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Changes in thermal indices on Herschel Island (Qikiqtaruk, Canada) between the periods 1899–1905 and 2008–2014

Krzysztof JARZYNA

Faculty of Geography and Regional Studies, University of Warsaw, Krakowskie Przedmieście 30, 00-927 Warszawa, Poland

<k.jarzyna3@uw.edu.pl>

Abstract: The paper provides a comparison of minimum air temperature (TN), maximum air temperature (TX), mean air temperature (T_{mean}) and a few derived temperature indices for Herschel Island (Qikiqtaruk) in the Yukon Territory, Canada for the periods 1899–1905 and 2008–2014. A significant increase in the TN was noted at +4.2°C, which was a larger increase than that for both T_{mean} (+3.7°C) and TX (+3.5°C). Air temperature increased the most in October, November, and December. In addition, the length of the frost-free season increased by 26 days and the length of the growing season increased by 25 days from the early 20th century to the early 21st century. The increase in the TN also triggered a change in the plant hardiness zone where Herschel Island is located. However, the daily air temperature range declined over the course of the study period as well as the annual total of heating degree days and the number of exceptionally cold days. No statistically significant change in the number of freeze-thaw days was found for the studied periods.

Keywords: Arctic, Yukon Territory, air temperature, temperature indices.

Introduction

The Arctic is the fastest warming region of the world, which is known as Arctic amplification (Serreze and Barry 2011). Trends as well as the variability in the surface air temperature in the Arctic are larger than in the other parts of the globe. This intense warming strongly affects the functioning of ecosystems and the quality of life for humans living in the Far North (Larsen *et al.* 2013).

The increasing Arctic air temperature trend was detected via an analysis of long-term meteorological data series. Measurements conducted in the Arctic in the late 19th century and early 20th century are of particular importance. Most of 19th century climate data come from research or whaling expeditions to this part of the world. Measurements were obtained either for a single winter season when ships would become trapped in sea ice (Przybylak and Vizi 2005) or single summer season when whaling ships would traverse the region (Brohan *et al.* 2010).

Longer air temperature data series from the late 19th century and early 20th century are quite rarely available. A total of 25 stations were operational during the First Polar Year from April 1882 to April 1883 (Wood and Overland 2006). An even longer meteorological data series was generated during an expedition headed by Fridtjof Nansen (Przybylak 2002) when his ship, the *Fram*, drifted in Arctic waters for three years (1893–1896). However, this data series did not come from one site. The oldest weather stations located in the Arctic that have been providing continuous measurements since the 19th century are located along the western coast of Greenland and in northern Norway (Førland *et al.* 2002).

In the western part of the Canadian Arctic, the first weather stations were established in the 1890s in mining towns and at trading posts along the Yukon and Mackenzie rivers. The weather station at Simpson Point on Herschel Island was also established at that time (Thompson 1948). The weather station on Herschel Island was operational, with some interruptions, from 1896 to 1918 (https://climate.weather.gc.ca/historical_data/). Thus, it is the second oldest weather station, after Barrow, on the coast of the Beaufort Sea. An automatic weather station was installed on Herschel Island in 1994. The station has been in operation ever since, with some interruptions. The availability of these two data series thus makes it possible to compare air temperature in northwestern Canada in the early 20th century and early 21st century.

Annual and monthly T_{mean} values on Herschel Island in the early 20th century and early 21st century have already been compared by Burn and Zhang (2009). The present paper focuses primarily on minimum daily air temperature (TN), maximum daily air temperature (TX) and several air temperature-based climatic indices. It provides a review of changes in these thermal indices in the early 20th century and early 21st century.

Study area

Herschel Island (Inuit Qikiqtaruk) lies in the southeastern part of the Beaufort Sea, 5 km off the Yukon Coastal Plain in Canada (Fig. 1A). The island, with an area of 116 km^2, consists of perennially frozen sediments of mostly marine and

