Regional impact of large-scale climate oscillations on ice out variability in New Brunswick and Maine

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ABSTRACT

The available ice out (the date of disappearance of ice from a water body) records were analyzed from four relatively closely spaced lakes in southwestern New Brunswick (Harvey, Oromocto, Skiff) and eastern Maine (West Grand Lake), with the longest set of available observations being for Oromocto Lake starting in 1876. Results of a coherence analysis carried out on the ice out data from the four lakes indicates that there is regional coherence and correspondingly, that regional drivers influence ice out. These results also indicate that ice out dates for lakes from the region where records have not been kept can also be interpolated from these results. As the ice out record was coherent, further analysis was done for only Oromocto Lake on the basis of it having the longest ice out record. Cross-wavelet analysis was carried out between the ice out record and a variety of cyclic climate teleconnections and the sunspot record to identify which phenomena best explain the observed ice out trends. The most important observed contributors to ice out were the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO), with observed periodicities at the interannual scale. At the decadal scale the Pacific Decadal Oscillation (PDO) and the 11-year solar cycle were the only patterns observed to significantly contribute to ice out.

INTRODUCTION

Ice phenology data comprises a series of annual dates corresponding to when ice forms in the fall (ice in/on) and recedes in the spring (ice out/off) (*Jensen et al., 2007*; *Latifovic & Pouliot, 2007*; *Patterson & Swindles, 2015*; *Imrit & Sharma, 2021*). Ice in/out dates are considered to be influenced by precipitation, insolation, discharge, humidity, and most significantly, air temperature (*Walsh et al., 1998*; *Futter, 2003*; *Livingstone et al., 2010*; *Patterson & Swindles, 2015*; *Imrit & Sharma, 2021*). The variation in ice phenology and—by extension—the length of ice-free seasons can impact lake chemistry, productivity, and overall ecosystem health (*Blenckner et al., 2007*; *Couture et al., 2015*; *Tan, Yao & Zhuang, 2018*). For example, changes in ice out dates have a significant influence on the hydroecology of lakes with earlier ice out dates resulting in warmer spring water temperatures, increased light availability, and changes to circulation patterns (*Hodgkins, 2013*). Ensuing changes in spring and summer development of phytoplankton and zooplankton communities significantly

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impact the trophic structure of lake ecosystems (*Blenckner, Omstedt & Rummukainen, 2002*; *Arhonditsis et al., 2004*). As an example, the occurrence of potentially harmful cyanobacteria blooms, an emergent concern in this region, are significantly influenced by the length of the open water season in lakes (*Ewing et al., 2020*; *Sivarajah et al., 2021*). A full understanding of the dynamics of changes in ice out dates over time thus has important implications for determining the impact of climate variability on the hydrology, aquatic ecosystems, and a regional economy that relies heavily on lakes as an important recreational resource.

In many lakeside communities in North America and elsewhere, ice out dates are available from local lake associations and individual or groups of citizen scientists who have kept records for over a century in the interests of transportation, recreation, lotteries, or simply out of curiosity (*Futter, 2003*; *Benson et al., 2012*; *Patterson & Swindles, 2015*). Given their length—into the 19th century for many eastern North American lakes—it is possible to attempt to identify interannual, interdecadal, and multidecadal climatic drivers from these time series (*Patterson & Swindles, 2015*). Such an approach is useful when instrumental records are not available, or to complement data from nearby weather stations, which may not be as long or as complete. These records have been used previously to examine the interconnectivity of ice out and climate records, as well as to assess trends and cycles archived in these data sets. Strong links between ice out and winter air temperature have been noted, as well as the influences on ice out dates by a variety of large-scale climatic oscillations (*e.g.*, Quasi-Biennial Oscillation (QBO), North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO)) has been recognized (*Livingstone, 2000*; *Magnuson, Benson & Kratz, 2004*; *Bonsal et al., 2006*; *Ghanbari et al., 2009*; *Livingstone et al., 2010*; *Bai et al., 2012*; *Mudelsee, 2012*; *Sharma et al., 2013*; *Fu & Yao, 2015*; *Patterson & Swindles, 2015*; *Imrit & Sharma, 2021*). However, more robust time series analyses have not yet been widely carried out to verify these oscillations as the drivers of local or regional ice out patterns or to understand the time-varying relationship between ice out and the climate oscillations.

The purpose of this article is to use statistical and time series analysis techniques to: (1) determine the spatial coherence of lake ice out in four closely spaced inland lakes from southwestern New Brunswick, Canada and eastern Maine, USA; (2) provide a robust assessment of the periodic nature of the ice out records; and (3) assess and correlate potential drivers of the periodic changes in ice out dates. The trends and cycles documented for seven well-known climatic oscillations—the Schwabe Solar Cycle (SSC), Arctic Oscillation (AO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), Quasi-Biennial Oscillation (QBO), North Atlantic Oscillation (NAO), and El Niño Southern Oscillation (ENSO)—will be compared against year over year changes in lake ice out dates to assess their relationships. Each of these oscillations and their effects on the study region are described in Table 1. To assess the relationships between the non-linear lake ice out time series and large-scale climate oscillations, various spectral analyses were carried out. These methods allow for the conversion of time-domain data (*e.g.*, a time series) to its frequency-domain counterpart, revealing the cyclic components of a given signal. Spectral analysis techniques have been used in many climate and environmental studies to provide

information on the periodic nature of various systems and improve the understanding of recurrent patterns. Recognizing periodic patterns in natural systems helps provide context for observed changes, particularly when assessing the impact of quasi-linear processes (*e.g.*, anthropogenic climate change) (*Ng & Chan, 2012*; *Colombo, Magazù & Caccamo, 2018*). Furthermore, demonstration that the ice out trends and cycles observed in the studied lakes are comparable is important as it would infer that limnological impacts influenced by ice out variability could be applied to lakes in the region where ice out data is not available. The understanding of lake ice out variability and its influencing factors could assist policy makers and local communities in the planning and preparation of lake-related activities and ecological monitoring in future seasons.

