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Thermal conditions on the coast of Labrador during the late 19th/early 20th century

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Abstract

The long-term Moravian missionary meteorological observations, conducted from the late 18th century until the 2nd World War, provide a unique perspective on climate conditions along the Labrador coast. The present paper focuses on the analysis of air temperature in the late 19th and early 20th centuries based on sub-daily observations (three to five times a day) available for six stations: Rama (1882–1890), Hebron (1882–1918), Okak (1883–1889), Nain (1882–1913, 1926-1939), Zoar (1882–1894), and Hopedale (Hoffenthal) (1882–1898). The meteorological observations were carried out by the missionaries on behalf of the Deutsche Seewarte and are preserved in the archives of Deutscher Wetterdienst (Germany).

Quality-controlled and corrected mean daily air temperature-were used to calculate standard climatic characteristics, including monthly, seasonal, and annual means; climate continentality indices; day-to-day temperature variability; thermal seasons; and other characteristics. In addition to extending the climate analysis, a set of additional useful climatic indices was calculated, including Growing Degree Days (GDD), Air Thawing Index (ATI), Positive Degree Days (PDD), and Air Freezing Index (AFI). Historical temperature data from the coast of Labrador were compared with contemporary thermal conditions from 1990 to 2020. At Nain, the mean annual air temperature during 1882–1892 was 2.3 °C lower than during 1990–2020. The separate Nain record for the Early Twentieth Century Warming (1926–1939) remained 0.8 °C lower than the modern mean. At Hopedale, the mean annual temperature was −3.2 °C during 1882–1898 and −1.5 °C during 1990–2020, giving a historical–modern difference of −1.7 °C. At Nain, warmer temperature classes occurred more frequently during the modern period, particularly in autumn and summer, whereas the differences at Hopedale were most apparent in summer. The historical records also indicate a slightly greater annual temperature range and stronger climate continentality than in the modern period, with the largest temperature changes occurring during the cold season.

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1 Introduction

The Labrador coast or coast of Nunatsiavut (in the Inuktitut language) is an area of the North Atlantic subarctic which is exposed to cold Arctic air masses, close to the southward-drifting flow of the Labrador Current and in which there is a strong seasonal signal associated with sea-ice conditions (Drinkwater, 2006; Barry, 2008). It is therefore very relevant for understanding long-term climate variability in the Arctic-subarctic region (Drinkwater, 2006; Barry, 2008). Because of its remoteness and late incorporation into national meteorological networks, however, long instrumental climate records do not exist for the Labrador coast before the middle decades of the 20th century (Demarée & Ogilvie, 2008). One of the best sets of early instrumental climate records from the North Atlantic subarctic region was, nonetheless, initiated on the coast of Labrador by the Moravian missionaries, who began collecting a regular series of meteorological measurements in the late 18th century to track and improve mission logistics. The resulting series of sub-daily air temperatures, atmospheric pressures, winds and qualitative assessments of the weather have continued up until the present time at five mission centres (at Hebron, Okak, Nain, Zoar, and Hopedale) and constitutes one of the longest-running instrumental climate records anywhere in the world outside the auspices of any national meteorological service (Demarée & Ogilvie, 2008; Demarée et al., 2020). Beginning in the 1770s, the records span the climatically significant transition from the Little Ice Age to the Industrial Era (PAGES 2k Consortium, 2013).

During the late 19th and early 20th centuries, the global climate system transitioned from lingering cold conditions to the onset of modern warming (IPCC, 2021). Therefore, this time period is important for differentiating between natural and anthropogenic climate change. However, there is a lack of information about the Arctic climate during this time, particularly in the subarctic, including the Labrador coast. While many broad climate reconstructions have used proxies such as tree rings, ice cores, and marine sediment cores (Mann et al., 2009; PAGES 2k Consortium, 2013), instrumental records from the early period provide an opportunity for more specific measurements to augment these proxy records.

The study by Uebe (1909) highlights that the meteorological data available for this region is "extremely sparse", given the vast area it encompasses. Data on the northern coastline were primarily collected by Moravian missionaries in Okak and Rama between 1882 and 1889. To reconstruct data for the interior and western parts of the area, researchers leaned heavily on the expeditionary journals kept by A.P. Low during his travels in 1885, 1887/88, 1895, and 1896. For these expeditions, permanent weather stations recorded temperatures three times a day at

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7:00 AM, 2:00 PM, and 9:00 PM. In cases where consistent recording wasn't feasible, a specific arithmetic formula was used to calculate daily averages from morning, midday, and evening observations, denoted v, m, and n, respectively. The reliability of these meteorological series was further enhanced by the work of Hann (1896), whose contributions in 1896 and 1897 included calculations for key stations like Rigolet, Okak, and Ramah. Systematic meteorological data for these locations, some extending back as far as 1867 for Hopedale, provide a robust dataset for analysing the seaboard's climate. In his synthesis, Tanner (1944) notes that while early climatologists such as Hann (1896) and Connor (1938) published slightly divergent average figures, the data were eventually refined by Professor Osc. V. Johansson. Johansson reduced these disparate observations to a comparable "normal series" for the twenty years of 1883–1902, specifically addressing "inexactness" driven by historical changes in station positions. A study was conducted by Tietze (1950), to investigate one of the earliest scientific studies about climatic conditions along the coast of Labrador. The main focus was to examine the region's climate, with particular emphasis on temperature variability. Tietze points out that winter conditions in Labrador are exceptional in severity; temperature variability from one day to the next (interdiurnal) is extremely large, and winter temperatures in Labrador, although located well below the Arctic Circle , are very low because of the influence of sea ice and the coldness of the ocean reinforced by the cold Labrador Current. Even though summer is short, temperatures can still be high. Tietze's work demonstrates significant seasonal differences and the instability of the transitional seasons (particularly during winter and early spring). The weather data indicate that the Labrador coastline experiences a harsh sub-arctic climate, characterised by a significant thermal gradient from north to south (Döll, 1937).

The climate system in Labrador's subarctic has been reconstructed from several records, including early temperature readings and recent proxy reconstructions. Among the available methods, long-term weather records are especially relevant. While historical proxy data offer broad insights into post-Little Ice Age patterns, early instrumental data provide significantly higher temporal resolution and precision for tracking true climate variability. The literature defines this coastal chain by a pronounced negative thermal anomaly, identifying it as one of the coldest regions in the Northern Hemisphere at its latitude.

Moravian missionaries began instrumental meteorological observations at Nain in 1771, and observations were later made at other mission stations along the Labrador coast (Lüdecke, 2005; Demarée and Ogilvie, 2008). Information about these measurements is preserved in missionary journals, manuscript registers, handwritten copies and published extracts (Lüdecke, 2005;

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Demarée and Ogilvie, 2008, 2011). During the First International Polar Year (1882–1883), the Deutsche Seewarte organised observations at the six Moravian stations and supplied the instruments (Lüdecke, 2005). However, the available records differ among stations in their observation times, format and completeness. These differences must be considered when processing and comparing the series. Therefore, we document the source data, unit conversions, quality-control procedures, corrections and station metadata used in this study (Slonosky, 2014; Brönnimann et al., 2019; Slonosky et al., 2026).

In addition to land-based observations, marine proxy reconstructions have provided new information about sea-ice fluctuations and the impacts of sub-arctic climate systems on those fluctuations. One of the most robust marine proxy data for sea ice is presented by Halfar et al. (2013), who reconstructed an annual resolution multi-century record of sea ice based on the growth rings of the crustose coralline alga Clathromorphum compactum. This alga is sensitive to the amount of sea ice and the amount of light that is available to it (Halfar et al., 2013). Their study was conducted at several locations across the Canadian Arctic and eastern Labrador and indicates that there was extensive but variable sea ice cover during the Little Ice Age and that, since the end of the Little Ice Age (on the order of 150 years ago), there has been an unprecedented and rapid decline in the extent of sea ice compared to the previous 600 years of record. In the context of the Moravian temperature records, these records provide a marine cryosphere record against which to evaluate the thermal trends observed and demonstrate the significant influence of sea ice and sea ice dynamics at the regional level in the modulation of climate at coastal regions (Halfar et al., 2013). The integrative approach is additionally supported by further interdisciplinary studies. For instance, Ouellet-Bernier et al. (2021) used Moravian sources in conjunction with other historical data to assess the occurrence of extreme climate events on the Labrador Coast from 1780 to 1950. These authors found that many of the cold and hot anomalies corresponded well with regional ice storm data. Similarly, Newell (1990) demonstrated that spring and summer sea ice in the Labrador Sea significantly affected temperature trends in the surrounding region, thereby enhancing previous studies that utilised both marine and terrestrial data types. Tanner attributes this persistent cooling to the Labrador Current, which he characterises as a "cooling apparatus" that transports Arctic ice drift along the seaboard. This oceanic influence suppresses radiation-driven heating in early summer, resulting in a unique thermal lag in which the warmest month at stations like Hopedale, Nain, and Hebron is typically August rather than July.

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Overall, these works provide a solid foundation for reconstructing past thermal patterns in the Labrador Sub-Arctic; however, the interval from approximately 1880 to 1920 has not been adequately examined, particularly regarding the climate variability of that period and its transitional character between the pre-industrial era and the modern warming era. To fill this gap, the current study uses a detailed analysis of the Moravian air temperature records during this interval and, therefore, places the observed trends into context with reconstructive sea ice data and other wider climatic changes. This study presents the first reconstruction of thermal conditions along the northern and north-eastern Labrador coast during the late nineteenth and early twentieth centuries.

2. Area, data and methods

2.1. Area

This paper analyses the thermal conditions along the coastal region of northern Labrador during the late 19th and early 20th centuries using instrumental meteorological observations carried out by Moravian missionaries at six settlement sites: Rama, Hebron, Okak (spelled also as Okkak), Nain, Zoar, and Hopedale (also known as Hoffenthal) (Fig. 1). Historical sources provide only limited and sometimes inconsistent information on the precise geographical positions of these stations, particularly with respect to longitude, owing to the absence of a universally accepted prime meridian prior to the International Meridian Conference of 1884, which established Greenwich as the global reference (Black et al., 1984). Consequently, early geographic coordinates must be treated with caution. To ensure accurate spatial referencing, this study adopts station locations reconstructed from late-19th- and early-20th-century climatological and geographical compilations, supplemented by modern geospatial verification where applicable. According to Hann (1896) and Döll (1937), the approximate late-19th-century locations and elevations are as follows: Ramah (ϕ =58°52′ N, λ = 63°14′ W; H =4 m a.s.l.), Hebron (ϕ = 58°12′ N, λ = 62°38′ W; H = 8 m a.s.l.), Okak (ϕ = 57°34′ N, λ = 61°59′ W; H = 3 m a.s.l.), Nain (ϕ = 56°33′ N, λ = 61°41′ W; H = 4.2 m a.s.l.), Zoar (ϕ =56°08′ N, λ = 61°23′ W; H = 5 m a.s.l.), and Hopedale (ϕ = 55°27′ N, λ = 60°12′ W; H = 7.6 m a.s.l.). According to the modified Köppen climate classification applied to the 19th-century American Arctic by Vízi (2008), this coastal corridor marks a highly dynamic boundary between polar tundra (ET) and sub-arctic sub-polar (Dfc) zones. The thermal regime along this maritime boundary layer is heavily governed by topographically induced microclimates and

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seasonal oceanographic shifts, which underscores the necessity of analyzing multiple adjacent stations to capture a representative regional signal. These reconstructed locations are consistent with the spatial distribution of Moravian mission stations documented in modern historical-climatological studies (Demarée & Ogilvie, 2008; Demarée et al., 2020; Singh et al., 2025). The use of standardised geographic coordinates enables reliable comparison between historical observations and contemporary climatological reference stations, forming a robust spatial framework for the thermal analyses presented in this study.

