Ice Bridges on the St. Lawrence River as an Index of Winter Severity from 1620 to 1910

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ABSTRACT

Temperature reconstruction of the last thousand years suggests that an unprecedented warming (+0.6°C) occurred over the globe in the last century. However, regional variations in climate are not resolved by Northern Hemisphere reconstructions. In northeastern North America, past climate and, particularly, past winter variations are poorly known. Here, the authors report on the variation of a winter temperature index during the 1620–1910 period, based on the ice bridge formation (IBF) rate on the Saint Lawrence River at Québec City (Canada), combined with instrumental data (1876–2000). During this 300-yr period, the IBF rate shows that winters in the seventeenth and eighteenth centuries were warmer than those in the nineteenth century. In particular, the IBF rate suggests that winter severity culminated in the 1850–1900 period, while very few ice bridges were reported between 1620 and 1740, presumably because of warmer temperatures and the relative scarcity of historical documents for the 1680–1740 period. These data suggest that winter temperature, particularly between ~1800 and 1910, was 2.4° to 4.0°C colder than the last 30-yr average. Major volcanic eruptions had a significant positive impact on IBF rates, which is consistent with their role as important climate-forcing events.

1. Introduction

There is considerable evidence that climate warming in the range of 0.6°C, unprecedented in the past 1000 years (Crowley 2000), occurred over the globe in approximately the last 100 years (Houghton et al. 2001). The abruptness of this change was emphasized by the fact that the recent warming came just after the so-called Little Ice Age (LIA), a period of global climatic cooling that extended from about 1425 to 1850 (Grove 1988; Jones et al. 1998; Mann et al. 1998, 1999), although the timing varies considerably spatially. Between 41% and 64% of the variation in the decadal-scale temperature of the globe between 1000 and 1850 can be explained by changes in solar irradiance and in the frequency of volcanic eruptions (Crowley 2000). Additional evidence of the effect of major volcanic eruptions on tree-ring records in the Northern Hemisphere (NH) were provided by Briffa et al. (1998).

However, the reconstructed temperatures at the NH scale have a strong summer or annual component, and past winter variations are not well known. The influence of summer on inferred temperature reconstructions is due to the widespread use of tree growth data. Borehole-based temperature reconstructions and those including this type of data also have a "warm season" bias because they mostly originate from regions where snow cover insulates the soil from winter temperatures (Mann et al. 2003). Reliable reconstructions of past winters is important because winter temperature and duration have a strong effect on ecosystems and biota (Saether et al. 2000; Walther et al. 2002; Parmesan and Yohe 2003; Root et al. 2003).

As compared to northeastern North America, European temperature estimates are more reliable at a regional scale, because both historical data and the more frequent occurrence of instrumental data series reinforce the more widespread proxy data, such as tree rings in the proxy network reconstruction (Shindell et al. 2003). Based on tree rings, Fritts and Lough (1985) provided reconstructed regional average annual temperatures for North America for the 1602–1961 period. However, the few sites used in this regional reconstruction that were located in Canada were in the west or in the Great Lakes region, leaving most of eastern Canada