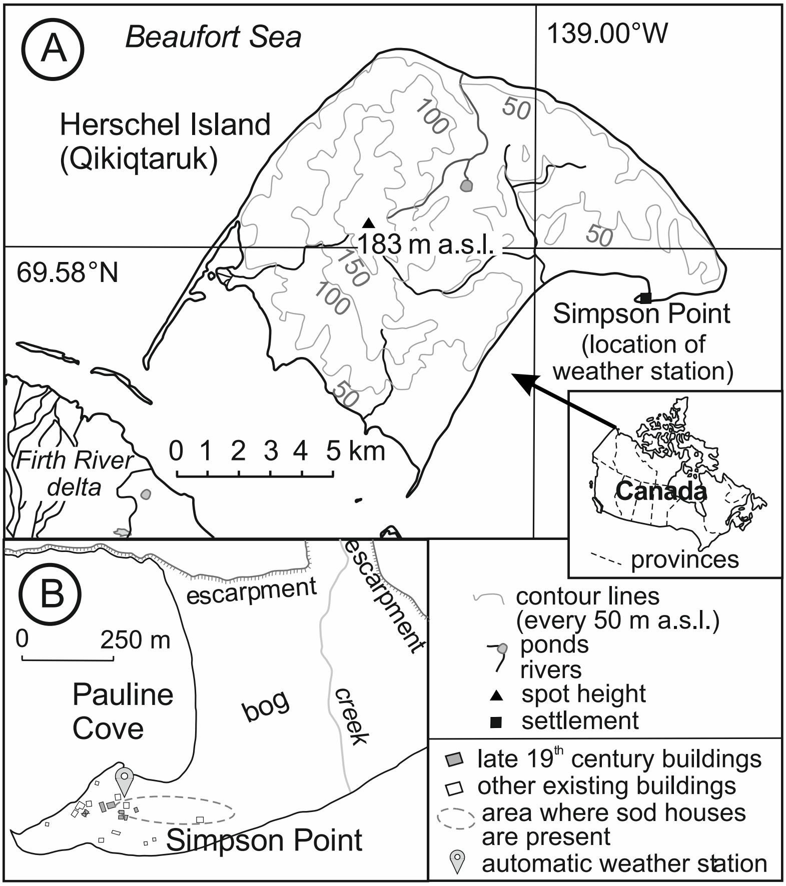

Fig. 1. Study area of Herschel Island (**A**) and Simpson Point settlement (**B**) after *Herschel Island* 2019.

glacial origin (Burn 2012). The maximum elevation of Herschel Island is 183 m a.s.l. Steep bluffs of the NW and NE coasts of the island are prone to coastal erosion. Retrogressive thaw slumps are also common on the island (Burn 2012; Radosavliejvic *et al.* 2015). The gravel spits are formed by longshore drift of sediments eroded from the bluffs. One of such gravel spits is the Simpson Point spit. Its thaw-stable surface caused that a whaling settlement has been erected there in the late 19th century (Fig. 1).

Located north of the Arctic Circle, Herschel Island enjoys the polar day between May 19 and July 24 and the polar night from November 29 to January 14. According to the Köppen–Geiger world climate classification (Peel *et al.* 2007), Herschel Island shows intermediate characteristics between the continental climate without dry season and with cold summer (Dfc) and tundra climate (ET). Herschel Island is located at the northern extent of tall shrubs which are the dominant island's vegetation along with the moist acidic tussock tundra and the herbaceous and grassy tundra (Myers-Smith *et al.* 2019).

Herschel Island was discovered by Europeans in 1826, by the British Polar explorer John Franklin (Burn 2009). In the 1890s it became a hub for American whaling ships which spent the winter in the Arctic (Stone 1981). A total of fifteen vessels and 500 whalers wintered on Herschel Island at the peak of whaling activity. The wintering typically lasted 10 months, from September to mid-July. The number of wintering vessels and whalers diminished in the last years of the 19th century, as the productivity of the whaling in the Mackenzie River delta region declined. Only three vessels wintered on Herschel Island during 1896–1897 winter season. Majority of whalers wintered on the board of their ships and only several frame building were erected at the Simpson Point spit in the late 19th and early 20th century. Moreover, some whalers wintered in the sod huts (Fig. 1B). Winter 1907–1908 was the last one when the whalers wintered on the Herschel Island.

The presence of American whalers in the region was perceived as a challenge to the domination of that part of the Arctic by the British Dominion of Canada (Smith 2014). Anglican missionaries became the first Canadian representatives on Herschel Island in 1893. The mission was initially headed by Isaac O. Stringer who also began to collect weather data on the island (Thompson 1948; Burn 2012). In 1903, the Royal Canadian Mounted Police (RCMP) established an outpost on Herschel Island (Morrison 1985). In 1915, the Hudson Bay Company (HBC) established a trading post on the island. Whaling at this time had declined in the area (Usher 1975). The HBC trading post was closed in the late 1930s, while the RCMP remained on the island until the mid-1960s.

Today, Herschel Island is a part of the Herschel Island Territorial Park. It no longer has any permanent inhabitants, although it remains an important hunting ground for local Inuits (Burn 2012). Just a few buildings in the former Simpson Point settlement are currently used by park rangers during the summer in the Northern Hemisphere, as well as by scientists who regularly visit Herschel Island. Tourists who visit the park for a few days or more need to use their own camping equipment. Other buildings existing at the Simpson Point (Fig. 1B) are preserved as historic monuments. The island is a candidate for a UNESCO World Heritage site (Radosavliejvic *et al.* 2015).

Data and methods

Meteorological data for Herschel Island are available for several time intervals: 1896–1906, 1915–1918, 1974–1975 and from 1994 onwards, with numerous time gaps. The author has found no information on the exact location of the first weather station operating on Herschel Island. However, we can assume, it was located close to the Anglican mission created in the Simpson Point settlement. The weather station operating in the late 19th and early 20th century was equipped with minimum and maximum thermometers and rain gauge

(*Encyclopedia Arctica* 1947-51). Contemporary automatic weather station is located on the periphery of the former Simpson Point settlement, Yukon Territory, Canada (69°34'05.5"N, 138°54'48.2"W, 1.3 m a.s.l.) (Fig. 1). As the Simpson Point settlement is only 900 m long and 200–250 m wide, weather data collected from historic and contemporary weather stations were assumed homogeneous enough to compare them effectively (Burn and Zhang 2009).

The present paper utilizes data from Herschel Island from two 7-year long periods: 1899–1905 and 2008–2014. The data series for these two periods are the most complete available. Only 4.1% of data period is missing for the first and 1.9% of data is missing in the second period.