METHODS

Ice out records from three southwest New Brunswick lakes (Oromocto Lake (1876–2021), Skiff Lake (1933–2021), and Harvey Lake (1975–2021)) and one inland eastern Maine lake (West Grand Lake, 1878–2021), all located within 75 km of each other (Fig. 1), were obtained from local lake associations and the Maine Department of Agriculture, Conservation and Forestry (Article S1). While definitions of ice out may vary slightly between each lake and its ice out observers, ice out is generally defined as the first day that a lake is navigable with no impedance from ice cover. Depending on the ice out observers, criteria may also include the disappearance of ice from major coves (Article S1).

All data analysis was completed using Matlab. Each ice out record was checked for normality and detrended prior to applying any spectral analysis techniques. The Julian date of recorded ice out was used in each of the analyses completed. These dates are relative to each lake. As the patterns in the ice out records are the points of interest in this study, this relative data did not require standardization. The Harvey, Skiff, and West Grand lakes ice out records were each, in turn, compared to the Oromocto Lake record using wavelet coherence (WTC) and Pearson's correlation coefficients to assess spatial relationships within the study region. Oromocto Lake was chosen for this role due to it having, by two years, the longest ice out record of the four lakes. WTC transformations were carried out as they have been demonstrated to reliably identify local correlations between oscillating time series (*Grinsted, Moore & Jevrejeva, 2004*). The use of WTCs build upon linear correlation, as information about the covariance of two time series and their intermittent and time-varying correlations are provided. These results are presented by a series of arrows on a time-frequency spectrum, where the direction of the arrows indicates the relative phase of the two time series at a given time-frequency coordinate. Arrows pointing to the right (left) indicate that the time series are in-phase (anti-phase), whereas downward (upward) arrows indicate that one signal is being led by (lagged by) the other. In this case, downward (upward) arrows indicate that the Oromocto Lake record is oscillating ahead of (behind) the respective lake record it is being compared to. A strong coherence and correlation between the lake ice out records are indicative of regional trends in ice out

Table 1 Descriptions and regional effects of various climatic oscillations known to impact Atlantic Canada and United States.

Climatic oscillation	Notation	Cycle length (years)	Description	Common impact on eastern North American climate	Citations
Schwabe Solar Cycle	SSC	~11, 8–17	An oscillation in the annual number of sunspots occurring, relating to total solar irradiance. The increases in total solar irradiance and UV irradiance during sunspot maxima drive dynamic changes in global stratospheric and tropospheric temperatures.	Increases in temperature during sunspot maxima, decreases in temperature during sunspot minima. Various links to precipitation and precipitation-related parameters.	*Lassen & Friis-Christensen (1995)*, *Rind et al. (2008)*, *Lockwood (2012)* and *Hathaway (2015)*
Atlantic Multidecadal Oscillation	AMO	~64, 50–90, 16–24 subharmonics	An oscillation in the circulation pattern of warm and cool Atlantic ocean surface waters. Warm (AMO+) phases occurred from ~1925–1965 and ~1990-present, cool (AMO-) phases occurred from ~1900–1925 and ~1965–1990.	AMO+ is associated with increased temperatures, decreased precipitation, and greater drought probability.	*Schlesinger & Ramankutty (1994)*, *Enfield, Mestas-Nuñez & Trimble (2001)*, *Knight, Folland & Scaife (2006)*, *Dima & Lohmann (2007)*, *Feng, Hu & Oglesby (2011)*, *Knudsen et al. (2011)*, *Ruiz-Barradas, Nigam & Kavvada (2013)* and *Alexander, Kilbourne & Nye (2014)*
Pacific Decadal Oscillation	PDO	~Interannual–multidecadal; strongest oscillations in the 15–25 year and 50–70 year bands	Characterized by fluctuations in sea-surface temperature; during PDO+ phases, the western mid-latitude Pacific cools, whereas eastern mid- and low-latitude Pacific warms. Interannual fluctuations in the PDO are linked to ENSO and Aleutian Low variability.	PDO+ phases are associated with decreased precipitation in the Great Lakes region and cooler temperatures southeastern North America. Opposite patterns occur during PDO-.	*Trenberth (1990)*, *Latif & Barnett (1994)*, *Minobe (1997)*, *Minobe (1999)* and *Mantua & Hare (2002)*
North Atlantic Oscillation	NAO	Poorly defined, typically interannual–interdecadal	A localized oscillation in the sea level pressure differential between the Azores High and the Icelandic Low in the northern Atlantic Ocean.	NAO+ phases are typically associated with more moderate temperatures and wetter conditions in eastern North America, and drier, more extreme temperatures during NAO-phases.	*Hurrell (1995)*, *Hurrell, Kushnir & Visbeck (2001)*, *Hurrell et al. (2003)* and *Olsen, Anderson & Knudsen (2012)*

Table 1 (*continued*)

Climatic oscillation	Notation	Cycle length (years)	Description	Common impact on eastern North American climate	Citations
Arctic Oscillation	AO	Poorly defined, typically interannual–interdecadal	A broad oscillation in sea-level pressure in the Northern Hemisphere, occurring in an annular band around the northern mid-latitudes. During its positive phase, the AO supports a low-amplitude jet stream, during an AO-phase the jet-stream becomes a high-amplitude waveform. The localized NAO is a constituent of the broad scale AO.	Brings cool Arctic air to the mid-latitudes during AO+; cool Arctic airmasses travel further south into North America during AO-.	*Deser (2000)*, *Ambaum, Hoskins & Stephenson (2001)*, *Rogers & McHugh (2002)* and *Li et al. (2017)*
El Niño Southern Oscillation	ENSO	2–10	An oscillation characterized by the changes in sea surface temperatures in the tropical Pacific. Driven by the variation in strength of tropical trade winds—causing greater or weaker degrees in the upwelling of cool, deep ocean water during El Niño (ENSO+) and La Nina (ENSO-), respectively—this oscillation influences many regions of the world via various teleconnections.	Warmer, drier conditions during El Niño; cooler, wetter conditions during La Nina.	*Philander (1983)*, *Ropelewski & Halpert (1986)*, *Philander (1989)*, *Moy et al. (2002)* and *Hu & Feng (2012)*
Quasi-Biennial Oscillation	QBO	2.1–2.4	The oscillation between westerly and easterly winds in the equatorial stratosphere. Air masses then propagate downward to the troposphere and are subsequently propagated poleward via teleconnections with surface waves.	Cooler temperatures during the westerly (QBO+) phase, warmer temperatures during the easterly (QBO-) phase.	*Lindzen & Holton (1968)*, *Dunkerton (1997)*, *Baldwin et al. (2001)*, *Chattopadhyay & Bhatla (2002)*, *Sharma & Magnuson (2014)*, *Patterson & Swindles (2015)* and *Gray et al. (2018)*

and, by extension, climate, whereas weak correlations indicate more climatic variation in the Atlantic region.