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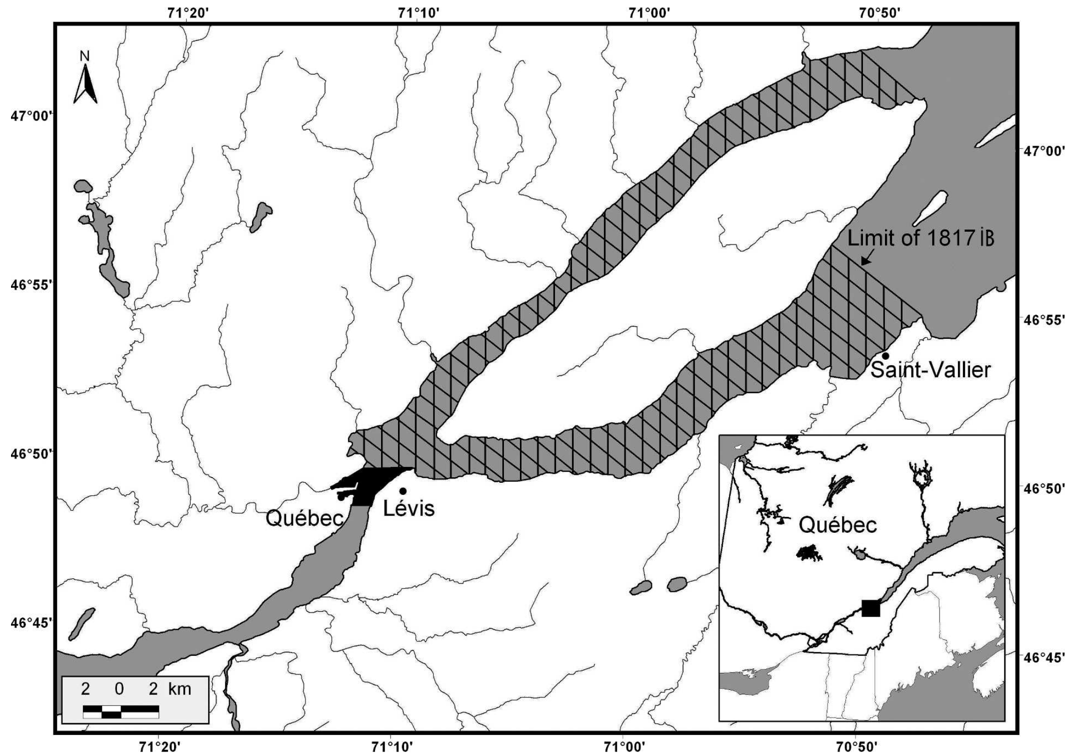

FIG. 1. Map of the Québec City region. The dark area shows the area usually covered by the ice bridges that formed during the study period. The crisscrossed surface shows the exceptional extent of the 1817 IB, which was probably due to the Tambora volcanic eruption (see text).

and the northeastern United States with no or few regional reconstructions. An instrumental dataset also exists for Minnesota, which however began in 1820 (Baker et al. 1985). A better knowledge of past temperatures in these latitudes is particularly important because they are expected to experience greater warming than the global NH (Houghton et al. 2001).

With the objective of creating a picture of past winter variations for a region of northeastern North America, a new winter temperature index (1620–1910) based on the ice bridge formation (IBF) rate on the Saint Lawrence River at Québec City (Fig. 1) was developed by systematically scrutinizing historical documents. At Québec City, the river is approximately 1 km wide, with a depth of 20–40 m, and has an average annual water flow of 11 000 $m^3 s^{-1}$. When an ice bridge (IB) formed, covering the river from shore to shore, it allowed the settlement inhabitants to easily cross; its formation was something expected and awaited, as is related in historical documents.

2. Methods

The monthly temperature data for the Québec City region was provided by the Québec Ministry of the Environment (1876–1959) and by Environment Canada (1895–2000; L. Vincent 2003, personal communication). This dataset combines two stations, one located at the Québec Seminary and the other at the Québec International Airport. The data from these two stations have been merged, taking into account potential heterogeneity in the temperature series (Vincent 1998) to produce a 125-yr (1876–2000) dataset. The monthly Icelandic temperatures (Stykkisholmur, western Iceland) from 1824 to 2000 were provided by the Icelandic Meteorological Office (T. Jonsson 2004, personal communication).

To establish the chronology of IBF, many historical sources were systematically scrutinized (see the appendix). In addition, many other historical documents were read by the third author over a 25-yr period, but not with the specific goal of looking at the presence of an IB. However, every mention was carefully noted.

The chronology of the IBF is unsure for approximately six decades (1680–1740) because of the relative scarcity of historical documents; the Jesuit Relations were interrupted in 1678, while the existence of other documents became more frequent around 1740. However, the consultation of the *Colonial Archives* (see the appendix) as well as historical descriptions of life in the colonies (J. Provencher 2004, unpublished manuscript), which report many natural phenomena such as famines, earthquakes, and insect invasions during the 1680–1740 period, resulted in no IB reports.

Similarly, although theoretically the IB could have formed until 1959, the year winter navigation began on the Saint Lawrence River, the absence of IBF after 1910 cannot be attributed solely to warmer winters because of ice-breaker ships active at Québec City. However, the use of ice breakers, particularly in the 1910–30 period, was somewhat occasional and the relatively small boats probably were limited in their ability to prevent IBF during the coldest winters.