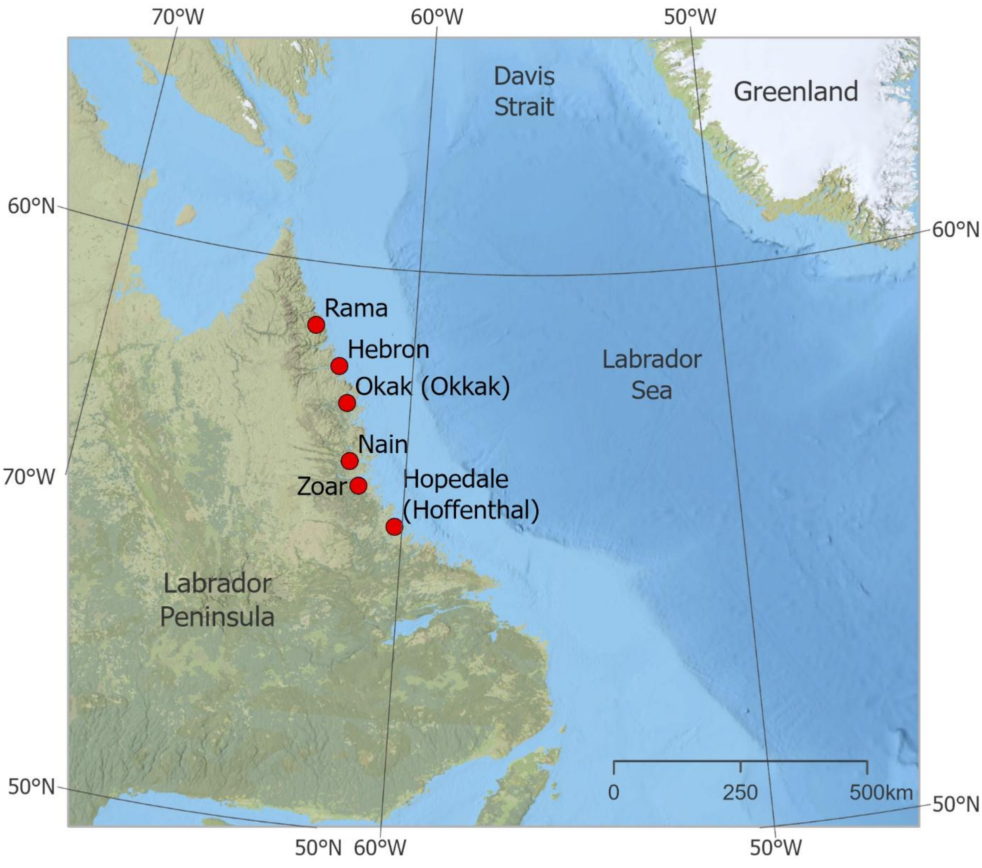

Fig.1. Study area where meteorological measurements were taken. Source: author's own work in ArcGIS Pro 3.5.4.

2.2. Data and methods

The late 19th/early 20th-century Moravian missionary observations, made three or five times a day, offer an exclusive perspective on the climate of the Labrador coast, providing essential

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data on air temperature, air pressure, cloud cover, precipitation and wind characteristics, as well as short descriptions of the weather. This study analyses air temperature conditions in Labrador's coastal region using invaluable instrumental meteorological observations collected by Moravian missionaries on behalf of the Deutsche Seewarte.

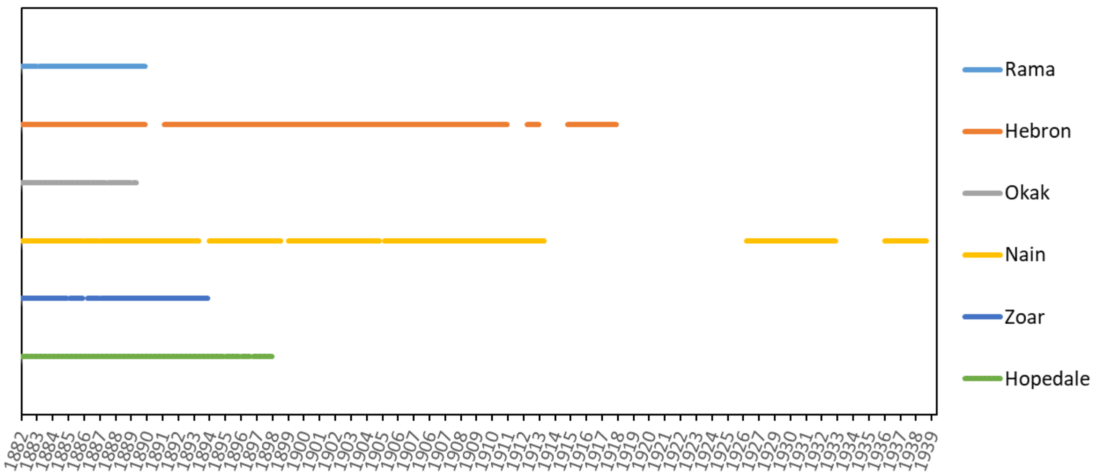

Fig. 2. Temporal distribution of the air temperature observations from meteorological land stations used in the study from 1882 to 1939.

The historical observations were obtained from the Deutscher Wetterdienst (DWD), where the original records had been manually digitised, arranged chronologically and converted to SI units. During this processing, the air-temperature data underwent formal, climatological, chronological and repetition checks using the DWD validation software. Each observation was assigned a quality code (Möller, 2022). We then calculated and corrected MDAT and filled missing observations using overlapping records from neighbouring stations, as described below. The historical air-temperature series analysed here cover Nain (1882–1913 and 1926–1939), Okak (1883–1889), Hopedale (1882–1898), Zoar (1882–1894), Rama (1882–1890) and Hebron (1882–1918) (Fig. 2). In the processed database, air temperature is designated as *TT* and expressed in tenths of a degree Celsius (1/10°C). Measurements in Nain were generally taken at 08:00, 14:00, and 20:00 local time (LT), though some records include up to five daily observations. In Okak and Hopedale, a more regularised schedule was followed, with observations conducted at 08:00, 12:00, 16:00, and 20:00 LT (Demarée & Ogilvie, 2008; Singh et al., 2025). For comparison with the contemporary period, materials collected by the Canadian

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Centre for Climate Services were used, specifically stations Nain_A (8502800) and Hopedale_8502400 for the years 1990-2020. The complete historical records available for each station, the periods actually analysed, and the completeness of the resulting MDAT series are summarized in Table 1.

Table 1. Availability and use of historical and modern air-temperature records at the six Labrador stations, including the periods analysed and completeness of the mean daily air-temperature (MDAT) series after infilling.

Station	Complete historical record available	Period analysed	Infilled daily MDAT, n (%)	Daily MDAT missing after infilling	Observation times (LT)	MDAT formula(s) and correction source	Modern reference station/dataset and period	Use of modern reference
Rama	1882-09-07 to 1890-07-31	1882-09-07 to 1890-07-31	42 (1.46%)	0	Mainly 08:00, 14:00 and 20:00 LT; occasional five-observation days (06:00, 08:00, 14:00, 20:00 and 21:00/22:00)	MDAT2–MDAT10, selected according to the available daily observation-time combination (Table S1); monthly correction derived from modern Nain	Nain A (station 8502800), 1990–2020	Regional climatic context only; no station-matched quantitative temporal comparison
Hebron	1882-09-07 to 1918-07-31	1882-09-07 to 1918-07-31	2016 (15.38 %)	0	Mainly 08:00, 14:00 and 20:00 LT or 07:00, 14:00 and 21:00 LT; occasional five-observation days	MDAT2–MDAT10, selected according to the available daily observation-time combination (Table S1); monthly correction derived from modern Nain	Nain A (station 8502800), 1990–2020	Regional climatic context only; no station-matched quantitative temporal comparison
Okak	1883-09-01 to 1889-12-31	1883-09-01 to 1889-08-31	139 (6.34%)	0	Mainly 08:00, 14:00 and 20:00 LT.	MDAT2–MDAT10, selected according to the available daily observation-time combination (Table S1); monthly correction derived from modern Nain	Nain A (station 8502800), 1990–2020	Regional climatic context only; no station-matched quantitative temporal comparison
Nain	1882-09-01 to 1913-12-31; 1926-11-24 to 1939-03-31	1882-09-01 to 1913-12-31; 1926-11-24 to 1939-03-31 (second segment analysed separately for the Early Twentieth Century Warming)	2210 (13.85 %)	0	Mainly 08:00, 14:00 and 20:00 LT; also 07:00, 14:00 and 21:00 LT; occasional five-observation days	MDAT2–MDAT10, selected according to the available daily observation-time combination (Table S1); monthly correction derived from modern Nain	Nain A (station 8502800), 1990–2020; hourly Nain data, 2011–2020, for MDAT correction	Station-matched historical–modern comparison; 2011–2020 used only to derive observation-time corrections
Zoar	1882-08-24 to 1894-07-31	1882-08-24 to 1894-07-31	292 (6.70%)	0	Mainly 08:00, 14:00 and 20:00 LT; occasional five-observation days (06:00, 08:00, 14:00, 20:00 and 22:00)	MDAT2–MDAT10, selected according to the available daily observation-time combination (Table S1); monthly correction derived from modern Nain	Nain A (station 8502800), 1990–2020	Regional climatic context only; no station-matched quantitative temporal comparison
Hopedale (Hoffenthal)	1882-08-14 to 1898-08-31	1882-08-14 to 1898-08-31	417 (7.11%)	0	Mainly 08:00, 14:00 and 20:00 LT; occasional five-observation days (06:00, 08:00, 14:00, 20:00 and 22:00)	MDAT2–MDAT6, selected according to the available daily observation-time combination (Table S1); monthly correction derived from modern Hopedale	Hopedale (station 8502400), 1990–2020; hourly Hopedale data, 2011–2020, for MDAT correction	Station-matched historical–modern comparison; 2011–2020 used only to derive observation-time corrections

The NORTHERN data-rescue project is described by Slonosky et al. (2026). Its public station inventory and data files were examined to identify observations suitable for an independent

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regional comparison (Slonosky et al., 2025). None of the six Moravian stations analysed here, Rama, Hebron, Okak, Nain, Zoar and Hopedale, is included in the inventory. The only Labrador station included is Rigolet, whose record extends from 1 July 1860 to 30 June 1863 and therefore does not overlap the period analysed here. Consequently, the NORTHERN dataset provides no series suitable for an independent regional comparison of the 1882–1939 observations.