To assess long-term trends and fluctuations, locally weighted linear regressions (LOWESS) was carried out for each of the four lake ice out records over 20-year periods (*Cleveland, 1979*; *Cleveland, 1981*). The 95% confidence intervals on the LOWESS models were calculated by bootstrapping without replacement (1,000 replicates).

Due to strong correlation and coherence between each of West Grand, Harvey, and Skiff lakes to Oromocto Lake, only the ice out record for Oromocto Lake was assessed for its periodic components (for simplicity) using spectral and wavelet analysis. Thomson's
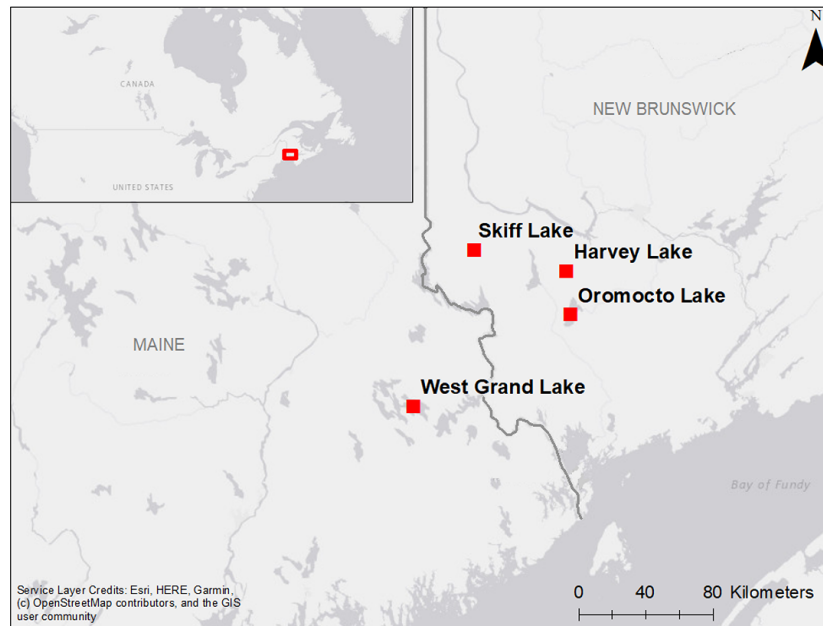
Figure 1 **Location of lakes in New Brunswick and Maine for which ice out records were obtained.**

Multitaper Method (MTM, *Thomson, 1982*; *Dorothée, 2020*) was used to transform the time series data into its corresponding frequency domain by comparing various sine functions of different amplitudes and wavelengths to the time series. High correlation of a given sine curve to the input time series results in higher spectral power at the corresponding frequency of the sine curve, which is shown on one axis of the spectral analysis plots. Frequency is shown on the other axis. With this method, one can discern discrete frequency information of the input time series by examining the peaks of the resulting periodogram. Furthermore, the MTM uses multiple 'tapers', unlike other nonparametric spectral analysis methods. Tapers, or windows, are symmetric, zero-sum curves that are pairwise orthogonal to the input time series. A time series can be multiplied by a taper to minimize the spectral leakage of the signal. The MTM uses a set of idealized tapers to transform the input time series before comparing it to the various sine curves. The spectra of all tapered time series data are then averaged, ultimately resulting in a more stable and robust spectral estimate (*Schulz & Mudelsee, 2002*; *Husson et al., 2014*).

The mean spectral estimate was compared to 80, 90, 95, and 99% false alarm levels, calculated using chi-square confidence estimate, and the red noise (AR1) model, calculated using a Monte Carlo loop (1,000 replicates) (*Schulz & Mudelsee, 2002*; *Husson et al., 2014*; *Dorothée, 2020*).

Continuous wavelet transforms (CWTs) were used in tandem with the MTM to assess the time-frequency variation of the time series. Similar to the MTM, CWTs compare a waveform to a time series, the results of which present the spectral information of a time series; this method differs from the MTM, as it does not provide discrete spectral peaks, though it does indicate the variation in these signals in time (*Torrence & Compo, 1998*;

Grinsted, Moore & Jevrejeva, 2004). This time-varying spectral estimate is computed by comparing a waveform (in this case, the Morlet wavelet) at a range of frequencies and amplitudes to the time series throughout a sequence of time steps. The correlation of the given waveform at each time step results in a spectral estimate unique to that moment in time. This time-varying frequency estimate is presented in three axes: an *x*-axis indicating the time, a *y*-axis indicating the frequency or period, and a colour axis representing the spectral power. The 95% confidence interval was calculated using the chi-square estimate (*Torrence & Compo, 1998*) and is shown as a solid black line on the resulting wavelet scalograms. Cones of influence are also depicted on the scalograms; these cones indicate the time-frequency information on a given scalogram that may be subject to 'edge effects' from the boundaries of the time series. Using both the MTM and CWT in tandem provide both discrete and continuous frequency domain data.

The Oromocto Lake ice out record was then compared to each of the SSC (*SILSO, 2021*), PDO (*Deser et al., 2016*), AMO (*Trenberth et al., 2021*), AO (*NCAR, 2020*), NAO (*Hurrell & NCAR, 2020*), ENSO (*Trenberth & NCAR, 2020*), and QBO (*NCAR, 2013*) *via* cross wavelet transforms (XWTs). XWTs are a type of spectral transform similar to a CWT, in that the time-varying frequency information of time series is computed. However, the purpose of an XWT is not to present only this time-frequency information, but rather to compare a reference signal with an analyte signal to assess the common time-frequency components to the two signals. The resulting XWT scalogram appears the same as that of a CWT, though only the common elements time-frequency spectrum is displayed (*Grinsted, Moore & Jevrejeva, 2004*). Using this method, we can assess the relationships between the reference signal (*i.e.,* Oromocto Lake ice out) and each analyte signal (*e.g.,* the AMO or the PDO).