The frequency of the IBF was graphically expressed as a 5-yr running average and compared with existing inferred temperature reconstructions for the NH (Mann et al. 1999). For this purpose, 5-yr means were calculated with the published annual data and correlated with the IBF frequency using 5-yr classes. To test the influence of volcanic eruptions on the IBF rate, we identified the 4-yr periods that follow volcanic eruptions ($n = 5$) and those nonoverlapping periods preceded by at least 4 yr without volcanic eruptions ($n = 33$). Within each of these categories, we discriminated between the number of periods with formation of 0, 1, or 2 IBs, and the number with 3 or 4 IBs. The data were expressed as a contingency table (not shown) and compared with an exact unilateral Fisher's test.

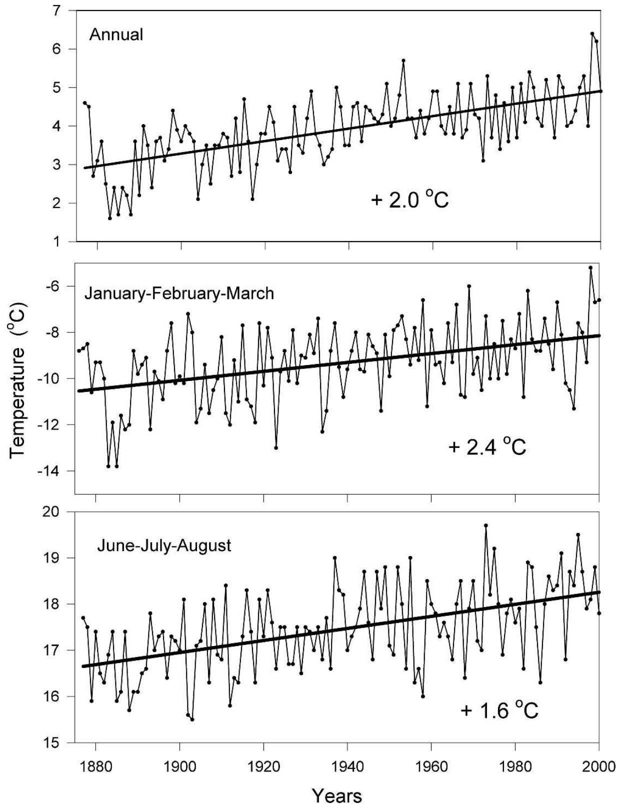

Fig. 2. Annual, winter, and summer temperature for the Québec City region from 1876 to 2000. The lines indicate the linear trends for each dataset.

3. Results and discussion

a. Instrumental data

The 125-yr temperature data from a meteorological station near Québec City shows a 2.0°C increase between 1876 and 2000 (Fig. 2). This is one of the sharpest temperature increases reported for northeastern North America (Zhang et al. 2000). Interestingly, the winter and summer warming rates differ greatly, with respective increases of 2.4° and 1.6°C. This was reflected in the poor relationship ($r = 0.29$, $p < 0.001$, $n = 124$) between winter (January–March) and summer (June–August) temperatures. The greater warming rate observed in winter and the weak relationship between summer and winter temperatures suggest that NH-inferred temperatures, which have an important summer component, missed a significant part of the trend in past winter variations in northeastern North America. Striking differences were also reported between summer and winter temperature trends in Europe in the last 500 years (Luterbacher et al. 2004). This stresses the importance of developing winter proxies for specific regions of the NH.

b. Ice bridge formation on the St. Lawrence River

A total of 83 IBFs were identified between 1620 and 1910 (Fig. 3). The mean freeze-up and breakup dates were 30 January and 19 April, respectively, with an average IB duration of 72 days. During this 300-yr period, the IBF rate shows that the seventeenth and eighteenth centuries (1620–1800 period; 16%) had warmer winters, while the nineteenth century (1801–1910 period; 48%) had colder winters. More particularly, winter severity culminated in the 1850–1900 period (IBF rate = 64%), including an IBF rate of 80% between 1866 and 1885, while the warmest period was 1620–1740 (IBF rate = 6%; seven IBFs between 1620 and 1660 and none between 1661 and 1740).

c. IBF versus published inferred temperatures

To investigate the agreement between the IBF data and temperature trends at the NH scale, we examined the relationships between the IBF rate and published