Minimum diurnal air temperature (TN), maximum diurnal air temperature (TX), mean diurnal air temperature (T_{mean}), heating degree days (HDD) were used in the study. All of the above data were downloaded from the Historical Climate Data portal of the Government of Canada website available at https://climate.weather.gc.ca/historical_data/. The obtained T_{mean} data is calculated as arithmetic average from TX and TN values. HDD is the difference between the base temperature of 18.0 °C and T_{mean}. The value of 18.0 °C is a threshold for air temperature, below which human inhabitants need to turn on their heating systems (Büyükalaca *et al.* 2001). HDD equals zero above this threshold value. Diurnal HDD values were added together to calculate annual totals of HDD.

TN, TX, and T_{mean} were also used to calculate additional temperature-based indices, described in Table 1. Definitions of two thermal indices, namely exceptionally cold days and exceptionally warm days, were adopted from Przybylak *et al.* (2022). The mean lowest TN of the year was calculated to determine the plant hardiness zone where Herschel Island was located during each studied time interval. Plant hardiness zones were assessed using methods proposed by the U.S. Department of Agriculture (Daly *et al.* 2012) – Table 2.

Table 1.

Air temperature indices used in this study.

Indices	Definitions
TN	minimum daily air temperature
TX	maximum daily air temperature
T_{mean}	mean daily air temperature – T_{mean} = (TN + TX) / 2
DTR	daily temperature range – DTR = TX – TN
Ice days	number of days with TX≤0.0°C in a year
Freeze-thaw days	number of days with TN<0.0°C and TX≥0.0°C in a year
Exceptionally cold days	number of days with TX<–30.0°C in a year
Exceptionally warm days	number of days with TX>15.0°C in a year
5^{th} perc. TN	5^{th} percentile of TN
95^{th} perc. TX	95^{th} percentile of TX

Table 1 – *continued.*

Indices	Definitions
Mean lowest TN	mean lowest minimum daily air temperature in the year
Frost-free season	maximum annual number of consecutive days with TN>0.0°C
Growing season	the interval between the date on which T_{mean}>5.0°C for six consecutive days and the date on which T_{mean}<5.0°C for six consecutive days
GDD	the total of T_{mean}>0.0°C counted in the period since 1st June
HDD	the annual total of differences between the base temperature of 18.0°C and daily T_{mean} values

Table 2.

Temperature ranges of USDA plant hardiness zones
(Daly *et al.* 2012).

Plant hardiness zone	Mean lowest minimum air temperature in the year (°C)
1a	–51.1 to –48.3
1b	–48.3 to –45.6
2a	–45.6 to –42.8
2b	–42.8 to –40.0
3a	–40.0 to –37.2
3b	–37.2 to –34.4
4a	–34.4 to –31.7
4b	–31.7 to –28.9
5a	–28.9 to –26.1
5b	–26.1 to –23.3
6a	–23.3 to –20.6
6b	–20.6 to –17.8
7a	–17.8 to –15.0
7b	–15.0 to –12.2
8a	–12.2 to –9.4
8b	–9.4 to –6.7
9a	–6.7 to –3.9
9b	–3.9 to –1.1
10a	–1.1 to 1.7
10b	1.7 to 4.4
11a	4.4 to 7.2
11b	7.2 to 10.0
12a	10.0 to 12.8
12b	12.8 to 15.6
13a	15.6 to 18.3
13b	18.3 to 21.1

The definition of the frost-free season was adopted from the Glossary of Meteorology of the American Meteorological Society (2012) and the definition of the growing season was adopted from Vincent *et al.* (2018).

The threshold of T_{mean}=0.0°C was adopted for the calculation of growing degree days (GDD). It is assumed that the occurrence of T_{mean}>0.0°C enables the emergence of mosquitoes, black flies and oestrids in the study area. Human populations tend to view these insects as a nuisance (Witter *et al.* 2012). Diurnal GDD values were added together in each year, beginning with June 1, which is when the snow cover disappears along the coast of the Beaufort Sea in the Mackenzie River Delta (Morse *et al.* 2012). The disappearance of snow cover enables the formation of thermokarst lakes wherein larvae of mosquitoes and black flies can thrive.

In order to assure comparability between annual GDD and HDD totals, any gaps in diurnal T_{mean} and HDD values were filled with diurnal mean values of the two indices, calculated based on the remaining years of the two examined periods. As examined time periods are short, 14-years long in total, no reliable trends could be obtained. Instead of it, arithmetic mean of TN, TX, and T_{mean} and temperature-based indices for the two examined periods were compared. The statistical significance of differences between the examined temperature indices was tested using the nonparametric Mann-Whitney *U*-test.

Results

Average, minimum and maximum air temperature. — In the years 2008–2014, mean TN for Herschel Island was higher by 4.2°C than in the years 1899–1905, while TX was higher by 3.5°C. Finally, T_{mean} increased by 3.7°C during the same period. In the years 1899–1905, daily temperature range (DTR) noted for Herschel Island equaled, on average, 6.7°C. Average DTR in 2008–2014 was lower by 0.9°C (Fig. 2, Table 3). All aforementioned differences are statistically significant at $p \leq 0.05$. Differences between TN, T_{mean} and TX in 1899–1905 and 2008–2014 varied seasonally. The increase in the air temperature was the most evident in October and November, with the biggest increase found between November 11 and November 20, equaling on average 6.7–7.3°C. Moreover, a remarkable increase in TX was detected in July and August. Relatively small increase in TN, T_{mean} and TX was found in March and June in the years 2008–2014 compared to 1899–1905. Average TX value decreased in the years 2008–2014 during the time interval from March 11 to March 20 when compared to the years 1899–1905. It was 1.3°C lower during the years 2008–2014 than in 1899–1905 (Fig. 3).