RESULTS

General trends in lake ice phenology

While ice out dates can fluctuate by as much as 20 + days year over year, long-term averages in lake ice phenology are generally more consistent, only varying up to 10 days decade over decade (Fig. 2). On West Grand Lake, ice persisted latest in the spring on average from ~1880–1890 before trending to earlier ice out dates until ~1900, shifting later in the spring again until ~1910. In contrast, average ice out dates for Oromocto Lake were relatively consistent from 1876–1910. From the mid to late 1910s onward, ice out on both West Grand Lake and Oromocto Lake shifted earlier in the year until the 1930s. Average ice out dates shifted later again through the next decade until the early 1940s on each of West Grand Lake, Oromocto Lake, and Skiff Lake before becoming earlier around 1950. These three lakes each exhibit a later ice out peak, spanning the entire record in the 1960s and 1970s before generally declining towards 2000 (Harvey Lake also exhibits this decline). Since the early 2000s, average ice out dates have generally shifted later in the year on all lakes except West Grand Lake. West Grand Lake ice out indicates the most substantial change between the late 19th century and the early 21st century, with the average ice out date lowering from approximately Julian Day 124 to Julian Day 115. Oromocto Lake does

not show this same change, with average late 19th century ice out occurring prior to Julian Day 120 and early 21st century ice out occurring around Julian Day 115.

Lake ice out coherence and correlation

Oromocto Lake exhibited very strong coherence with each of the three other lakes in this study, particularly in the latter 20th century. The coherence with each lake spans interannual to interdecadal bands at the 95% confidence level (Figs. 3D, 3E and 3F), though notable non-significant coherence bands include ~10 years (all lakes), ~21 years (Skiff Lake), and ~42 years (West Grand Lake). West Grand Lake has the most comparable record length to Oromocto. Prior to ~1940, these records have less coherence and only a moderate correlation ($r^2 = 0.355$, $p = 0.004$, $df = 62$), but are strongly coherent and correlated afterwards ($r^2 = 0.921$, $p < 0.001$, $df = 78$; Figs. 3F and 4). The Skiff Lake record is similar in that correlation was initially lower ($r^2 = 0.401$, $p = 0.038$, $df = 26$) with coherence primarily at interdecadal scales but increased after 1960 (Fig. 3E), whereafter the records are coherent and strongly correlated ($r^2 = 0.895$, $p < 0.001$, $df = 49$). Harvey Lake has the shortest available ice out record and shows strong and significant coherence (Fig. 3D) and correlation with Oromocto Lake over the available dates ($r^2 = 0.966$, $p < 0.001$, $df = 45$, Fig. 4). The strong overall correlation and coherence of all three lakes with Oromocto Lake ice out justifies the use of the Oromocto Lake record as a representative sample for the region, particularly for the mid-20th century to present-day interval.

Periodicity in lake ice out

Figure 5 shows a periodogram and a continuous wavelet transform for the ice out record from Oromocto Lake. The time series is primarily characterized by interannual oscillations with periods ranging from 2.1 to 8.3 years. These oscillations are most significantly (>95% confidence) concentrated between approximately 1900–1940 and 2000–2015, but they also occur intermittently with lower significance throughout the ice out record, as recognized in both the MTM periodogram and the CWT. Some interdecadal oscillations are also present at a lower significance; ~9–18 year oscillations persist from approximately 1940–1990 (significant at the 95% confidence level from approximately the mid-1940s to ~1970), as well as a ~23–34 year oscillation from 1920–2000.

   The XWTs between the Oromocto Lake ice out time series and the records for seven known regional climate oscillations are provided in Fig. 6, while the XWTs for Harvey, Skiff, and West Grand lakes where observed large-scale climate oscillations can be viewed in Fig. S1. A comparison of the XWT results with the CWT and periodogram helps clarify which climatic oscillations best explain observed oscillations in the ice out record.