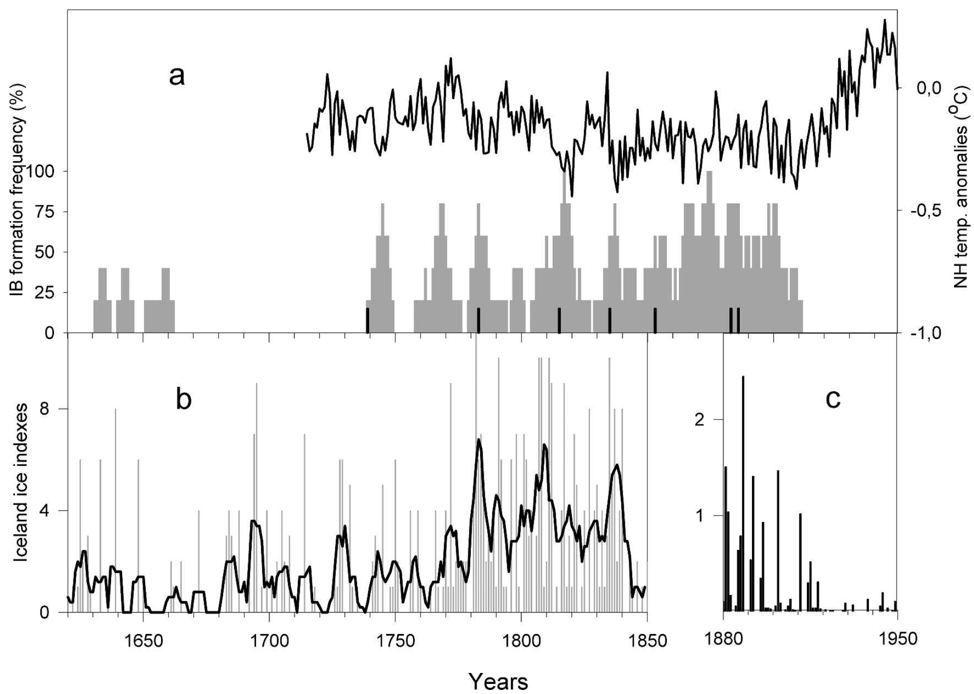

FIG. 3. Moving averages (5 yr) of the (a) Québec IB formation rate [gray area (left axis)] between 1620 and 1950 and NH temperatures anomalies [solid line, right axis, adapted from Mann et al. (1999)]. The dark lines projected from the bottom axis represent the volcanic eruptions listed in Table 1. (b) The yearly Iceland Ice index (solid line: 5-yr moving average) and (c) the Iceland Koch index are also shown. Both indexes are adapted from Ogilvie and Jónsson (2001).

inferred NH temperatures (Mann et al. 1999). The result shows that the IBF rate was not significantly correlated (Spearman coefficient) with the reconstructed NH temperature (Mann et al. 1999) ($r = -0.18$, $p = 0.17$). The lack of agreement, however, appears to be caused by a discrepancy in the first part of the time period (from 1620 to ~1740) when few IBs formed, as compared to significant cooling observed in the NH reconstructions (Mann et al. 1999), and in most of Europe (Luterbacher et al. 2004) and the United States (Fritts and Lough 1985). The low formation rate in the 1630s is qualitatively supported by the Jesuit missionaries' writings, stating that the presence of an IB is something rare (Clermont 1996). A part of the cooling observed in the NH during the seventeenth and eighteenth centuries, approximately the 1645–1715 period, was attributed to a decrease in solar irradiance known as the Maunder Minimum (Vaquero et al. 2002). Obviously, the IBF data suggest that the Maunder Minimum period was warmer than the 1800–1910 period, in disagreement with the NH reconstructions. The relative scarcity of historical reports between ~1680 and 1740 may have played a role in the observed IBF rate, although historical comments from the Québec inhabitants qualitatively support the fact that the winters were warm in the decades preceding the 1740/41 winter, which was qualified as extremely severe (Clermont 1996). The bridge that formed that winter had one of the longest durations in our dataset (95 days; mean = 72 days) and broke at the latest date (9 May). Many documented observations from New England settlements also pointed out that the winter was clearly the coldest in the first half of the 1700s (Ludlum 1966, p. 48).

The overall pattern of IBF (Fig. 3a) is in good agreement with proxies of winter variations based on Iceland Ice indexes (Ogilvie and Jónsson 2001; Figs. 3b and 3c). The Iceland and Québec indexes suggest that the period between 1620 and 1770 was warmer than the 1770–1850 period. But the comparison is limited by the absence of a published Iceland sea ice index for the 1850–80 period. Nevertheless, similar to the IBF data, the Maunder Minimum was not seen in the Iceland index. The high IBF rate between 1880 and 1900 (67%) and the very scarce IB events after 1910 also agrees well with the variation in the Iceland Koch Ice index (Fig. 3c). The relatively good agreement between the Iceland and the Québec indexes argues in favor of a global pattern of winter variation for a large region of the North Atlantic.