Using modern hourly observations from Nain and Hopedale for 2011–2020, MDAT1 was first calculated as the average of the 24 hourly values:

MDAT1=(T1+T2+T3+….+T24)/24,

where T1–T24 represent the hourly air temperatures. Daily means were then calculated for each combination of observation times listed in Table S1. For example:

MDAT2=(T8+T14)/2.

For each day, the difference between each reduced-observation MDAT and the 24-hour mean (MDAT1) was calculated (e.g. MDAT2−MDAT1). The daily differences were averaged separately for each month and each MDAT formula. The appropriate monthly correction value from Table 2 or Table 3 was then subtracted from the corresponding historical MDAT value. The same procedure was applied to the other MDAT formulas. The monthly correction values derived from the Nain hourly observations were applied to Rama, Hebron, Okak, Nain and Zoar, whereas those derived from the Hopedale hourly observations were applied only to Hopedale. The monthly correction values are presented in Tables 2 and 3.

Table 2. Air temperature corrections (°C) used to calculate MDAT for Rama, Hebron, Okak, Nain and Zoar.

Formula	J	F	M	A	M	J	J	A	S	O	N	D
MDAT2-MDAT1	0.3	0.3	0.6	0.8	1.0	1.4	1.3	1.3	1.1	0.6	0.3	0.2
MDAT3-MDAT1	-0.4	-0.7	-0.6	-0.3	-0.2	-0.2	-0.1	-0.4	-0.4	-0.4	-0.3	-0.3
MDAT4-MDAT1	0.5	1.3	1.4	1.5	1.1	1.2	1.2	1.2	1.1	0.7	0.4	0.4
MDAT5-MDAT1	0.2	0.2	0.2	0.3	0.2	0.4	0.4	0.2	0.2	0.1	0.1	0.1
MDAT6-MDAT1	0.1	0.3	0.5	0.7	0.6	0.8	0.8	0.7	0.6	0.3	0.1	0.1
MDAT7-MDAT1	0.1	0.2	0.4	0.5	0.5	0.6	0.6	0.5	0.5	0.3	0.1	0.1
MDAT8-MDAT1	0.0	-0.2	-0.2	-0.1	0.1	0.2	0.2	0.1	-0.1	0.0	0.0	0.0
MDAT9-MDAT1	0.0	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.2	-0.3	-0.1	-0.1	-0.1
MDAT10-MDAT1	0.0	-0.1	-0.2	-0.1	-0.1	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0

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Table 3. Air temperature corrections (°C) used to calculate MDAT for Hopedale.

Formula	J	F	M	A	M	J	J	A	S	O	N	D
MDAT2-MDAT1	0.1	0.2	0.4	0.7	0.4	0.8	0.7	0.6	0.6	0.4	0.2	0.2
MDAT3-MDAT1	-0.3	-0.5	-0.5	-0.3	-0.5	0.0	-0.2	-0.3	-0.3	-0.3	-0.2	-0.1
MDAT4-MDAT1	0.7	1.1	1.2	1.4	1.2	0.9	0.7	0.7	0.8	0.6	0.4	0.5
MDAT5-MDAT1	0.5	0.6	0.8	1.0	0.8	0.8	0.7	0.6	0.7	0.5	0.3	0.3
MDAT6-MDAT1	0.3	0.3	0.5	0.6	0.5	0.4	0.4	0.3	0.3	0.2	0.1	0.1

To address missing values in the historical record, the stable difference method was used, in which monthly mean differences between adjacent stations were used to estimate missing daily or monthly data. This method has been used successfully in previous studies involving sparse historical datasets (Demarée et al., 2020; Singh et al., 2025).

Through this process of temperature standardisation, bias correction and data gap filling, the historical datasets were prepared for comparative statistical analysis with modern and late 18th century climatological conditions. The corrected MDAT data were used to calculate standard climate statistics (monthly, seasonal and yearly means, day-to-day temperature variability [DDTV], thermal seasons, etc., for details see Przybylak et al., 2024) as well as to calculate climate indices such as growing degree days (GDDs), air thawing index (ATI), positive degree days (PDDs) and air freezing index (AFI) (for details see Nordli et al., 2020, Table S2). For AFI, negative daily MDAT values were converted to their absolute values, whereas days with MDAT equal to or above 0 °C were assigned a value of zero. These daily values were summed separately for each month from October to April. AFI is expressed in degree-days (°C d), with higher positive values indicating stronger freezing. Thermal seasons were defined using the thresholds proposed by Baranowski (1968). Winter was defined by temperatures ≤ -2.5 °C, spring and autumn by temperatures > -2.5 °C and < 2.5 °C, and summer by temperatures ≥ 2.5 °C. Season-boundary dates were estimated by linear interpolation between consecutive monthly mean temperatures that bracketed the relevant threshold, with each monthly mean assigned to the 15th day of the month. Each season ended when the following season began. The estimated dates were rounded to the nearest day. Because the boundaries

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were based on monthly mean temperatures, short-lived daily crossings of the thresholds were not considered. The infilled daily MDAT values were included in all index calculations. After infilling, no daily MDAT values remained missing. The detailed analysis of air temperature characteristics, together with our earlier work on the late 18th century (Chmist et al., 2025; Singh et al., 2025), will help improve our understanding of the region's climate variability during the early instrumental period. Quantitative historical-modern comparisons were restricted to Nain and Hopedale, where station-matched modern observations were available. For Rama, Hebron, Okak and Zoar, the historical series are used only to describe historical spatial conditions. Modern Nain is shown as a regional climatic context and is not used to quantify temporal changes at these locations.

3. Results

3.1 Monthly resolution

The annual courses of air temperature from historical records at the six Moravian stations have been compared with the 30-year modern period, September 1990 to August 2020, using data from contemporary meteorological stations in Nain and Hopedale (Fig. 3). In both the historical and modern periods, the warmest month was August and the coldest was February, consistently across all stations. This seasonal structure highlights the persistent influence of the Labrador Current and the Atlantic Ocean in modulating coastal thermal regimes.

The annual temperature range (difference between the warmest and coldest months) in Nain reached 29.4°C during the historical period and 28.7°C in the modern period, suggesting slightly greater climate continentality in the past. According to Ewert's index of continentality (Ewert, 1972), this corresponds to values of 66.7% in the late 19th/early 20th century and 64.9% in the present, indicating a modest reduction in seasonal temperature contrast over time.

The overall thermal difference between the historical and modern periods was most pronounced in Nain, where the mean annual temperature was on average 2.3°C colder in the former period. This cooling was particularly strong in winter (DJF), where anomalies reached −3.5°C, while the smallest difference occurred in spring (MAM), at 0.8°C. Similar patterns were observed at Okak and Hopedale, although the magnitude of historical cooling was lower: 0.5°C and 0.7°C, respectively. Interestingly, both stations recorded slightly warmer spring temperatures in the historical period compared to the present: by 1.3°C in Okak and 2.3°C in Hopedale.

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These variations are likely due to differences in the time spans of the historical series analysed at each station, as well as local influences such as site elevation, sea-ice exposure, and topographic sheltering. At the stations (Rama, Hebron, and Zoar), the historical air temperature series also exhibit patterns largely consistent with those from Nain, falling mostly within one standard deviation (±1 SD) of the modern 30-year mean values. This confirms that, while historical temperatures were generally colder, they remained within the bounds of modern interannual variability, especially in autumn and spring. A slight exceedance of the ±1 SD threshold was observed in autumn months in Nain, suggesting more pronounced inter-seasonal divergence at higher latitudes (Fig. 3).

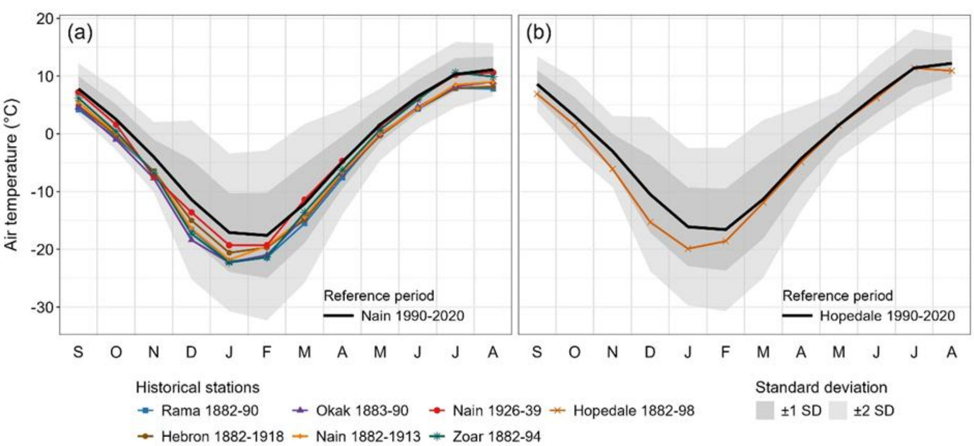

Fig. 3. Mean annual cycles of monthly mean air temperature (°C) for (a) historical Rama, Hebron, Okak, Nain and Zoar, together with modern Nain (1990–2020), and (b) historical Hopedale, together with modern Hopedale (1990–2020). Historical periods are indicated in the figure legend. The grey bands represent ±1 and ±2 standard deviations calculated from the corresponding modern monthly data. Quantitative historical–modern comparisons are restricted to Nain and Hopedale; the Rama, Hebron, Okak and Zoar series are presented only to describe historical spatial conditions.

Table 4. Mean monthly, seasonal and annual values of air temperature on the Labrador coast during the observation period (1882-1892) and their differences from the Nain data.