Values of both 5th percentile of TN and 95th percentile of TX increased in 2008–2014 compared to 1899–1905 (Fig. 2, Table 3). The lowest TN, –46.7°C, in the period 1899–1905 recorded on Herschel Island was noted on January 20,

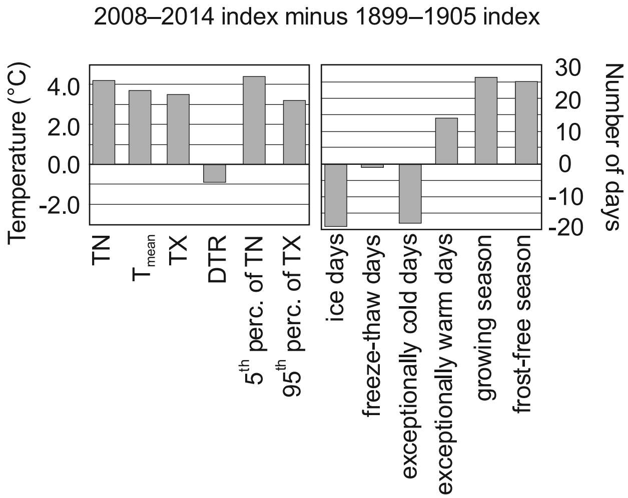

Fig. 2. Difference of minimum daily (TN), mean daily (T_{mean}), maximum daily (TX) air temperature and chosen thermal indices on Herschel Island between 2008–2014 and 1899–1905 periods.

Table 3.

Air temperature indices for Herschel Island for the years 1899–1905 and 2008–2014. Explanation of air temperature indices are provided in Table 1.

Indices	Unit	Periods		(2) – (1)
		1899–1905 (1)	2008–2014 (2)	
TN	°C	–15.4	–11.2	4.2 (p<0.001)
TX	°C	–8.9	–5.4	3.5 (p<0.001)
T_{mean}	°C	–12.0	–8.3	3.7 (p<0.001)
DTR	°C	6.7	5.8	–0.9 (p<0.001)
Ice days	days	248	229	–19 (p=0.015)
Freeze-thaw days	days	32	31	–1 (p=1.000)
Exceptionally cold days	days	23	5	–18 (p<0.001)
Exceptionally warm days	days	8	22	14 (p=0.013)
5th perc. TN	°C	–37.2	–32.8	4.4
95th perc. TX	°C	12.8	16.0	3.2
Mean lowest TN	°C	–42.9	–38.1	4.8 (p=0.011)
Frost-free season	days	50.6	77.0	26.4 (p=0.055)
Growing season	days	47.4	72.6	25.2 (p=0.014)
GDD	degree days	491	833	342 (p=0.002)
HDD	degree days	10 941	9 596	–1 345 (p=0.002)

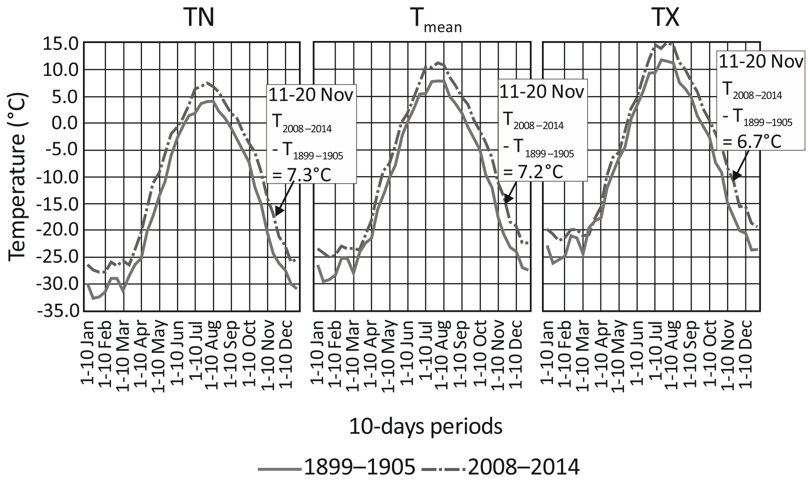

Fig. 3. Annual variability of minimum daily (TN), mean daily (T_{mean}) and maximum daily (TX) air temperature on Herschel Island in the years 1899–1905 and 2008–2014. 10-days periods with the biggest temperature differences between years 2008–2014 and 1899–1905 are given in boxes.

1901, while the highest TX, 20.6°C, was noted on July 22, 1902. In 2008–2014, the lowest TN was noted on February 1, 2012 (–42.8°C), while the highest TX was noted on July 31, 2012 (28.1°C) (Table 4). All the lowest monthly TN values were found to be higher in 2008–2014 than in 1899–1905. The most evident increase was found in May and October. Clear increase in the monthly highest TX values was found in June, July, August and September. In 1899–1905, extreme TX values noted in February, March and May were higher compared to 2008–2014 (Table 4).