Interestingly, when the relationship between the winter North Atlantic Oscillation (NAO) index (Luterbacher et al. 2002) and the winter temperatures of both Iceland (western Iceland, 1824–2000: $r^2 = 0.001$, $n = 177$) and southern Québec (Québec 1876–2000: $r^2 = 0.007$, $n = 125$) was investigated, we found no significant correlations. This indicated that neither location was affected by the winter NAO, at least for the time period considered. That could explain the poor relationships between the Iceland and Québec indexes, with both past winter variations in Europe (Luterbacher et al. 2004) and ice data from the Baltic Sea (Koslowski and Glaser 1999); the NAO, being an important source of variability for the Baltic Sea and northwestern European winters (Marshall et al. 2001). Results relatively similar to the IBF and the Iceland index were also obtained for Labrador from a record of 1650 to 2000, based on tree-ring density data (D'Arrigo et al. 2003). In this latter study, the 1800s was clearly identified as the coldest period, while the 1650–1800 period was warmer.

It was suggested that a patch covering the northwestern Atlantic, including most of the northern half of Québec, Labrador, and Iceland, was almost the only small area of the NH that escaped the cooling induced by the Maunder Minimum, based on a global circulation model reconstruction of 1680 relative to 1780 and mapping of reconstructed temperatures from multiple proxy data (Shindell et al. 2003). This area was experiencing either no temperature changes or warming, as compared to the vast majority of the NH that was clearly colder, but in good agreement with our data and the findings for Labrador (D'Arrigo et al. 2003) and Iceland (Ogilvie and Jónsson 2001).

When the 1715–1910 period is used to remove the contrasting influence of the Maunder Minimum, a significant relationship is obtained ($r = -0.46$, $p = 0.003$) between the IBF data and the NH reconstruction. This shows that the IBF rate reflected, to some extent, the large-scale variability trends in NH climate after the Maunder Minimum period. Relatively weak correlations were somewhat expected because of, among other reasons, the error associated with the inferred temperature reconstructions (Mann et al. 1999) and because regional climate may differ from larger trends observed at the NH scale (Luterbacher et al. 2004; Williams and Wigley 1983; Shindell et al. 2001).

At a much more local scale, some clues for past summer conditions in Québec are provided by tree growth studies. Between 1398 and 1982, Payette et al. (1985) observed an increased growth for black spruce (*Picea mariana*) beginning in 1870 in northern Québec, suggesting a warmer climate after 1870. Archambault and Bergeron (1992), looking at the 1186–1987 period, also observed an increased growth of cedar (*Thuja occidentalis*) that began around 1860 in the Abitibi region in southwestern Québec; this was attributed, however, to the start of a higher precipitation regime rather than to increased temperatures. According to tree ring data taken in northern Canada, including some Québec sites, the 1810–1900 period was particularly cold (Jacoby and D'Arrigo 1989; D'Arrigo and Jacoby 1992), which is in very good agreement with the high IBF rate (54%) observed during this period.

d. IBF versus volcanic eruptions

Volcanic eruptions are known to have a pronounced effect on climate. They can produce a decrease in global surface temperatures for 3–4 years following the eruptions (Mass and Schneider 1977; Self et al. 1981; Kelly and Sear 1984; Briffa et al. 1998). The IBF rate was compared with volcanic activity chronology after 1715. Because the use of a volcanism chronology may be affected by subjectivity, we used the data from Briffa et al. (1998), which identifies the eruptions using a volcanic explosivity index (VEI) equal to or greater than 5, that had a great effect on NH climate, as deduced from tree ring data originating from 380 sites spanning the entire NH. The major eruptions between 1740 and 1910 led to a significantly ($p < 0.05$) higher rate of IBF in the four years following the event, as compared to the period between eruptions, thus confirming their important climatic effects (Fig. 3a, Table 1). Among the volcanic eruptions included in our chronology, the Tambora (1815) was the largest, with a VEI of 7 (Briffa et al. 1998) and was responsible for the "year without summer" in 1816. Interestingly, the IB that formed in 1817 captured the catastrophic character of this climate-forcing event—it was the biggest that ever formed, and extended to the town of Saint-Vallier, located approximately 25 km downstream from Québec City (Fig. 1). The IBF data also suggest that the Tambora eruption had a lasting effect on average global temperature since the IB formed for four consecutive years following 1815.