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Station	S	O	N	D	J	F	M	A	M	J	J	A	SON	DJF	MAM	JJA	Sep-Aug
Mean temperature (ºC)																	
Rama (R)	4.2	-0.7	-6.5	-16.6	-22.1	-21.4	-15.5	-7.6	0.1	4.3	7.9	7.8	-1.0	-20.0	-7.7	6.7	-5.5
Hebron (He)	4.1	-1.2	-7.4	-17.1	-22.0	-21.6	-14.9	-7.5	-0.3	4.6	8.1	8.1	-1.5	-20.2	-7.6	6.9	-5.6
Okak (O)	4.4	-0.8	-7.7	-18.5	-22.4	-21.5	-14.3	-6.8	-0.1	4.6	8.3	9.0	-1.4	-20.8	-7.1	7.3	-5.5
Nain (N)	5.6	-0.5	-7.3	-17.0	-22.0	-21.3	-13.5	-6.7	-0.2	5.0	8.7	9.4	-0.7	-20.1	-6.8	7.7	-5.0
Zoar (Z)	5.9	0.0	-7.2	-17.5	-22.6	-21.3	-13.4	-6.1	0.7	5.9	10.7	9.5	-0.4	-20.5	-6.2	8.7	-4.6
Hopedale (Ho)	6.3	0.5	-6.2	-15.5	-20.7	-19.8	-12.3	-5.7	0.5	5.6	10.4	10.4	0.2	-18.7	-5.8	8.8	-3.9
Differences																	
Station	S	O	N	D	J	F	M	A	M	J	J	A	SON	DJF	MAM	JJA	Sep-Aug
R -N	-1.4	-0.2	0.8	0.4	-0.1	-0.1	-2.0	-0.9	0.3	-0.6	-0.8	-1.6	-0.3	0.1	-0.9	-1.0	-0.5
He - N	-1.5	-0.8	-0.1	0.0	0.0	-0.3	-1.5	-0.8	-0.1	-0.4	-0.6	-1.3	-0.8	-0.1	-0.8	-0.8	-0.6
O - N	-1.3	-0.3	-0.5	-1.4	-0.4	-0.2	-0.9	-0.1	0.1	-0.4	-0.5	-0.5	-0.7	-0.7	-0.3	-0.4	-0.5
Z - N	0.2	0.5	0.1	-0.5	-0.6	0.0	0.1	0.7	0.9	0.9	2.0	0.0	0.3	-0.4	0.6	1.0	0.4
Ho - N	0.6	1.0	1.0	1.5	1.3	1.5	1.2	1.0	0.7	0.6	1.6	1.0	0.9	1.4	1.0	1.1	1.1

*Rama (1882 Sep to 1890 Jul)

*Okak (1883 Sep to Aug 1889)

Overall, the results support the interpretation that thermal conditions along the Labrador coast in the late 19th and early 20th centuries, including the observation period (1882-92), were colder than today, especially in winter, but were not outside the modern envelope of natural variability (Table 4, Fig. 3).

To broaden the assessment of thermal differences between the historical period of observations (1882–1892) and modern (1990–2020) period, temperature indices (GDD, ATI, PDD and AFI) derived from MDAT data were analysed for all stations along the Labrador coast (Figs. 4–9).

At Nain and Hopedale, the station-matched comparisons show that historical GDD and ATI values were generally lower than the corresponding modern values, particularly during July and August (Figs. 7 and 9). Historical PDD values during the cold half-year were close to zero from December to February and increased mainly in October and April. Modern PDD values were generally equal to or higher than the historical values. Conversely, historical AFI values were higher during December–February, indicating stronger winter freezing. Together, these indices indicate lower warm-season thermal accumulation and greater cold-season freezing at Nain and Hopedale during 1882–1892 than during the modern index years.

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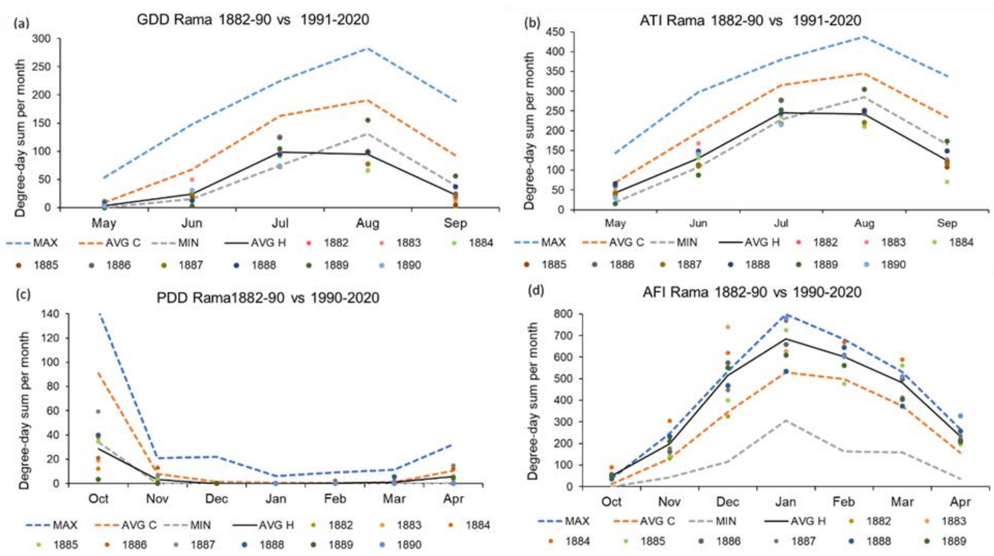

Fig. 4. Temperature indices (GDD, ATI, PDD and AFI) calculated for historical Rama (1882–1890), and modern Nain (1990–2020), shown only as a regional climatic context.

Key: dashed lines – contemporary period, MAX – highest monthly value, MIN – lowest monthly value, AVG C and AVG H – average values for contemporary and historical periods, respectively

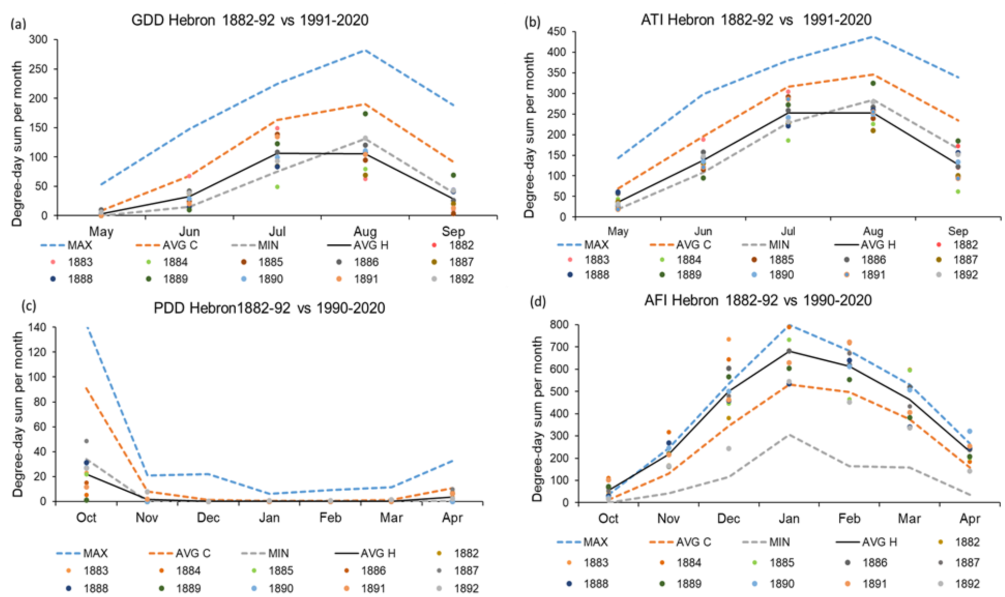

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Fig. 5. Temperature indices (GDD, ATI, PDD, and AFI) calculated for Hebron for historical (1882-92) and modern Nain (1990–2020), shown only as a regional climatic context. Key – as in Figure 4.

The historical index series for Rama, Hebron, Okak and Zoar describe spatial differences among the stations (Figs. 4–6 and 8). At all four stations, GDD and ATI accumulated mainly during the May–September warm season, whereas AFI was greatest during the December–February winter period. Cold-season PDD values were generally close to zero in midwinter and increased mainly during October and April. The differences among the historical stations broadly reflect the coastal latitudinal gradient, with stronger winter freezing at the more northerly stations. Modern values from Nain A are shown only as regional climatic context and are not used to calculate or interpret temporal changes at Rama, Hebron, Okak or Zoar.

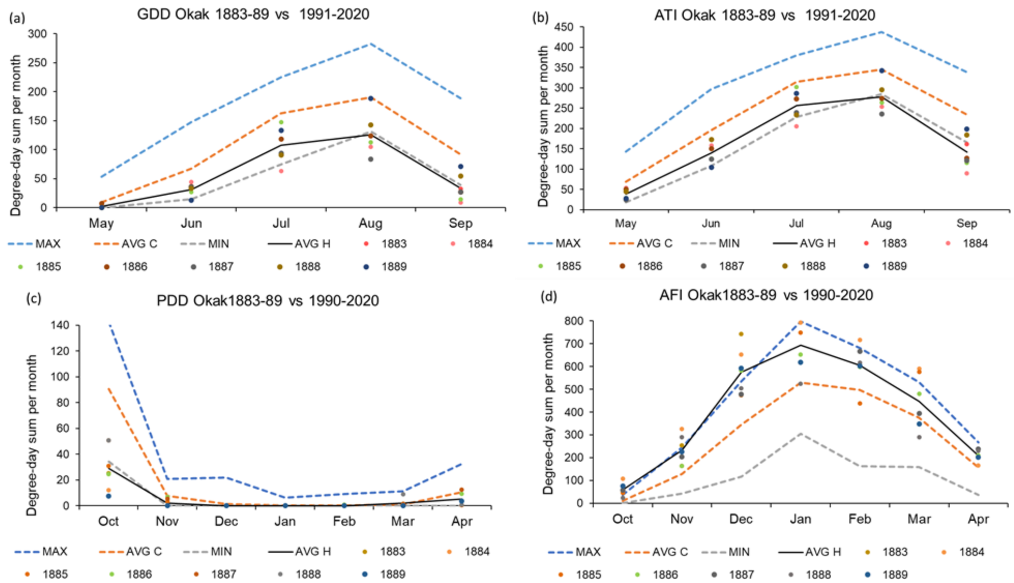

Fig. 6. Temperature indices (GDD, ATI, PDD and AFI) calculated for Okak for historical (1883-89) and modern Nain (1990–2020), shown only as a regional climatic context. Key – as in Figure 4.

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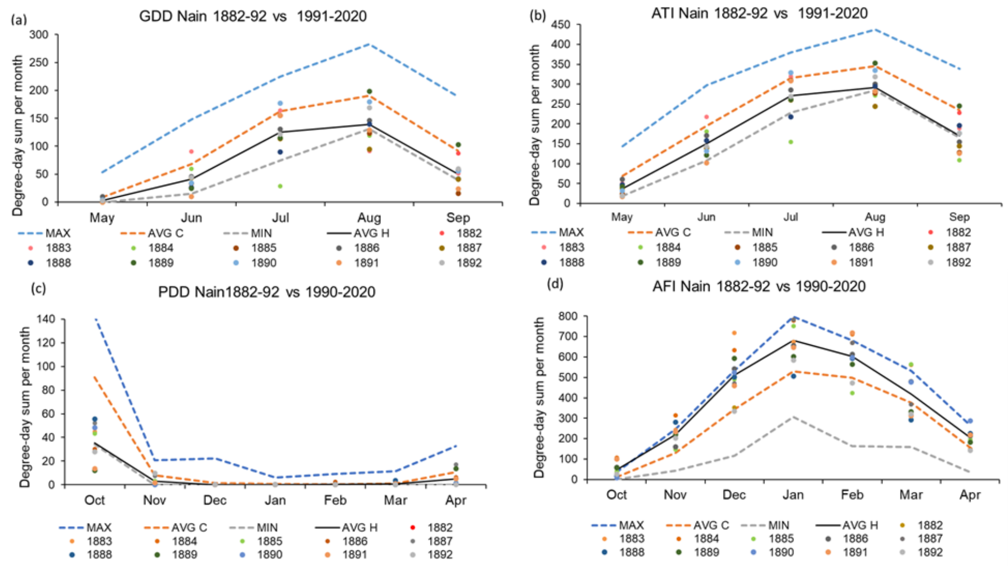

Fig. 7. Comparison of temperature indices (GDD, ATI, PDD and AFI) calculated for Nain for historical (1882-92) and contemporary (1990–2020) periods.