   At the interdecadal to multidecadal scales, the PDO, SSC, and AMO are of particular interest. The PDO shows strong relationships with cycles within the 15–18-year band (most significantly from ~1940–1960) as well as a 23–34-year oscillation from 1920–1965. The SSC is linked to ~7–13-year oscillations in the ice out dates, most significantly from 1900–1980. Less significant relationships exist during times of weak quasi-decadal oscillations in ice out (*e.g.*, 1995–2015). While the relationship for AMO is less significant (<95% confidence), there nevertheless exists an area of high incidence between the AMO
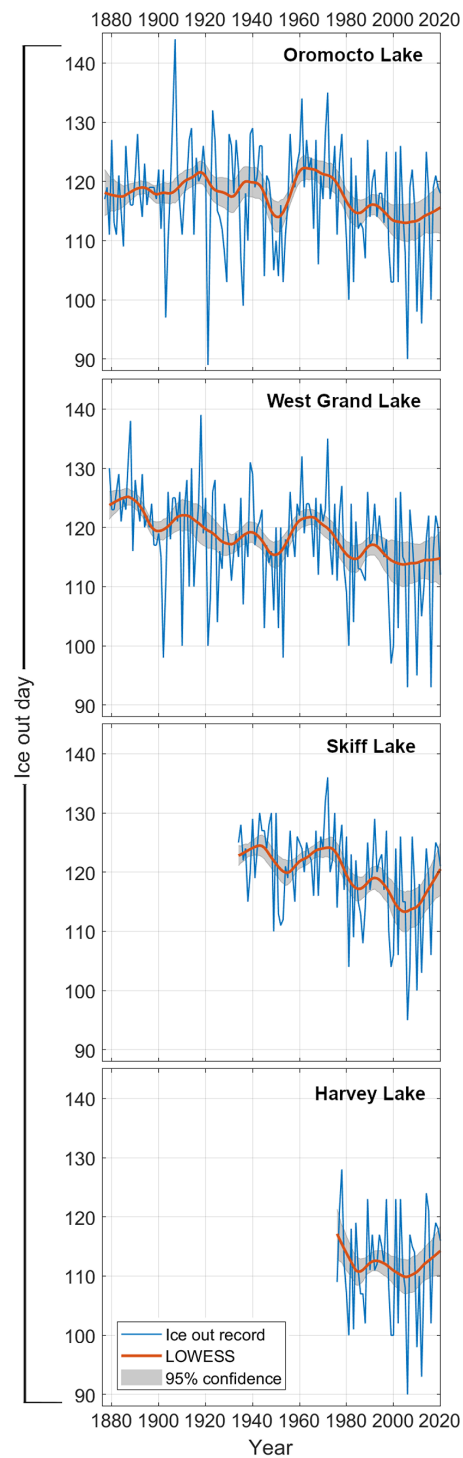
Figure 2   LOWESS regressions (span—20 years, ± 95% confidence) for each lake ice out record for their available time frames.
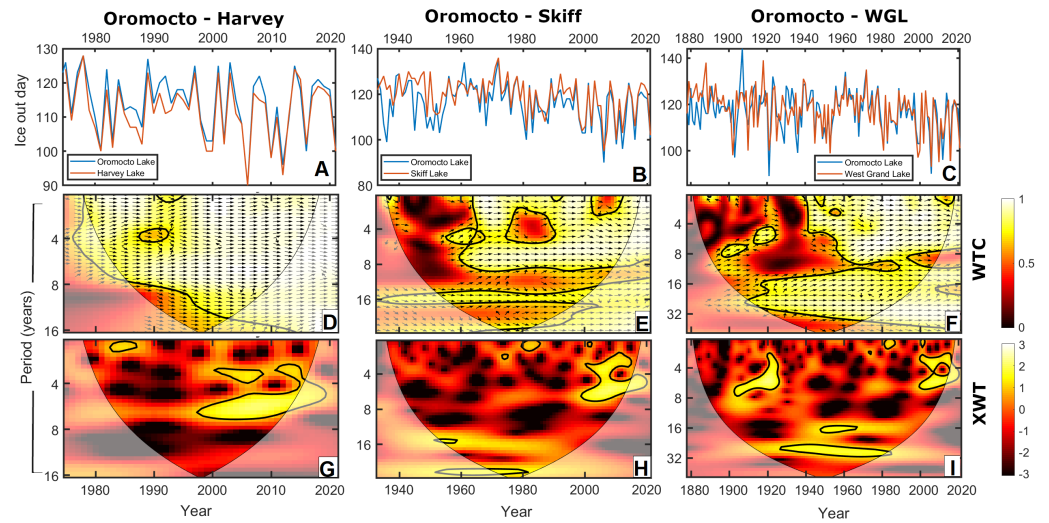
Figure 3 (A–C) Graphical comparisons, (D–F) wavelet coherence (WTC), and (G–I) cross wavelet transforms (XWTs) between the Oromocto Lake ice out record and each of the Harvey Lake, Skiff Lake, and West Grand Lake ice out records during relative time intervals. Arrows on the wavelet coherence scalograms indicate locally phase locked behaviour, where right-pointing arrows indicate in-phase relationships, left-pointing arrows indicate anti-phase relationships, and up/down-pointing arrows indicate lagging/leading relationships.
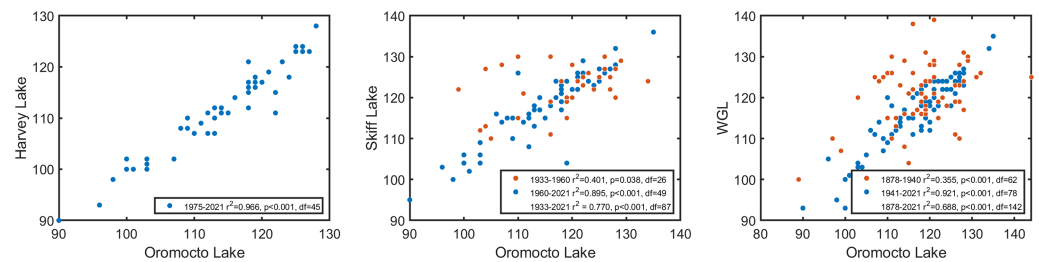
Figure 4 Correlations between the Oromocto Lake ice out record and each of the Harvey Lake, Skiff Lake, and West Grand Lake ice out records. Pearson's correlation coefficients and *p*-values are given. Multiple correlations for Oromocto Lake with each of Skiff and West Grand Lakes are given as these correlations strengthen during later time intervals.

and the ice out time series from approximately 1920 and 1980, with oscillations of 23–30 years. Furthermore, the beginnings of a 45+ year oscillation related to the AMO is just visible at the bottom of the AMO—ice out scalogram, indicating that the longer band of the AMO may have a relationship with ice out dates.

The most prevalent oscillations at the interannual scale are primarily associated with ENSO, NAO, AO, and QBO (Figs. 6F–6I). Both ENSO and NAO appear to have the strongest relationship with the interannual oscillations occurring between 1900–1920 (~5–8-year oscillations). The AO exhibits a weaker relationship at this time-frequency location, though this may be influenced by the AO's shorter temporal record. Each of these three climatic oscillations also exhibit significant relationships with the ice out record
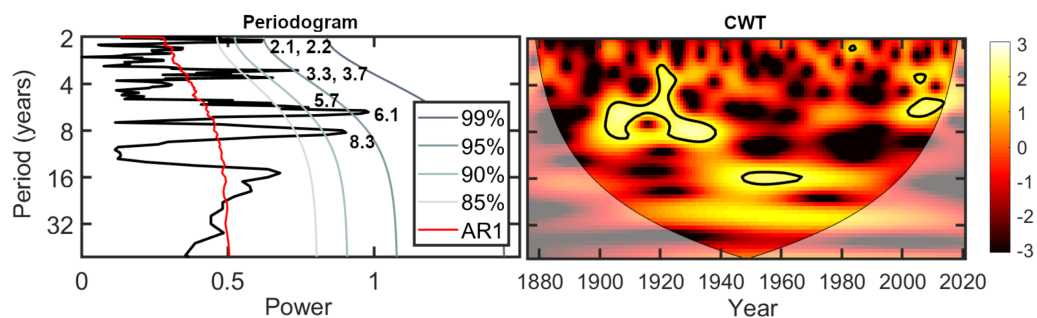
Figure 5 Spectral analysis and the continuous wavelet transform (CWT) for the Oromocto Lake ice out record, 1876–2021.

from approximately 2000–2015, in the 3–6-year return time range. The QBO primarily exhibits significant cyclic relationships with the ice out record at a period of 2.1–3.1 years (*e.g.*, ~1966–1968, 1980–1990, Fig. 6I). A 12–18-year common oscillation is also present between ice out and the QBO from approximately 1953–1975. While they are usually associated with interdecadal to multidecadal oscillations, the PDO and AMO also show some instances of significant (>95% confidence) relationships, primarily in the 3–8-year return time bands during the time intervals spanning 1900–1940 and 2000–2015.