The average lowest annual TN was –42.9°C in the period 1899–1905, while it was –38.1°C in the period 2008–2014 (Table 3). Thus Herschel Island belonged to 2a USDA hardiness zone in the late 19th century and early 20th century. In the

Table 4.

Highest maximum daily air temperature and lowest minimum daily air temperature on Herschel Island during the years 1899–1905 and 2008–2014. The most extreme air temperature values recorded in each studied period are in bold.

Index/period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lowest minimum daily air temperature (°C)												
1899–1905	**–46.7**	–45.6	–41.7	–33.9	–29.9	–11.1	–2.8	–4.4	–13.3	–27.2	–35.6	–41.7
2008–2014	–42.5	**–42.8**	–36.6	–31.0	–17.0	–6.0	0.9	–2.0	–8.0	–17.2	–33.8	–37.0
Highest maximum daily air temperature (°C)												
1899–1905	2.2	1.7	3.3	0.6	11.7	18.3	**20.6**	17.8	13.3	9.4	1.1	–2.2
2008–2014	4.3	-1.1	-6.4	2.0	9.7	25.5	**28.1**	25.6	18.0	9.3	2.8	2.5

period 2008–2014, the island belonged to the 3a USDA hardiness zone. In effect, the threat to plant life from extreme frost is now smaller than that of >100 years ago. The increase in the lowest annual TN average is statistically significant at $p \leq 0.05$.

Number of days with specific thermal conditions. — The mean annual number of ice days decreased by 19 days on Herschel Island in the years 2008–2014 when compared to the years 1899–1905. There were 222–261 ice days per year in the 1899–1905 period and 219–239 ice days per year in the 2008–2014 period. This decrease is statistically significant at $p \leq 0.05$. The number of exceptionally cold days decreased by 18 days in the years 2008–2014 when compared to 1899–1905. A number of these days varied from 1 to 9 per year in 2008–2014, whereas there were 10–33 exceptionally cold days per year in 1899–1905. This decrease is statistically significant at $p \leq 0.05$. A number of exceptionally warm days increased by 14 days between the periods analyzed. There were 5–13 exceptionally warm days per year in the 1899–1905 period and 9–69 such days per year in the 2008–2014 period. This increase is statistically significant at $p \leq 0.05$. It is noteworthy that 69 exceptionally warm days occurred in 2012. The remaining years of the 2008–2014 were not so warm. A number of exceptionally warm days did not exceed 18 days during these years. A number of freeze-thaw days was almost the same in both studied periods (Fig. 2, Table 3).

Frost-free season and growing season. — The length of the frost-free season on Herschel Island in 1899–1905 was, on average, 50.6 days. This season started on July 2 and ended on August 20 on average. In the years 2008–2014, the length of the frost-free season equaled on average 77.0 days, and this period began on June 17 and ended on August 31 on average. In 2008–2014, the frost-free period begins on average 15 days earlier and ends 11 days later than in the early 20th century, while its length has extended by 26.4 days. The length of the frost-free period did vary remarkably from year to year, especially in the early 20th century. In 1905 the frost-free period was only 22 days long, from July 8 to July 29, while in 1902 this period lasted 95 days, from June 10 to September 13. In the years 2008–2014, the length of the frost-free period ranged from 57 days in 2009 to 95 days in 2010 (Fig. 4). The difference in the average length of the frost-free period between 1899–1905 and 2008–2014 is not statistically significant at $p \leq 0.05$ (Fig. 2, Table 3).

The research method applied in this study did not make it possible to unequivocally determine the length of the growing season for 1900 and 1904. Time intervals lasting more than six days with T_{mean}>5.0°C, occurring in the second half of June, were followed by a drop in T_{mean} below this threshold. A period with T_{mean}≤5.0°C lasted for 8 and 9 days and was followed by another series of days with T_{mean}>5.0°C, lasting more than six days. In the remaining 5 years of the 1899–1905, the growing period lasted on average 47.4 days. The longest period was noted for 1902 (66 days), from July 4 to September 7. In the remaining 4 years, the growing season on Herschel Island was shorter and ended

