September, 1898*. Symons's Monthly Meteorological Magazine, 33(393), 129–135.

Thorne, P.W., Willett, K.M., Allan, R.J., Bojinski, S., Christy, J.R., Fox, N. *et al*. (2011) Guiding the creation of a comprehensive surface temperature resource for twenty-first-century climate science. *Bulletin of the American Meteorological. Society*, 92, ES40–ES47.

Venema, V., Trewin, B., Wang, X., Szentimrey, T., Lakatos, M., Aguilar, E. *et al.* (2018) *Guidance on the homogenisation of climate station data*. (Draft version November 2018). https://eartharxiv.org/8qzrf/ (Last accessed on 7/04/2019).

World Meteorological Organization (2016) *Guidelines on best practices for climate data rescue*. WMO-No. 1182. Geneva, Switzerland: World Meteorological Organization.

Wynne, G.R. (1886) The climate of Killarney. *Quarterly Journal of the Royal Meteorological Society*, 12(59), 193–197.

Yeates, G. (1844) *Appendix No. V: Meteorological journal, commencing 1st January, 1843, ending 31st December, 1843*. Proceedings of the Royal Irish Academy (1836–1869), 2 (1840–1844): xxxix-liii.

Yeates, G. (1847a) *Appendix No. II: Meteorological journal, from 1st January to 31st December, 1844*. Proceedings of the Royal Irish Academy (1836-1869), 3 (1844-1847): xvii-xxx.

Yeates, G. (1847b) *Appendix No. VI: Meteorological journal, from 1st January to 31st December, 1845*. Proceedings of the Royal Irish Academy (1836-1869), 3 (1844-1847): lxi-lxvi.

Yeates, G. (1847c) *Appendix No. IX: Meteorological journal, from 1st January to 31st December, 1846*. Proceedings of the Royal Irish Academy (1836-1869), 3 (1844-1847): xcvii-cii.

Yeates, G. (1850a) *Appendix No. I: Meteorological journal, from 1st January, 1847, to 31st December, 1847*. Proceedings of the Royal Irish Academy (1836-1869), 4 (1847-1850): i-vi.

Yeates, G. (1850b) *Appendix No. III: Meteorological journal, from 1st January, 1848, and ending 31st December, 1848*. Proceedings of the Royal Irish Academy (1836-1869), 4 (1847-1850): xxi-xxvi.

Yeates, G. (1850c) *Appendix No. VII: Meteorological journal, from 1st January, 1849, to 31st December, 1849*. Proceedings of the Royal Irish Academy (1836-1869), 4 (1847-1850): lxxv-lxxx.

How to cite this article: Mateus C, Potito A, Curley M. Reconstruction of a long-term historical daily maximum and minimum air temperature network dataset for Ireland (1831-1968). *Geosci. Data J.*. 2020;7:102–115. https://doi.org/10.1002/gdj3.92