DISCUSSION

Regional coherence and long-term patterns in ice out

The strong coherence and correlation exhibited between lake ice out records between closely spaced Harvey, Oromocto, Skiff and West Grand lakes (Figs. 3 and 4), and the similarity in long-term observed trends (Fig. 2) are indicative of regionally consistent patterns in ice out and ice out forcings. While localized factors such as the surrounding landscape, lake basin and shoreline characteristics, and wind exposure may influence some minor variation between ice out dates of these four lakes, the main drivers of ice out appear active at a regional scale. The long-term patterns in lake ice out in these lakes suggests only limited changes in year over year (20 + days) ice out variation since the late 19th century. While several shifts towards earlier or later average ice out have been recognized, a substantial change in average ice out since the late 19th was not strongly apparent (late 19th century average ice out occurred around Julian Day 120 (125) on Oromocto (West Grand) Lake whereas early 21st century ice out occurred around Julian Day 115 (115)). Rather, interdecadal shifts in ice out dates dominate the long-term variation, culminating in a shift toward later average ice out beginning in the early 2000s and continuing to present.

The general long-term pattern in lake ice out closely resembles the findings of *Hodgkins, James & Huntington (2002)* for ice out on northern New England lakes(which are latitudinally similar to the four lakes examined here) between the late 19th century to the year 2000. *Hodgkins, James & Huntington (2002)* note that lakes in the northern and mountainous regions of New England did not exhibit as strong of shifts toward earlier ice out dates in this time frame as lakes of southern New England did. The authors suggest
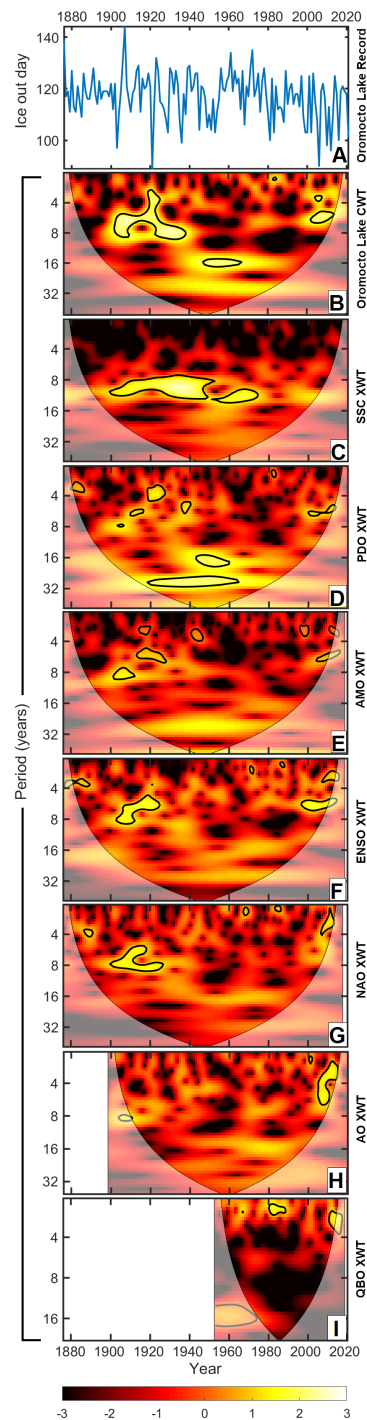
Figure 6 For Oromocto Lake ice out, (A) graphical representation, (B) the continuous wavelet transform (CWT), and (C–I) the cross wavelet transforms (XWTs) between Oromocto Lake ice out and each of the Schwabe Solar Cycle (SSC), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and Quasi-Biennial Oscillation (QBO).

that greater snow cover in the northern region decreases the sensitivity of lake ice cover to late winter regional air temperature, which is a primary driver of ice out. For the four lakes examined here, a similar moderation of ice out day may be occurring due to snow cover, subsequently decreasing the correlation to air temperature.

Prior to the mid-20th century, coherence and correlation between time series were lower though, for which a possible, but not confirmed explanation, may be related to a change in reporting methodology. For example, at Oromocto Lake, reporting of ice out dates have for decades been documented by citizen scientist Clayton Piercy who took over the duty of collating and recording ice out dates as a teenager in the 1940s. He used a single set of criteria (ice out declared when ice has disappeared from all coves) from the mid 20th century until his recent passing. The reporting of ice out on Oromocto Lake is now carried out collaboratively by many members of the Oromocto Lake Association using the same criteria as used by Clayton Piercy, but now aided by real time simultaneous social media monitoring of the entire lake. Prior to the mid 20th century, reports were made by many people at different locations on the lake, where based on examination of the data, ice out may have been declared when ice disappeared from the main body of the lake, and not slightly later when it disappeared from coves (Article S1). This unconfirmed hypothesis may explain the reduced coherence between the ice out record for Oromocto Lake and that from West Grand Lake through the earlier part of the ice out record.