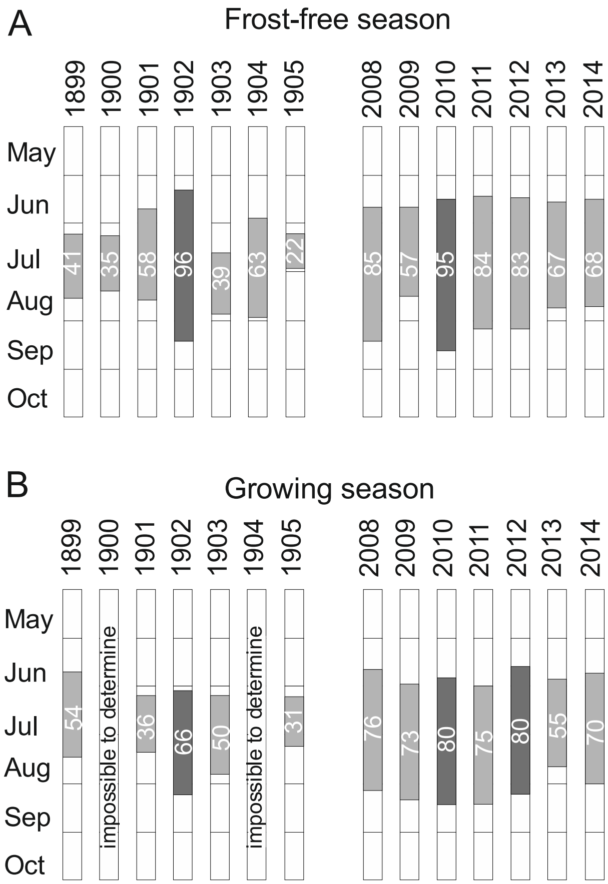

Fig. 4. Range and duration (in days) of the frost-free season (**A**) and the growing season (**B**) on Herschel Island in the years 1899–1905 and 2008–2014.

in August. In the years 2008–2014, the growing season on the island was much longer, lasting on average 72.7 days. Generally, it covered the last 10 days of June and ended in the first or second week of September (Fig. 4). The difference in the length of the growing season in the periods 1899–1905 and 2008–2014 is statistically significant at $p \leq 0.05$ (Fig. 2, Table 3).

Growing degree days and heating degree days. — The annual total of growing degree days (GDD) above the T_{mean} threshold of 0.0°C increased between the early 20th century and early 21st century by 342 degree days. The said increase was statistically significant at $p \leq 0.05$ (Table 3). The annual GDD total was calculated starting on June 1. It equaled, on average, 491 degree days per year in the period 1899–1905, while in the period 2008–2014 it reached, on average, 833 degree days per year (Fig. 5). This last value can be overestimated due to an especially warm year 2012. GDD total equaled 1 241 degree days in 2012. In the period 1899–1905, the highest GDD total occurred in 1902 and was twice as low as that in 2012 (620 degree days).

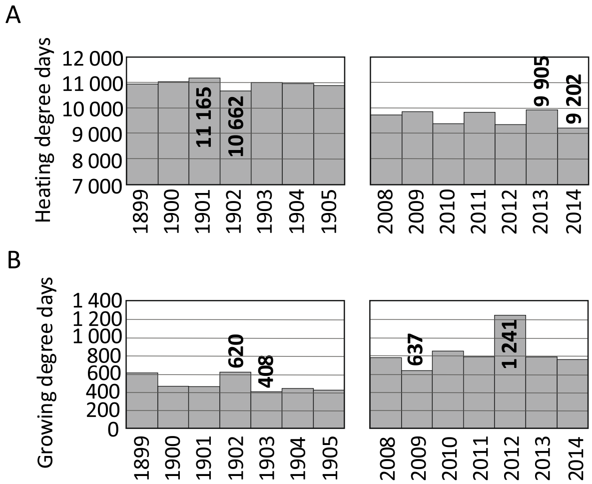

Fig. 5. Annual totals of heating degree days (**A**) and growing degree days with T_{mean}>0.0°C (**B**) on Herschel Island in the years 1899–1905 and 2008–2014. Highest and lowest values in each period are given in diagrams.

The HDD value for Herschel Island has changed substantially since the early 20th century. In the years 1899–1905, the annual total of HDD equaled an average of 10 941 degree days while in modern times it equals an average of 9 596 degree days, which is 1 351 degree days less. This large difference is statistically significant ($p\leq0.05$). HDD values varied remarkably in particular years in each of the studied periods. In the period 1899–1905, annual HDD total ranged from 10 873 to 11 165 degree days while in the period 2008–2014 the range was between 9 202 and 9 945 degree days (Table 3, Fig. 5).

A T_{mean} values greater than 18.0°C was not noted for Herschel Island in the period 1899–1905. Thus the annual HDD value is a total of values derived from all days in this period. However, a T_{mean}>18.0°C did occur in the period 2008–2014, however, only six times and only in July 2012 and August 2013. According to the definition of HDD, the heating of buildings was not needed on these particular days of the year. In fact, one could calculate here a cooling degree days index for these days in order to assess the need for air conditioning in residential buildings in the summer.

Discussion

The increase in T_{mean}, TN, and TX and also changes of air temperature-based climatic indices determined in this paper for Herschel Island for the last 100 years or so is consistent with the results provided by earlier studies on climate change on Herschel Island, the Yukon and Alaska, and the entire Canadian Arctic (Wood and Overland 2006; Burn and Zhang 2009; Vincent *et al.* 2018; Przybylak *et al.* 2022).

Trends in T_{mean}. — Many papers cover T_{mean} trends for the second half of the 20th century and early 21st century. Research studies conducted throughout the entire Canadian Arctic region have shown that T_{mean} increased in the period 1951–2015 by 2.1°C (Przybylak and Wyszyński 2020). It is also noteworthy that air temperature has risen the most in the Yukon, western Nunavut, and Northwest Territories in Canada. This is especially true for the winter season when the T_{mean} value increased up to 6.0°C in the period 1948–2015 (Vincent *et al.* 2015).