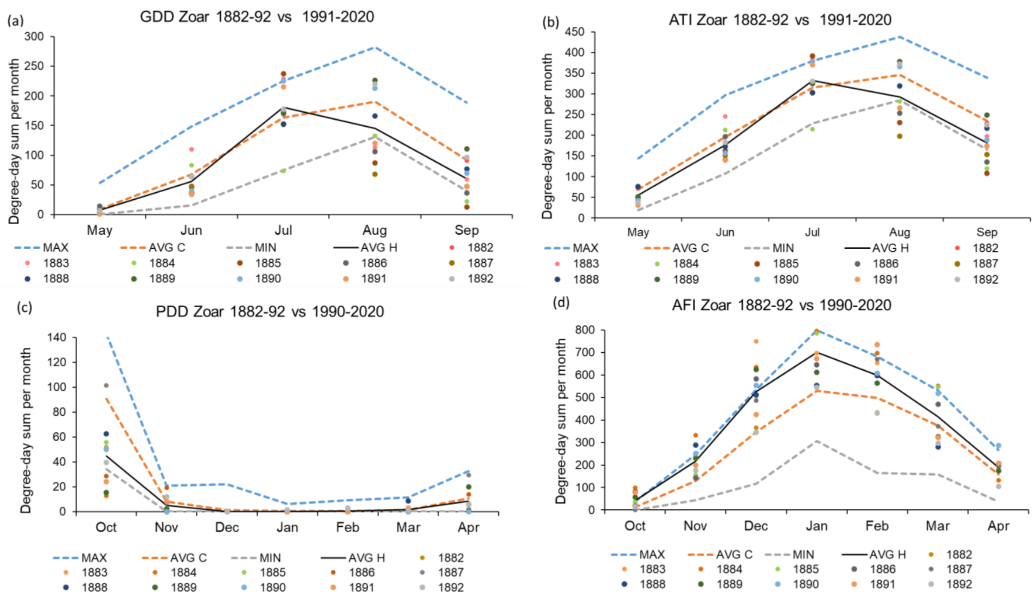

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Fig. 8. Temperature indices (GDD, ATI, PDD and AFI) calculated for Zoar for historical (1882-92) and modern Nain (1990–2020), shown only as a regional climatic context. Key – as in Figure 4.

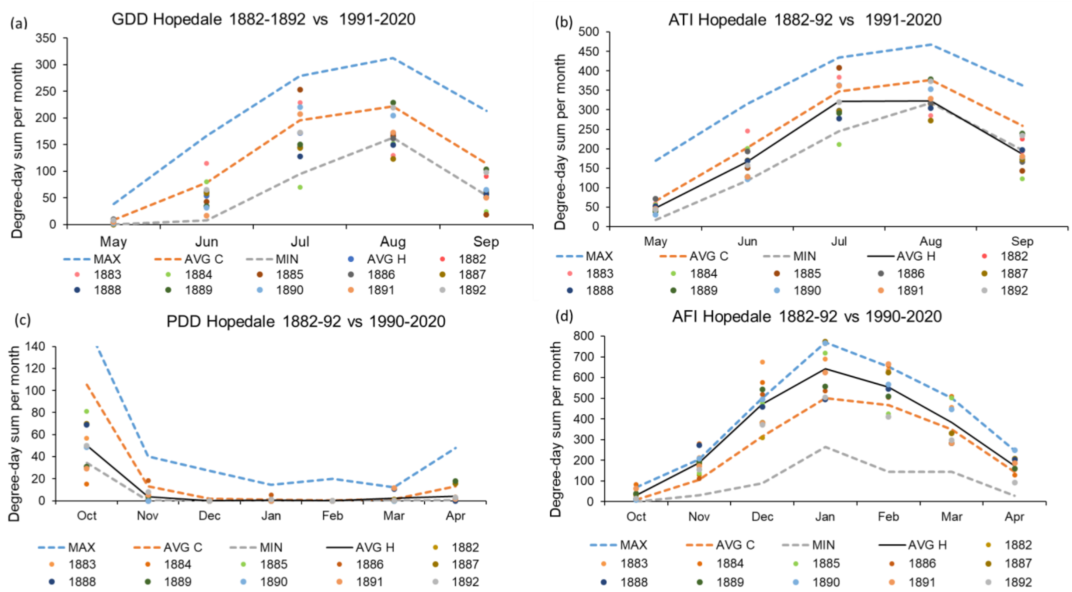

Fig. 9. Comparison of temperature indices (GDD, ATI, PDD and AFI) calculated for Hopedale for historical (1882-92) and contemporary (1990–2020) periods. Key – as in Figure 4.

3.2 Daily Resolution

The annual courses of MDAT for Nain, Okak, Hopedale, Zoar, Rama, and Hebron during their respective historical periods show a clear and coherent seasonal structure that closely resembles the modern climatological regime (1990–2020) (Fig. 10). In all cases, maximum temperatures occur in August and minimum values in February, confirming the persistence of a maritime-controlled annual temperature cycle along the Labrador coast. Although the seasonal timing remains stable, differences in temperature magnitude are evident between the historical and contemporary periods. The most pronounced deviations are observed during the winter season. At all stations, historical winter temperatures were lower than the 1990–2020 mean. The strongest negative anomalies occur at the more northerly stations, particularly Hebron and Rama, where mid-winter temperatures approach or occasionally exceed the distance of 1 SD threshold relative to modern mean values (Fig. 10). Nevertheless, historical winter values generally remain within the ±2 standard deviation envelope derived from the contemporary

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dataset, indicating that the observed cooling does not exceed the range of modern interannual variability.

In contrast, differences during spring and summer are considerably smaller. In several cases, especially at Hopedale and Okak, late-spring and early-summer temperatures in the historical period are close to or only slightly below present-day means. The summer months show the smallest overall divergence, with historical values typically remaining well within ±1 SD of the modern average (Fig. 10). A spatial gradient is also evident. The magnitude of historical winter cooling decreases southward, with Hopedale exhibiting weaker anomalies than Hebron and Rama. This pattern suggests that northern stations are more sensitive to cold-season atmospheric circulation and sea-ice conditions, whereas southern stations experience a comparatively moderate response.

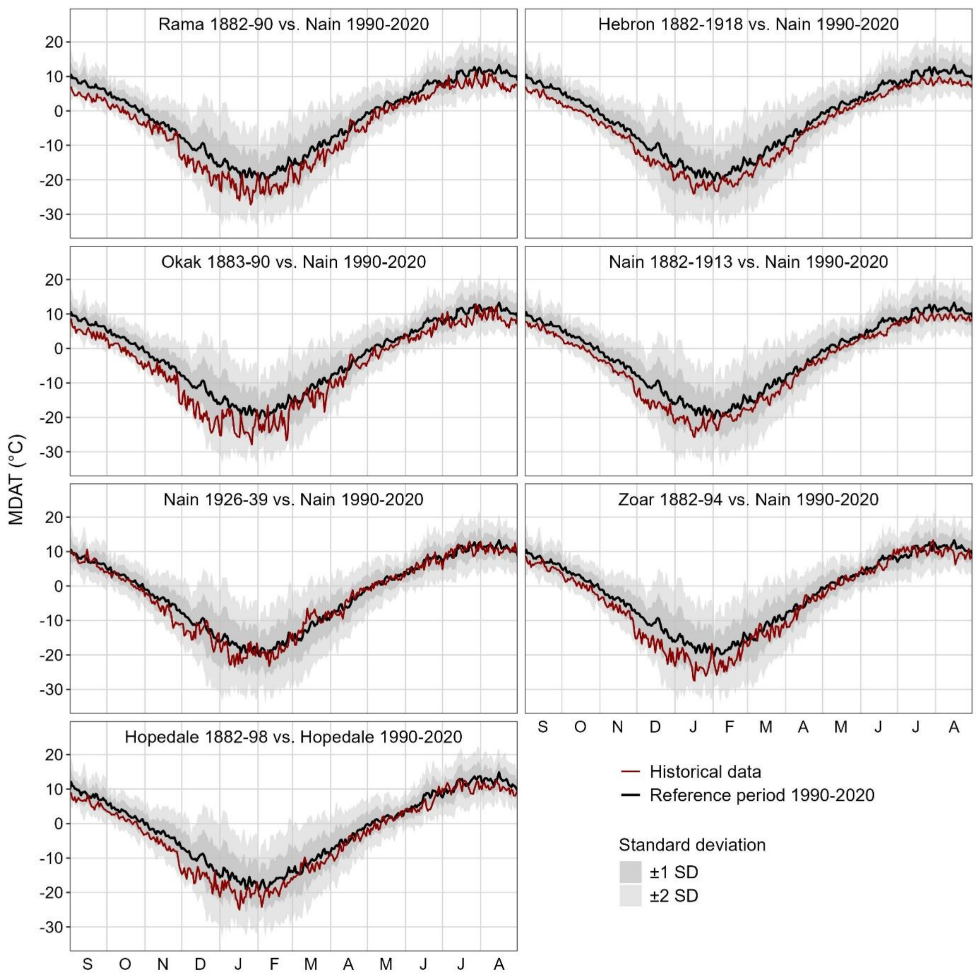

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Fig. 10. Mean annual cycles of MDAT (mean daily air temperature) at Rama, Hebron, Okak, Nain, Zoar and Hopedale during their respective historical periods (red lines), together with modern station data (1990–2020; black lines). Modern data are from Nain (the Rama, Hebron, Okak, Nain, and Zoar panels) and from Hopedale (the Hopedale panel). The dark- and light-grey bands represent ±1 and ±2 standard deviations, respectively, calculated from the corresponding modern station data. Quantitative historical-modern comparisons are restricted to Nain and Hopedale. For Rama, Hebron, Okak and Zoar, modern Nain is shown only as a regional climatic context.

Overall, the historical annual temperature courses indicate systematically colder winter conditions during the late nineteenth and early twentieth centuries, but without a fundamental alteration of the seasonal temperature regime. The differences relative to the modern period are primarily quantitative, reflecting lower cold-season means rather than structural changes in the annual thermal cycle (Fig. 10).

Averaging can sometimes significantly obscure important climatic details (Przybylak et al., 2016; Przybylak & Wyszyński, 2017). To address this issue, a more detailed representation of thermal conditions along the Labrador coast during the observing period (1882–1892) is provided using daily-resolution data. One of the approaches applied is the analysis of relative frequencies of occurrence (in %) of (MDAT) in the historical and contemporary periods. The relative frequencies of MDAT were stratified into 1 °C intervals (Figs 11), and the distributions were characterised by skewness (γ_1) and kurtosis (γ_2). At Nain, skewness values ranged from −0.68 (MAM) to 0.62 (JJA) during the historical period and from −0.50 to 0.36 during 1990–2020. The reported kurtosis values were generally between −0.63 and 0.23. These statistics were used only as descriptive measures of distribution shape and not as tests of normality. Warmer temperature classes occurred more frequently during 1990–2020, particularly in autumn and summer, whereas the historical and modern distributions were most similar in spring.