Interannual variations

Ice out in the study area is primarily dominated by interannual oscillations in the ∼2–8 year range (Figs. 3 and 5). A correlation with these periodicities is most apparent in the scalograms with ENSO and NAO (Fig. 6). These oscillations have also previously been related to variations in temperature and precipitation in the region (*Shabbar, Bonsal & Khandekar, 1997*; *Shabbar, 2006*; *Toniazzo & Scaife, 2006*; *Bonsal & Shabbar, 2011*; *Zhao et al., 2013*; *Patterson & Swindles, 2015*; *Nalley et al., 2019*). The effects of ENSO and NAO on ice out are similar to one another, for which there are two main explanations. The simplest explanation is that the dominant frequencies of the two oscillations are similar. Both oscillations have a particularly strong 4–8 year band (*Rasmusson & Carpenter, 1982*; *Kestin et al., 1998*; *Setoh et al., 1999*; *Pozo-Vázquez et al., 2001*; *Barbosa, Silva & Fernandes, 2006*; *Olsen, Anderson & Knudsen, 2012*), which is abundant in the ice out time series. The alternate explanation is that there is a nonstationary relationship between the ENSO and NAO, in which the two climatic oscillations interact and covary depending on their phases (*Zanchettin et al., 2008*; *Seager et al., 2010*; *Zhang et al., 2019*). These interactions may amplify late winter/early spring temperature and precipitation anomalies depending on the state of the oscillations' nonstationary relationship, each of which are correlated to ice out dates (*Hodgkins, James & Huntington, 2002*; *Hewitt et al., 2018*).

The AO exhibited a relationship to ice out similar to that of the ENSO and NAO, though it was generally weaker (∼8 year common oscillations, ∼1910; 3–8 year common oscillations, ∼2000–2015). The NAO is a geographically localized subset of the AO with both being products of oscillations in atmospheric pressure which, in turn, impact atmospheric circulation and the movement of airmasses (*Thompson & Wallace, 1998*; *Ambaum, Hoskins*

& Stephenson, 2001; *Rogers & McHugh, 2002*; *Thompson & Lorenz, 2004*; *Cohen & Barlow, 2005*). While the AO has been found to influence ice out and other climate variables elsewhere in eastern North America (*Bonsal et al., 2006*; *Wang et al., 2010*; *Mishra et al., 2011*; *Wang et al., 2012*; *Imrit & Sharma, 2021*), its weaker influence on Oromocto Lake ice out may be a result of the AO's broader geographic expanse, in comparison to the NAO.

The QBO exhibited a relationship to observed ∼2–3 year oscillations in ice out, which suggests that it plays a role in driving interannual ice out variability, albeit less importantly than for the ENSO and NAO though. The QBO has previously been attributed as the driver of ∼2-year variations in ice out along the east coast of North America (*Sharma & Magnuson, 2014*; *Patterson & Swindles, 2015*; *Imrit & Sharma, 2021*), and has been related to other climatic variations, such as those in temperature or precipitation (*Lau & Sheu, 1988*; *Baldwin et al., 2001*; *Chattopadhyay & Bhatla, 2002*; *Becker et al., 2008*; *Cherenkova, Bardin & Zolotokrylin, 2015*). The QBO is linked to the strengthening/weakening and the overall stability of the Arctic polar vortex. The strength and stability of the polar vortex impacts the movements of large-scale airmasses, thus impacting mid-latitude temperatures, strom tracks, and precipitation (*Holton & Tan, 1980*; *Walter & Graf, 2005*; *Anstey & Shepherd, 2014*; *Overland & Wang, 2019*).

Interdecadal variations

Interdecadal oscillations in ice out in these lakes were primarily correlated to the SSC and the PDO. While the quasi-decadal signal in the ice out time series was generally weak, it has a strong relationship to the SSC. This result suggests that while quasi-decadal oscillations are not always prominent in the ice out record, in the instances when they are present, they are primarily driven by the SSC. A strong relationship between the SSC and quasi-decadal oscillations has been previously observed for both ice out records (*Sharma et al., 2013*; *Sharma & Magnuson, 2014*; *Fu & Yao, 2015*; *Hewitt et al., 2018*) and temperature and precipitation records (*Vines, 1984*; *Currie & O'Brien, 1988*; *Currie, 1993*; *Van Loon & Shea, 1999*; *Ogurtsov et al., 2008*; *Lockwood, 2012*; *Laurenz, Lüdecke & Lüning, 2019*; *Walsh & Patterson, 2022*; *Walsh & Patterson, 2022*) due to its relation to total solar irradiance, which subsequently influences atmospheric, oceanic, and terrestrial heating (*Yang et al., 2010*; *Kopp, 2014*).

The PDO appears to be the primary driver correlated to 15–18 year and 23–34 year oscillations in ice out record, which is largely consistent with the prominent 15–25 year band of the PDO (*Minobe, 1997*; *Minobe, 1999*; *Mantua & Hare, 2002*; *D'Orgeville & Peltier, 2007*; *Wu et al., 2011*). Similar to what was observed with the quasi-decadal oscillations, these oscillations are not very prominent in the ice out record, but they have a strong relationship with the PDO when they are present. The correlation of the PDO to ice out is strongest prior to the 1977 PDO regime shift. Other PDO regime shifts (*e.g.*, 1890, 1925, and 1947) are somewhat recognizable in the PDO–ice out relationships (Fig. 6), though not amongst the statistically significant correlations. PDO regime shifts, particularly the 1976–1977 "Great Regime Shift" from PDO+ to PDO-, have been recognized as contributors to abrupt changes in climate and ecological systems worldwide (*Hare & Mantua, 2000*; *Scheffer et al., 2001*; *Litzow, 2006*; *Le Goff et al., 2007*; *Wang et al., 2014*;

Jacques-Coper & Garreaud, 2015), and have been noted for influencing ice phenology, primarily *via* atmospheric temperature changes (*Magnuson, Benson & Kratz, 2004*; *Bonsal et al., 2006*; *Ghanbari et al., 2009*; *Mishra et al., 2011*; *Wang et al., 2018*).