A few weather stations in northern Alaska and northwestern Canada performed measurements in the first half of the 20th century. Przybylak *et al.* (2022) compared T_{mean} in Coppermine (Nunavut, Canada) during the contemporary Arctic warming (2007–2016) and the early-twentieth-century Arctic warming (1934–1950). They identified an increase of 1.9°C in T_{mean} in the 2007–2016 period compared to the 1934–1950 period. They also found that an increase in T_{mean} was largest during autumn and smallest during spring. These results are consistent with a seasonal variability of T_{mean} trends on Herschel Island where the largest increase in T_{mean} occurred in October and November.

Increase in T_{mean} on Herschel Island in the early 21st century relative to the early 20th century was larger than that one reported by Przybylak *et al.* (2022). Burn and Zhang (2009) reported an increase of 2.6°C in T_{mean} on Herschel Island between the periods 1899–1905 and 1999–2005. A comparison of results from this study with those provided by Burn and Zhang (2009) shows that the increase in air temperature in the western part of the Canadian Arctic is ongoing. This research covers a somewhat later period of 2008–2014, where an increase in T_{mean} was larger (by 3.7°C). As Burn and Zhang (2009) also utilized T_{mean} datasets from the Environment Canada website, the above-mentioned difference reflects only ongoing T_{mean} increase, not the difference of a T_{mean} calculating method.

Even fewer data is available on thermal conditions in the Canadian Arctic in the 19th century. One such T_{mean} data series was compiled in the course of the First International Polar Year (1882–1883) in the Alaskan town of Barrow (Wood and Overland 2006; Przybylak *et al.* 2010). T_{mean} for Barrow for that period was lower in most of the months relative to the period 1968–1997. However, in February 1883, the T_{mean} for Barrow was higher than in 1961–1990 by as much as 6.0°C. This positive deviation in T_{mean} was triggered by the arrival of exceptionally warm air masses driven by a strong Aleutian low (Wood and Overland 2006). It is plausible to suppose that the occurrence of some exceptional atmospheric circulation patterns is also responsible for the occurrence of above zero TX values on Herschel Island in wintertime during both studied periods (see Table 4). Atmospheric circulation, especially multi-decadal changes in the frequency of meridional flow explains to some degree differences in thermal conditions between the early-twentieth-century Arctic warming period and subsequent cold Arctic sub-period (Łupikasza *et al*. 2021).

TN and TX trends. — TN for Herschel Island increased more rapidly during the studied period compared to T_{mean}. However, the increase of TX was lower than T_{mean}. A similar pattern was noted in the case of trends associated with TN, T_{mean} and TX for the town of Dawson in central Yukon for the period 1902–2005. However, the increase in TN and TX values was smaller in Dawson than on Herschel Island (Werner *et al.* 2009).

The largest increase in TN and TX for Herschel Island was noted in October, November, and December. Readily recognizable seasonal differences of trends in extreme temperature values in Canada in the years 1961–2010 were described by Wang *et al.* (2014). They determined a trend of extreme TN and TX values occurring only once per 20 years. A stronger increasing trend was observed for wintertime extremes, *i.e.*, lowest TN and TX values occurring once per 20 years increased in northern Canada in the studied period of time by 6.8°C and 6.2°C, respectively. The increase in TN and TX summertime extremes occurring once per 20 years was much smaller and did not exceed 2.0°C. On the other hand, Vincent *et al.* (2018) noted an increase in the 5th percentile of TN and TX in the winter months in northern Canada by 5.4 to 5.7°C.

Trends in air temperature-based climate indices. — The number of ice days with TX≤0.0°C has also decreased in northern Canada since 1948 by 12 days on average. No statistically significant trend was detected for the number of freeze-thaw days (Vincent *et al.* 2018). This is consistent with the research results provided in this study. The number of ice days on Herschel Island decreased by 19 days between the periods 1899–1905 and 2008–2014, while the number of freeze-thaw days virtually did not change. The annual number of exceptionally cold days decreased in Coppermine by 11 days between the periods 1934–1950 and 2007–2016 (Przybylak *et al.* 2022). A slightly larger decrease in the annual number of such cold days with TX<–30.0°C was found on Herschel Island. Conversely, the annual number of exceptionally warm days increased in Coppermine by 5 days between the studied periods (Przybylak *et al.* 2022). A remarkably larger increase in the number of the exceptionally warm days, by 14 days, occurred on Herschel Island. To some degree, this big increase in the number of these days resulted from the exceptionally warm 2012 summer when 69 days with TX>15.0°C occurred. The number of exceptionally warm days in remaining years of the 2008–2014 period did not exceed 18 days and their average number in a year was larger by 6 days than in the period 1899–1905.

No significant trend in the daily temperature range (DTR) was detected in annual time series in the westernmost part of the Canadian Arctic for the period 1950–1998 (Zhang *et al.* 2000). However, this area showed statistically significant increasing DTR trend in summer time series. An increase in the DTR was also detected in Coppermine (Przybylak *et al.* 2022). On Herschel Island, DTR decreased slightly between the periods 1899–1905 and 2008–2014.

The increase in air temperature over the last 100 years or so has led to a decreased need for heating. HDD declined on Herschel Island by more than

1 300 degree days. This decline only concerns the period since 1970. In 1941–1970, the mean HDD value for the Herschel Island region was 10 750 degree days (*Canada – heating degree days* 1981). This value was only somewhat smaller than that for the period 1899–1905 when it equaled 10 941 degree days. A statistically significant declining HDD trend was detected for all of northern Canada for the period 1948–2016 yielding an average of 257 degree days. However, individual weather stations noted a decline in HDD up to 500 degree days (Vincent *et al.* 2018).