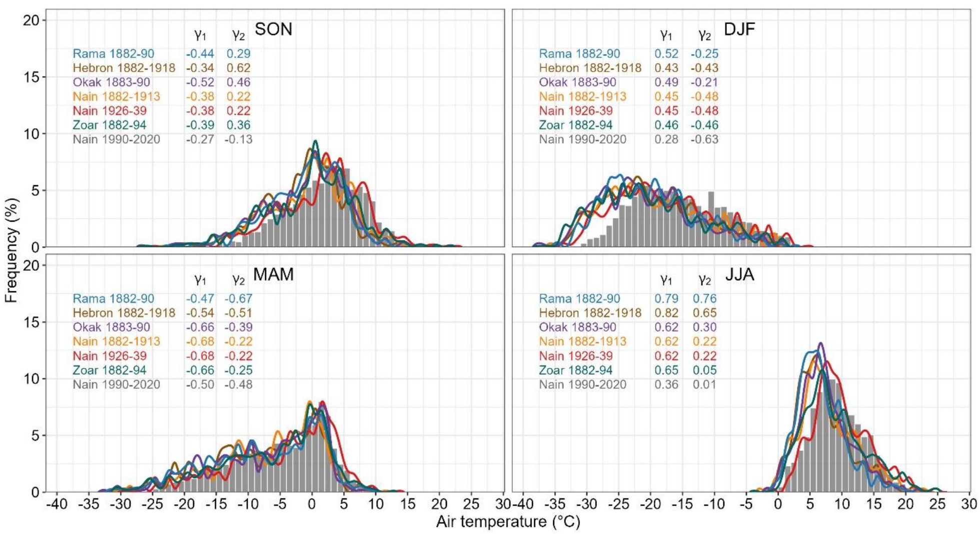

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Fig. 11. Seasonal relative frequencies of occurrence (%) of MDAT at Rama, Hebron, Okak, Nain and Zoar during their available historical periods (lines). The modern Nain distributions for 1990–2020 (bars) are shown as a regional climatic context. Skewness (γ_1) and kurtosis (γ_2) values for the historical station series and modern Nain are also shown.

The historical frequency distributions at Rama, Hebron, Okak and Zoar are shown in Fig. 11. The summer distributions at Rama and Hebron had relatively strong positive skewness, with values of 0.79 and 0.82, respectively. At Okak, historical skewness ranged from −0.66 in spring (MAM) to 0.62 in summer (JJA), while Zoar showed intermediate distributional characteristics. Skewness and kurtosis are reported only as descriptive measures of historical distribution shape. The modern Nain distributions shown in Fig. 11 provide a regional climatic context and were not used to quantify temporal changes at these stations.

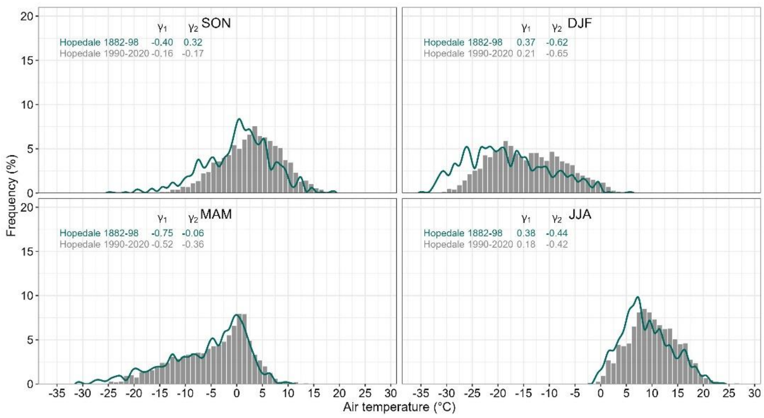

Fig. 12. Seasonal (September–November, December–February, etc.) relative frequencies of occurrence (in %) of MDAT in Hopedale in historical time (1882-1898, lines) and at present (1990–2020, bars). Values of skewness ($\gamma 1$) and kurtosis ($\gamma 2$) for historical (h) and contemporary (c) times are also shown.

At Hopedale, the historical and modern distributions were similar during the winter half-year, while larger differences occurred in summer (Fig. 12). Summer skewness was 0.39 in 1882–1898 and 0.18 in 1990–2020, showing a more pronounced warm tail in the historical period. Across both periods and all seasons, skewness ranged from −0.75 to 0.39 and kurtosis from −0.61 to 0.33. These values were used to describe the shapes of the distributions.

Overall, the historical seasonal MDAT frequency distributions differed among the stations, particularly in winter and summer. Direct historical–modern comparisons were restricted to Nain and Hopedale. Skewness and kurtosis were treated only as descriptive measures of distribution shape and were not used to infer normality or equivalence between the historical and modern periods.

The relative frequency of different characteristic days in Nain during the historical period 1882–1892 is shown in Fig. S1. The extremely cold days (MDAT < −25 °C), very extremely cold days (MDAT < −30 °C), and exceptionally cold days (MDAT < −35 °C) occurred predominantly between December and March, with only sporadic occurrences in other months of the cold half-year. The remaining categories of cold days, representing progressively higher temperature thresholds (MDAT < −20 °C, < −15 °C, < −10 °C, and < −5 °C), were observed

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over a broader seasonal window, extending throughout the entire cold half-year from November to April.

All categories of warm days (i.e., MDAT > 5 °C, > 10 °C, > 15 °C, and > 20 °C) were recorded in Nain during the historical period, mainly from June to September, with the highest frequencies in July and August. In May and September, selected warm-day categories were also observed, albeit at considerably lower frequency, reflecting transitional thermal conditions. From May to September, positive MDAT values clearly dominated, whereas from October to April, negative MDAT values prevailed (Fig. 13). Nevertheless, both positive and negative MDAT values occurred during transitional months, particularly in May and October, indicating substantial intra-seasonal variability.

Figs. S2–S6, which illustrate the frequency of occurrence of characteristic days in Okak, Hopedale, Hebron, Zoar, and Rama, respectively, reveal a high degree of spatial coherence in the annual distribution of thermal categories along the Labrador coast. At all stations, extremely cold days were largely confined to the winter core months (December–March), while moderate cold days spanned the full cold half-year. Warm days were restricted to a short summer season (June–September), with peak occurrence in midsummer. Northern stations, particularly Rama and Hebron, display slightly stronger winter dominance and a somewhat shorter warm season compared to the more southerly stations (Hopedale and Nain), whereas Okak and Zoar exhibit intermediate characteristics. Despite these latitudinal differences, the overall structure of characteristic-day distributions remains remarkably similar across the region, confirming the spatial consistency of the late nineteenth-century maritime subarctic thermal regime.

The annual courses of historical–modern differences in the frequency of characteristic days at Nain and Hopedale are shown in Figs. 13 and 14, respectively. The extremely cold days (MDAT < −25 °C), very extremely cold days (MDAT < −30 °C), and exceptionally cold days (MDAT < −35 °C) were generally more frequent in the historical period, particularly from December to March and sporadically in other months of the cold half-year. The remaining categories of cold days (warmer than the previous ones) were also the most frequent in the historical period during the entire cold half-year (from November to April), although the differences were smaller than for the most extreme categories.

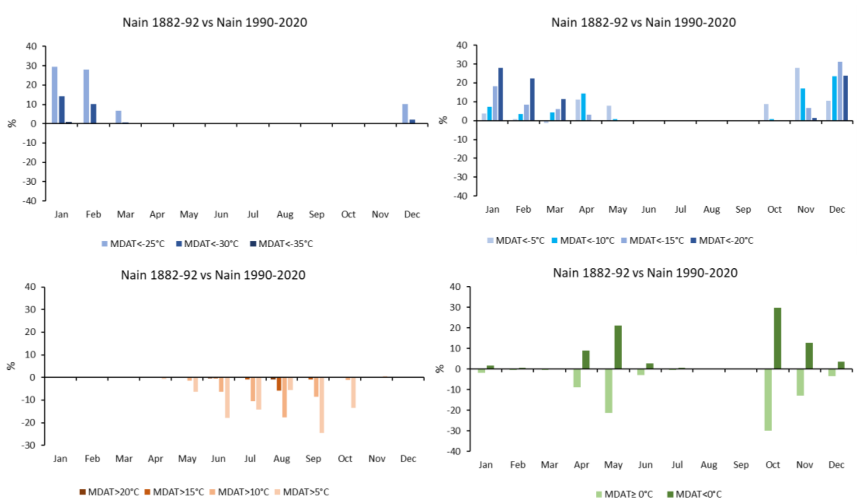

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Fig. 13. Annual courses of differences between the number of characteristic days (in %) in Nain in the historical and modern (1990–2020) periods. The differences were obtained by subtracting the modern values from the historical ones.

Thus, these statistics indicate that more severe winter conditions were observed during 1882–1892 than in the modern period. In contrast, the modern period is characterised by an increase across all categories of warm days, particularly during the summer months (June–August), with a lesser increase in September and a smaller one in October. Only in isolated months were selected warm-day categories slightly more frequent in the historical period, but these cases were rare and did not change the general pattern.

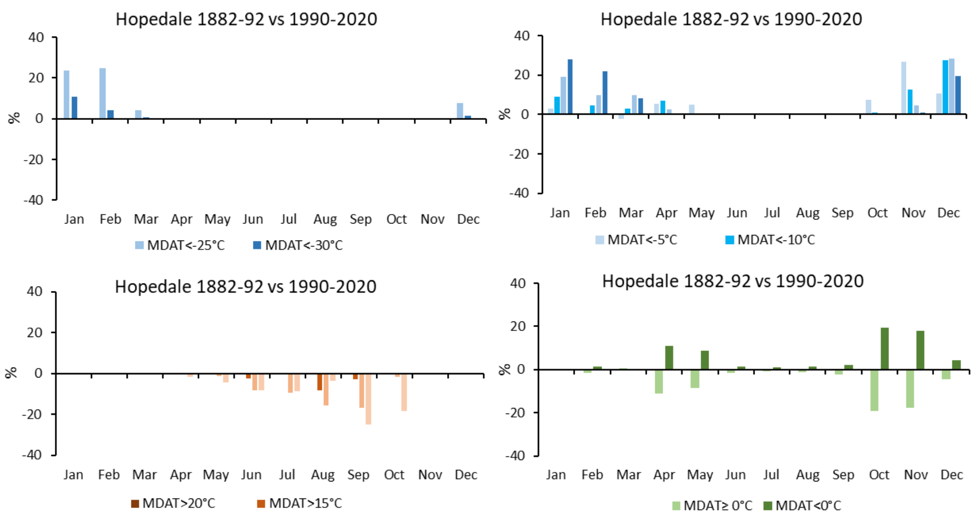

Fig. 14. Annual courses of differences between the number of characteristic days (in %) in Hopedale in historical and modern (1990–2020, Hopedale) periods. The differences were obtained by subtracting the modern values from the historical ones.