Another particularly cold winter period (1784–87), as identified by the IBF rate, was apparently associated with an important Icelandic volcanic eruption, the Laki (1783) (Fig. 3, Table 1), which was not listed by Briffa et al. (1998) because its VEI was below 5 (Newhall and Self 1982). The effect of the Laki eruption on North American climate remains controversial. Extremely small tree rings in 1783 in Alaska were attributed to the Laki eruption (Jacoby and D'Arrigo 1995), but another study (Briffa et al. 1994) stated that a direct effect of acidic aerosol on needles was potentially responsible

TABLE 1. Volcanic explosion and IB data between 1739 and 1910. The Laki was not included in the statistical test relating volcanic activity and IBF rate.

Volcanic explosion data			Ice bridge data	
Volcano and region	Year (month)	VEI*	IBF in the 4 yr after the eruption	IBF rate (%)
Shikotsu (Tarumai), Japan	1739 (Augt)	5	1741 and 1743	50
Laki, Iceland	1783 (Jun)	4	1784, 1785, and 1787	75
Tambora, Lesser Sunda Island	1815 (Apr)	7	1816, 1817, 1818, and 1819	100
Cosiguina, Nicaragua	1835 (Jun)	5	1836, 1837, and 1839	75
Chikurachki, Kurile Island	1853 (Dec)	5	1854, 1855, and 1857	75
Sheveluch, Kamchatka	1854 (Feb)	5		
Krakatau, west of Java	1883 (Aug)	6	1884, 1885, and 1887	75
Okataina (Tarawera), New Zealand	1886 (Jun)	5	1887 and 1888	50

* Estimate of explosive magnitude for historical volcanism (Newhall and Self 1982). This index varies from 0 and 8 and the scale is logarithmic. Volcanic eruption with VEI value of 5 and over are generally considered important (Briffa et al. 1998).

for the reduced growth instead of colder temperatures. The Laki eruption, however, coincided with the 26th coldest summer (1783) between 1400 and 2000 in the NH (Briffa et al. 1998), although the potential link was not discussed by Briffa et al. (1998). New evidence for an important Laki effect come from additional tree growth data from Alaska and Inuit oral history (D'Arrigo and Jacoby 1999; Jacoby et al. 1999). Its effect was also felt in the eastern United States, with the report of a large cold anomaly in the three years following the Laki eruption (Thordarson and Self 2003). The IBF data, as well as the latter observations suggest that the Laki eruption had significant effects on the climate of northeastern North America. Overall, our data also add to the growing body of evidence describing volcanic eruptions as very important climate-forcing events in past centuries (Briffa et al. 1998; Adams et al. 2003).

The Québec temperature record also captured the influence of the Krakatoa eruption (Fig. 3), which clearly had the strongest climatic effect of all volcanic eruptions between 1875 and 2000. The effects were particularly seen in winter temperatures as compared to summer. The temperature drop between 1884 and 1888 led to an average winter temperature (−12.3°C) that was 4.0°C lower than the 1981–2000 average (−8.3°C). During the same period, the IBF rate was 75%. These data suggest that other high IBF frequencies that were frequent, particularly during the 1830–1910 period, yielded winter temperatures in the same range (i.e., ~4.0°C lower than current winter temperatures). It would follow that northeastern North American winters during the 1830–1910 period were much colder than previously thought, based on previous NH temperature reconstructions with a summer component and that the winter warming rate since then would have been greatly underestimated. It emphasizes the need for regional proxies and reconstructions to document the real amplitude of past climate.

4. Conclusions

The ice bridge data clearly identify trends in past winter variations in the Québec City region. There was a particularly cold period between ~1800 and 1910 that culminated between 1850 and 1900, while the warmest period was 1620–1740. This warmer period contrasts greatly with a cold period recorded in most NH records (but not in Labrador and Iceland), which was partly attributed to the Maunder Minimum. Some of the high IBF rate episodes were initiated by major volcanic eruptions, which confirm their role as important climate-forcing events.

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APPENDIX

Historical Sources

The following section contains the historical sources that were consulted, which cannot be found in conventional periodicals. Some of them are only available in French as old documents, reproduction of old documents, or microforms at the National Archives of Quebec and at the National Assembly Library of the Quebec government.

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