A review of plant hardiness zones for Canada identified using USDA methods (McKenney *et al.* 2014) made it possible to show that in the period 1931–1960 the coastal plain of the Yukon Territory was part of zone 1b, but in the period 1981–2010 it was part of zone 2b. This means that the mean lowest annual TN had increased by 2.8 to 8.3°C. This research has shown that winters on Herschel Island are somewhat less severe in terms of air temperature. In the period 1899–1905 the mean lowest annual TN on the island placed it in zone 2a, while in the period 2008–2014 in zone 3a. This basic lack of agreement between the results of this study and the study by McKenney and coauthors may reflect differences in the study periods examined in both papers. Moreover, results presented in the paper by McKenney and coauthors are more generalized as this work covers all of Canada, while the present study is a local study.

The length of the frost-free season in northern Canada has increased since 1948 by *ca.* 24 days per year, although some sites report an increase of 45 days (Vincent *et al.* 2018). The increase in length of the frost-free season on Herschel Island between the early 20th century and early 21st century was similar to the average for the Canadian North in the second half of the 20th century at 26 days. In both study periods (1899–1905 and 2008–2014), the frost-free season on Herschel Island was longer than the mean value for the period 1941–1970, as interpolated from a map from the National Atlas of Canada (*Canada-Frost Free Period* 1981).

The length of the growing season characterized by the occurrence of T_{mean}>5.0°C has increased in northern Canada since 1948 by 15.5 days on average (Vincent *et al.* 2018). On Herschel Island, the length of the growing season increased by *ca.* 25 days between 1899–1905 and 2008–2014.

An increase in the annual total of growing degree days (GDD) between the early 20th century and early 21st century implies that parasitic insects' activity on Herschel Island also increased between the periods 1899–1905 and 2008–2014. Witter and coauthors (2012) utilized GDD as one of weather-based indices for the monitoring of insect harassment in Bathurst caribou post-calving and summer range. They found that the occurrence frequency of weather conditions conducive to high activity of black flies and oestrids increased and the occurrence frequency of weather conditions conducive to mosquitoes activity declined between 1957 and 2008. This last trend resulted from the decline in relative humidity and the increase in wind speed during the summer season.

Possible data inhomogeneities. — A possible bias should be kept in mind in TX and TN values due to the transition from manual to automatic observations (WMO 2017). We can assume this possible bias did not affect general trends in studied thermal indices on Herschel Island. It probably affected trends' magnitude. As no parallel manual and automatic observations were conducted on Herschel Island, an exact assessment of this bias is not possible without additional data from neighboring weather stations.

Other factor which could have caused inhomogeneity in the analyzed temperature datasets is a presumed difference in the location of weather stations. No information was found on the exact location of the weather station operating in the late 19th century and the early 20th century. We can, however, assume that both weather stations were located close to each other as the whole Simpson Point settlement is only 900 m long and 200–250 m wide (Fig. 1B). Therefore, a bias in TX and TN values caused by possible relocation of weather station should not be significant.

Many research studies have discussed the issue of urbanization effects on the mean and extreme temperature series (Kalnay and Cai 2003; Zhang *et al.* 2021). Identifying and separating urbanization signal in temperature time series is, of course, essential for the accurate assessment of the observed regional- and global-scale warming. The most intensive Urban Heat Island (UHI) effect in the Arctic cities occurs in the wintertime and is triggered mainly by the anthropogenic heat flux (Magee *et al.* 1999; Varentsov *et al.* 2018). If any urbanization signal occurred in Herschel Island temperature time series, it was present in the late 19th century and early 20th century when whaling ships' crews wintered in the Simpson Point settlement. Nowadays, Herschel Island settlement is abandoned for much of the year. Therefore, it is unlikely that the increase in air temperature observed on Herschel Island between periods 1899–1905 and 2008–2014 could be affected by an intensification of the UHI effect. Moreover, the warming during wintertime can be, to some degree, underestimated due to the possible UHI effect in Simpson Point settlement in the late 19th century and early 20th century. However, this effect was probably weak as Simpson Point settlement was small (see Fig. 1B) and the majority of whalers wintered on the board of their ships, not in the settlement itself.

Conclusions

The analysis of differences in all studied air temperature indices for Herschel Island for the period between the early 20th century and early 21st century made it possible to identify similar trends as in the Canadian Arctic and Alaska in the USA. Most of the changes in the temperature-based indices used in the study for Herschel Island were statistically significant and also more intense than those noted across adjacent regions.

It is noteworthy that minimum daily air temperature grew faster than maximum daily air temperature over the roughly 100-year study period and changes in minimum and maximum air temperature were more readily observable in the cold part of the year. Some of the most important observed changes in thermal conditions included (*i*) a considerable decline in the number of exceptionally cold days with maximum daily air temperature <–30.0°C and (*ii*) in the annual total of heating degree days as well as (*iii*) an increase in the length of the frost-free season and the growing season and (*iv*) an increase in the annual total of growing degree days above T_{mean} threshold value of 0.0°C. The observed temperature trends for Herschel Island are useful in explaining the rate of environmental change on the Beaufort Sea coastline.

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