At Nain and Hopedale, days with MDAT < 0 °C were more frequent during the historical period, particularly in winter. Days with MDAT ≥ 0 °C were more frequent during 1990–2020, mainly from late spring to early autumn. Smaller differences of both signs occurred during the transitional months.

Annual courses of DDTV at the six stations during the historical periods are presented in Fig. 15. All stations show a distinct seasonal cycle, characterised by higher DDTV during the cold season and lower values in late spring and early autumn. DDTV increases markedly in November and generally remains high from December to March. During this period, the Gaussian-filtered values reach approximately 4.0–5.5 °C, while individual unfiltered values occasionally exceed 8 °C at Nain, Okak, and Hopedale. DDTV subsequently decreases during

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spring, reaching annual minima of approximately 1.5–2.5 °C in May or early June. A secondary increase occurs in July and early August, when the filtered values generally range from approximately 2.5 to 4.0 °C. Despite moderate differences in magnitude among the stations, the timing of the cold-season maximum and late-spring/early-summer minimum is broadly consistent.

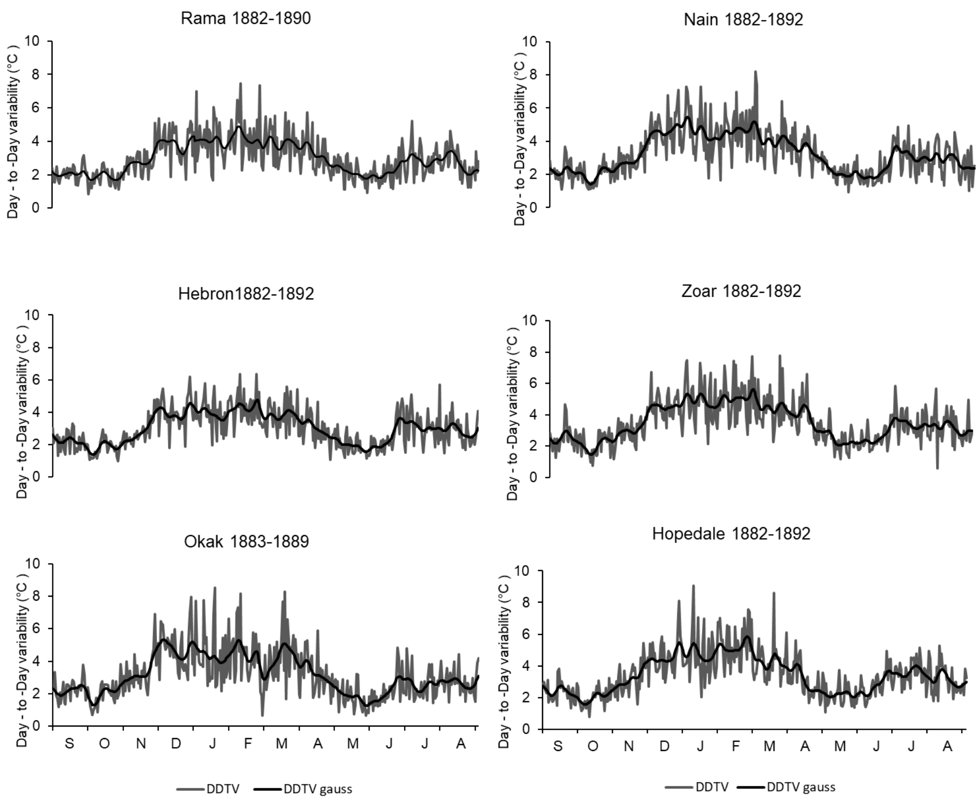

Fig. 15. Annual courses of day-to-day air temperature variability (DDTV) at the six stations during the historical periods. Individual days (grey) are filtered by a Gaussian low-pass filter (black) with a standard deviation of 3 d in its distribution, corresponding to a rectangular filter of about 10 d.

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For the DDTV comparison, 2010–2020 was selected to represent the most recent part of the modern record. At Nain and Hopedale, DDTV was generally higher in the historical records than during 2010–2020, particularly from November to March (Fig. 16). The differences were smaller and generally closer to 0 °C during late spring and summer. At both stations, the historical–modern difference in DDTV was most evident during the cold season.

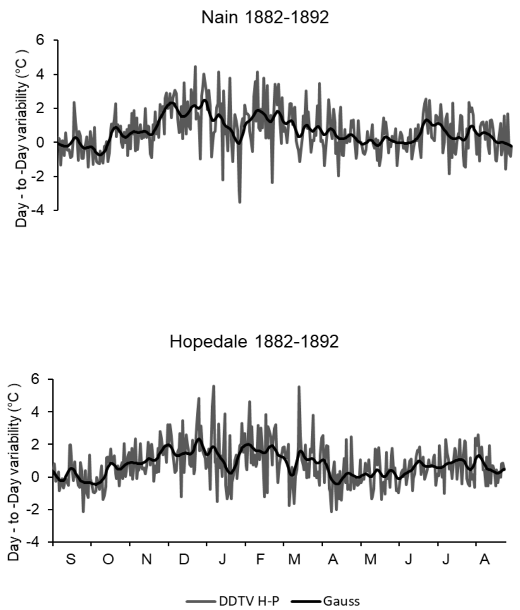

Figure 16. Differences in DDTV between the historical Nain and Hopedale periods and the contemporary (2010-2020) period. Individual daily differences (grey) are filtered by a Gaussian low-pass filter (black) with a standard deviation of 3 d in its distribution, corresponding to a rectangular filter of about 10 d.

To better understand seasonal boundaries in the Arctic, where conventional calendar-based classifications often mask a prolonged winter and a flatter annual cycle, we adopted the thermal criteria established by Baranowski (1968). Across Rama, Hebron, Okak, Nain, Zoar and Hopedale, winter was the longest thermal season. Mean historical winter duration ranged from 182.4 days at Hopedale to 196.7 days at Hebron, while historical summer duration ranged from 113.2 days at Hebron to 130.3 days at Hopedale. Quantitative historical–modern comparisons were restricted to Nain and Hopedale. At Nain, the historical winter was 21.2 days longer, and the summer was 25.3 days shorter than the corresponding durations derived from the 1990–2020 mean annual temperature cycle. At Hopedale, the historical winter was 18.4 days longer, and the summer was 19.7 days shorter. Differences in autumn and spring duration were small at both stations (Fig. 21).

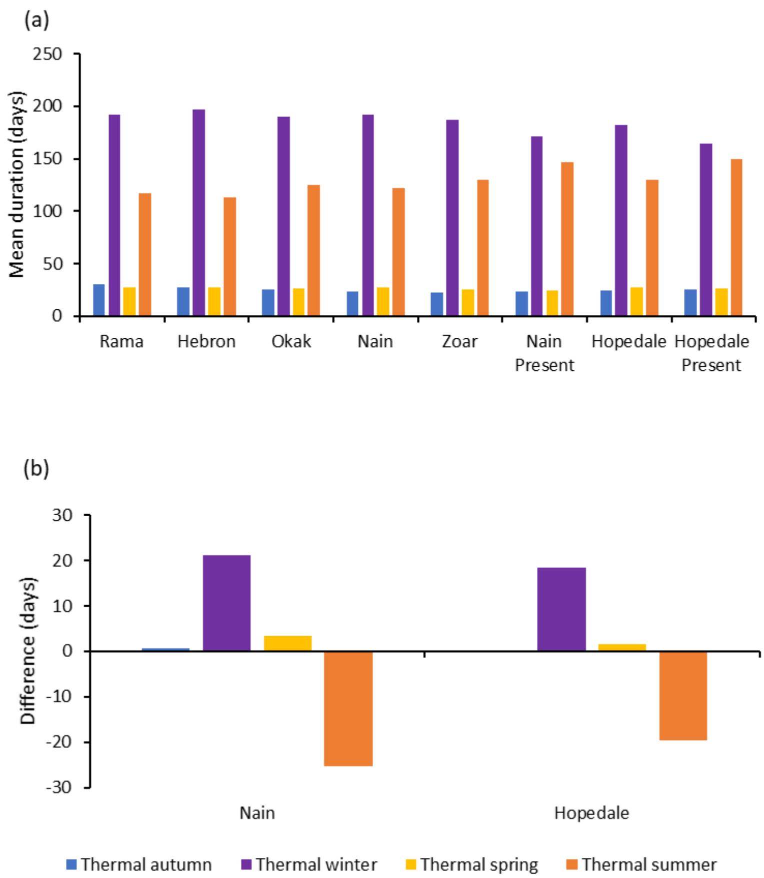

Fig. 17. (a) Mean historical thermal-season durations at the six Labrador stations and corresponding 1990–2020 values for Nain and Hopedale. (b) Historical–modern differences at Nain and Hopedale, calculated as historical minus 1990–2020 values.

4 Discussion

Early nineteenth-century accounts of the Labrador coast provide valuable contextual insight for interpreting the instrumental temperature records examined in this study. Contemporary descriptions portray the peninsula as extending roughly between 50° and 61° N, bordered by Hudson Strait to the north, the Atlantic Ocean to the east, and the Gulf of St. Lawrence to the south. The coastline is shown as steep and uneven topography, marked by numerous inlets,

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small bays, and offshore rocky islands, while the interior is mountainous, intersected by marshes, lakes, and numerous streams, and consists of elevated terrain interspersed with wetlands, lakes, and dense river networks (The Moravians in Labrador, 1835). These environmental characteristics promote strong maritime influence, increase exposure to cold northerly air masses, and contribute to pronounced seasonal variability in sea-ice conditions. The same historical source also highlights the dangers of coastal navigation, including submerged hazards and frequent fog, underscoring the severity of the regional climate. These qualitative observations closely correspond with temperature patterns reconstructed from missionary records, particularly the pronounced winter cooling and limited summer warmth evident also in the late nineteenth and early twentieth centuries. Taken together, these lines of evidence indicate that the historical temperature regime developed within a geographically constrained and climatically sensitive subarctic North Atlantic setting (The Moravians in Labrador, 1835).

The findings are consistent with Tietze's (1950) description of severe winter conditions along the Labrador coast. The high historical AFI values and frequent negative MDATs support this interpretation. At Nain and Hopedale, comparisons with 1990–2020 show lower freezing intensity and higher GDD and ATI values in the modern period, indicating warmer growing seasons. The historical results from Rama, Hebron, Okak and Zoar describe spatial differences and were not used to assess change over time.

The result that Nain was, on average, 2.3°C colder during the historical period, with winter anomalies reaching -3.5°C, agrees closely with the findings reported by Ouellet-Bernier et al. (2021) for the same location. Using early instrumental observations from the First International Polar Year, they showed that between 1884 and 1938, the mean annual temperature at Nain was - 4.82°C, roughly 3°C lower than contemporary values, with especially strong winter cooling. Likewise, Singh et al. (2025) documented that Nain temperatures on the late eighteenth-century Labrador coast were about 1.4°C lower than modern conditions, with the largest increase observed during the cold season (~2.5°C). Our data suggests that winter-focused warming is a persistent multi-century regional pattern rather than an anomaly caused by isolated station records or short-term fluctuations.

The low winter temperatures recorded at all six Moravian stations, from Hopedale in the south to Hebron and Okak in the north, are consistent with severe historical winter conditions reported elsewhere in the region. Ouellet-Bernier et al. (2023) found that temperatures in the Hudson Strait region (Kangiqsujuaq, Quaqtaq and Killiniq) during 1880–1950 were approximately 1.5 °C lower than recent values and documented several particularly harsh winters.

At the regional scale, Way and Viau (2015) estimated an overall warming of approximately 1.5 °C in Labrador between 1881 and 2011, with the greatest warming occurring in winter. The approximately 2.3 °C historical-modern difference found at Nain is slightly larger than this regional estimate and may reflect local sensitivity to sea-ice conditions and atmospheric circulation.

Temperature indices and growing season changes

At Nain and Hopedale, GDD and ATI were lower during the historical period than during 1990–2020, indicating cooler growing-season conditions (Figs. 7 and 9). Singh et al. (2025) found a similar pattern for the late eighteenth century. The results for Rama, Hebron, Okak and Zoar

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are discussed only as historical spatial differences because station-matched modern observations are not available

At Nain and Hopedale, AFI values from December to February were higher during the historical period than during 1990–2020, indicating stronger winter freezing. Ouellet-Bernier et al. (2021) also described periods of severe cold and early sea-ice formation along the Labrador/Nunatsiavut coast around the beginning of the twentieth century. These historical accounts provide a regional context for the high AFI values found in this study.

Large-scale climatic forcing

Previous instrumental and proxy-based studies also demonstrate substantial spatial and temporal variability in Labrador climate. Banfield and Jacobs (1998) documented regional patterns of temperature and precipitation across Newfoundland and Labrador, while D'Arrigo et al. (1996, 2003) used tree-ring records to reconstruct annual-to-multidecadal climate variability in the Labrador region. Labrador Sea ice variability is also associated with changes in North Atlantic sea-surface temperatures and large-scale atmospheric circulation (Deser et al., 2002).

The historical records show that winter conditions at Hopedale were milder than at the other stations. This spatial pattern may be related to regional differences in sea-ice conditions and atmospheric circulation. Enfield et al. (2001) identified a cool AMO phase during 1905–1925, while Ouellet-Bernier et al. (2021) noted that negative AMO values from the late nineteenth century to around 1920 coincided with extensive Arctic sea-ice cover. After 1925, positive AMO values occurred together with positive temperature anomalies. These regional changes provide context for the historical-modern differences found at Nain and Hopedale, but their influence was not tested directly in this study.

In addition, Ouellet-Bernier et al. (2023) reported that strongly positive NAO phases coincided with cold winters in the Hudson Strait region during 1883–1885, 1906–1907 and 1913–1914. A positive NAO strengthens the pressure gradient between the Icelandic Low and the Azores High and affects atmospheric circulation over the North Atlantic (Hurrell, 1995). Some of these cold intervals overlap the historical records examined here. However, the relationship between the NAO and temperatures at the six stations was not tested directly, and the NAO is therefore discussed only as a regional climatic context.

At both Nain and Hopedale, spring was cooler during 1882–1892 than during 1990–2020. The historical–modern difference was −1.6 °C at Nain and −1.1 °C at Hopedale (Fig. 3). This differs from findings for other parts of the Arctic. Przybylak and Vízi (2005) reported warmer springs in the Canadian Arctic during 1819–1859 relative to 1961–1990. Przybylak et al. (2010) also found that spring during the First International Polar Year (1882/83) was slightly warmer than the 1961–1990 reference period, with the largest difference occurring in April. However, these studies cover different locations, periods and reference intervals and are therefore not directly comparable with the present results.

Natural variability versus long-term warming

At Nain and Hopedale, most historical monthly values fell within the ±2 SD envelopes calculated from the 1990–2020 observations (Fig. 3). These envelopes show the position of the historical values relative to the modern distributions and were not used as statistical tests of

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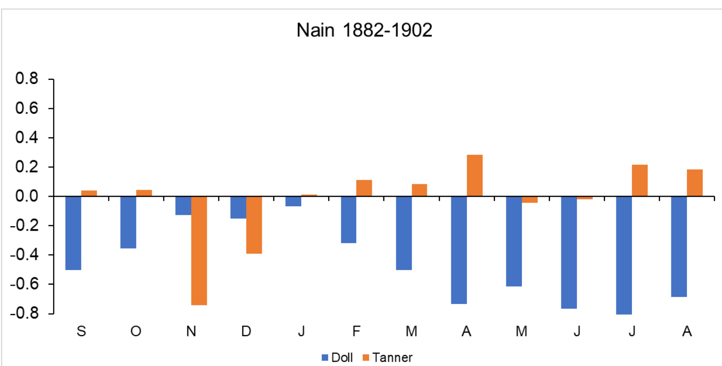
equality or natural variability. Markedly cold and warm years along the Labrador/Nunatsiavut coast have also been documented by Ouellet-Bernier et al. (2021). At broader spatial and temporal scales, decreases in high-frequency and cold-season temperature variability have been associated with warming (Karl et al., 1995; Screen, 2014). These studies provide a general context, as trends and mechanisms of temperature variability were not tested here. The frequency distributions, skewness and kurtosis were interpreted only as descriptive measures.

Taken together, the station-matched comparisons show that historical conditions at Nain and Hopedale were colder than during 1990–2020, particularly in winter. Both stations had greater historical freezing intensity, more cold days, longer winters and shorter summers. Similar historical–modern contrasts have been reported for early instrumental records from the Canadian Arctic (Przybylak & Vízi, 2005) and the Labrador coast (Singh et al., 2025). The records from Rama, Hebron, Okak, and Zoar describe only historical spatial conditions. Changes in sea ice and large-scale atmospheric circulation provide a possible regional context, but their effects were not tested directly in this study. The warmer modern conditions at Nain and Hopedale are consistent with the long-term regional warming reported for Labrador by Way and Viau (2015).

The historical records also show marked differences among individual years. Tanner (1944) identified 1901 as an unusually warm year at Nain and Hebron. Döll (1937) reported a south-to-north decrease in mean annual temperature during 1883–1902, from −3.0 °C at Hopedale (Hoffenthal) to −3.8 °C at Zoar, −4.4 °C at Nain and −4.6 °C at Hebron. These earlier results provide historical context for the temporal and spatial variation found in the Moravian observations but were not compared directly with the 1990–2020 reference period. The causes of individual warm or cold years were not examined in this study.

The larger historical–modern temperature differences in winter than in the warmer seasons at Nain and Hopedale are consistent with seasonal contrasts reported for the nineteenth-century American Arctic (Przybylak & Vízi, 2005; Vízi, 2008). Earlier studies indicate that sea-ice conditions and the Labrador Current influence the climate of coastal Labrador (Newell, 1990; Halfar et al., 2013).

We compared our corrected mean monthly data for Nain from 1882 to 1902 with those published by Döll (1937) and Tanner (1944), who utilised only the weighted average (T8+T14+2T21)/4, without correction to the "real" daily mean calculated from 24 measurements per day. The comparison shows that the three datasets have nearly identical seasonal temperature distributions, but Döll's data exhibit a warm bias in all months,



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particularly pronounced from May to September (0.5-0.8°C) (Fig. 18). On the other hand, Tanner's data revealed mainly a negative monthly bias, except for four months having a warm bias, particularly in November and December.

Fig. 18. Differences in monthly mean air temperature (°C) for Nain during 1882-1902 between MDAT data calculated in this study and those reported by Döll (1937) and Tanner (1944). The latter two datasets were subtracted from our corrected MDAT data.

5 Conclusions and Final Remarks

The presented comprehensive study based on quality-controlled and bias-corrected air temperature series from six Labrador stations (Nain, Okak, Hopedale/Hoffenthal, Hebron, Zoar, and Rama) for the late 19th and early 20th centuries (primarily 1882-1892), allows us to formulate the following conclusions:

- Thermal conditions along the Labrador coast during the late 19th and early 20th centuries were generally colder than in the present-day period (1990–2020). The strongest cooling occurred in winter, confirming that cold-season temperatures are the most sensitive to long-term climatic changes in this region. For example, in Nain, the mean annual air temperature was approximately 2.3 °C lower than today, with winter anomalies reaching about -3.5 °C. The other four stations were used only to describe historical spatial conditions.
- At Nain and Hopedale, most historical monthly values fell within the ±2 standard deviation envelopes of the corresponding 1990–2020 station distributions. These envelopes were used only for descriptive comparison, not as a test of natural variability or of equality between the historical and modern periods.
- The historical period was characterised by more frequent cold days and fewer warm days than the modern period (1990-2020).
- Temperature indices (GDD, ATI, PDD, AFI) confirm that the past climate had shorter growing seasons and stronger winter freezing conditions compared to today.
- The annual course of DDTV was broadly similar in the historical and contemporary periods. However, DDTV was generally greater during the historical period from November to March, whereas only small differences were observed in late spring and summer.
- At Nain and Hopedale, cold days were more frequent and warm days less frequent during the historical period than during 1990–2020.
- According to Ewert's index, the climate was slightly more continental during the historical period than at present.
- The observed changes are consistent with long-term regional warming, likely influenced by sea-ice variability and large-scale atmospheric circulation patterns.

Some uncertainties will still remain, for example, mainly related to the unknown exposure of thermometers and their quality. However, the data correction we carried out certainly significantly reduced the potential errors resulting from the lack of the above-mentioned information. Also, consistency across various stations and with independent studies substantiates the strength of the reconstructed thermal conditions. While it is unlikely that another comprehensive instrumental dataset for the coast of Labrador exists, there is still the possibility of using qualitative data (e.g., from missionary diaries, reports, or other historical sources). They may serve as a basis for further expanding our knowledge of the climate and its changes during the period under study, especially for years for which instrumental observations are unavailable.

Finally, the reconstructed monthly air temperature series derived from this research and resulting climatic indices will provide significant contributions to the science of climatology in the Arctic and sub-Arctic since they provide important validation points for proxy-based reconstructions as well as for models used to simulate past climates during an era of dramatic change from the end of the Little Ice Age to the modern warming of the last decades.

Data availability. Datasets for this research were derived from the following public domain resources:

1. Repository for Open Data (RepOD), Nicolaus Copernicus University Centre for Climate Change Research collection, as cited in https://repod.icm.edu.pl/dataset.xhtml?persistentId=doi:10.18150/YRJLV9
2. Canadian Centre for Climate Services, https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Author contributions. Garima Singh: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Interpretation of results, Writing – original draft, Writing – review & editing. Rajmund Przybylak: Conceptualization, Methodology, Investigation, Data collection and selection, Formal analysis, Funding acquisition, Project administration, Validation, Supervision, Interpretation of results, Writing – original draft, Writing – review & editing. Przemysław Wyszyński: Conceptualization, Data collection and selection, Software, Visualisation, Validation. Andrzej Araźny: Conceptualization, Data collection and selection, Validation. Konrad Chmist: Data curation, Visualisation.

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