The AMO also exhibited a correlation to the 23–34 year band in ice out, but not at a 95% confidence level. The observed AMO–ice out relationship is similar to that of the PDO, though weaker overall, exhibiting a statistically insignificant correlation to the 23–34 year band in ice out. As the AMO influences Atlantic climate events and patterns and is characterized by sea surface temperature variation, a relationship to east coast ice out variation is not unreasonable (*McCabe, Palecki & Betancourt, 2004*; *Alexander, Kilbourne & Nye, 2014*; *Wang et al., 2018*; *Abiy, Melesse & Abtew, 2019*). This weaker but persistent AMO–ice out relationship could also be related to the PDO, as it mirrors the PDO's relationship to 23–34 year oscillations in ice out. There exists a moderate correlation between the indices for the AMO and PDO (*McCabe, Palecki & Betancourt, 2004*; *D'Orgeville & Peltier, 2007*; *Wu et al., 2011*; *Ogunjo & Fuwape, 2020*; *Zhang et al., 2020*); thus, the similarity in their influence on ice out variation may stem from mutual interactions.

Furthermore, the beginnings of a 45+ year AMO relationship to Oromocto Lake ice out were exhibited in Fig. 6. This provides a preliminary indication that the primary multidecadal mode of the AMO likely influences ice out in the New Brunswick and Maine region; however, further validating this relationship with the methods used here is not possible due to the limited time frame of ice out data available. A longer ice out record is needed to robustly assess the common multidecadal signals of the AMO (50–90 years) and regional ice out.

It should be noted that the interdecadal oscillations are most strongly recognized in the ice out record and most strongly correlated to other oscillations within the cone of influence on each CWT or XWT. While this may be an accurate representation of the time series, it is also possible that the concentration of these interdecadal oscillations within the cone of influence could be attributed to edge effects, where the frequency information of the input signal(s) may be distorted outside of the cone of influence (*Grinsted, Moore & Jevrejeva, 2004*). The CWT and XWT techniques are limited in this sense. The timing of low frequency oscillations cannot be conclusively determined without longer data records.

Lastly, a brief instance of an interdecadal-scale relationship was depicted between ice out and the QBO between approximately 1953–1980. This result likely stems from a modulatory effect between the SSC and the QBO, reported in several studies (*Quiroz, 1981*; *Hamilton, 2002*; *Fischer & Tung, 2008*), which has not persisted since the early 1980s.

CONCLUSIONS

This study examined four inland lakes, all within 75 km of each other in eastern Maine and southwest New Brunswick, to assess regional drivers of ice out variability. The ice out records of three of these lakes (West Grand Lake in Maine, and Skiff Lake and Harvey Lake in New Brunswick) were first compared to that of Oromocto Lake in New Brunswick, as it had the longest record, to assess the presence of regionally consistent patterns. The

lakes in the region were strongly correlated and coherent with Oromocto Lake's ice out record, particularly from the mid-20th century, suggesting regional consistency in ice out patterns and their drivers. Inconsistencies prior to the mid-20th century may be attributed to changes in data-gathering methodology and personnel, though this hypothesis has not been confirmed.

Oromocto Lake ice out was then compared to various climatic oscillations *via* spectral, CWT, and XWT analysis. These time-series analysis techniques suggest that most ice out variation occurs primarily at the interannual scale. These variations are generally related to the ENSO and the NAO, particularly for periods of 4–8 years. Lower interannual oscillations (2–3 years), while less prominent in the ice out time series, are related to the QBO. Interdecadal to multidecadal variations form a secondary component of the ice out time series, and are most strongly driven by the SSC (quasi-decadal) and the PDO (15–25 year). A good understanding of the role of trends and cycles of regional climate drivers on ice out allows for the prediction of both future variation in regional lake ice out and regional climate. This is of importance as this data will inform policy makers and planners when considering future recreation, economic development, and environmental practices as they relate to adapting to changes in regional climate. Of particular environmental concern is that the length of the open water season is driven by ice out, which in turn significantly impacts lake ecosystems, particularly the significant emergent environmental threat to the region, cyanobacteria blooms.

ACKNOWLEDGEMENTS

We extend our gratitude to the various lake associations and citizen scientist ice out observers for sharing their data with us, as well as to the many citizen scientists that have participated in the collection of these records over the years.

Funding

This research was supported by a Natural Sciences and Engineering Research (NSERC) Discovery Grant (No. RGPIN-2018-05329) and Carleton University Multidisciplinary Research Catalyst Fund (MRCF) grant to R. Timothy Patterson. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Grant Disclosures

The following grant information was disclosed by the authors:
Natural Sciences and Engineering Research (NSERC) Discovery: RGPIN-2018-05329.
Carleton University Multidisciplinary Research Catalyst Fund (MRCF).

Competing Interests

The authors declare there are no competing interests.
Author Contributions

- Carling R. Walsh conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- R. Timothy Patterson conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The raw annual ice out data is available in the Supplemental Files.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.13741#supplemental-information.

REFERENCES

Abiy AZ, Melesse AM, Abtew W. 2019. Teleconnection of regional drought to ENSO, PDO, and AMO: Southern Florida and the everglades. *Atmosphere* **10(6)**:295 DOI 10.3390/atmos10060295.

Alexander MA, Kilbourne KH, Nye JA. 2014. Climate variability during warm and cold phases of the Atlantic Multidecadal Oscillation (AMO) 1871–2008. *Journal of Marine Systems* **133**:14–26 DOI 10.1016/j.jmarsys.2013.07.017.

Ambaum MHP, Hoskins BJ, Stephenson DB. 2001. Arctic oscillation or North Atlantic oscillation? *Journal of Climate* **14(16)**:3495–3507 DOI 10.1175/1520-0442(2001)014<3495:AOONAO>2.0.CO;2.

Anstey JA, Shepherd TG. 2014. High-latitude influence of the quasi-biennial oscillation. *Quarterly Journal of the Royal Meteorological Society* **140(678)**:1–21 DOI 10.1002/qj.2132.

Arhonditsis GB, Winder M, Brett MT, Schindler DE. 2004. Patterns and mechanisms of phytoplankton variability in Lake Washington (USA). *Water Research* **38(18)**:4013–4027 DOI 10.1016/j.watres.2004.06.030.

Bai X, Wang J, Sellinger C, Clites A, Assel R. 2012. Interannual variability of Great Lakes ice cover and its relationship to NAO and ENSO. *Journal of Geophysical Research: Oceans* **117(C3)**:C03002.

Baldwin MP, Gray LJ, Dunkerton TJ, Hamilton K, Haynes PH, Randel WJ, Holton JR, Alexander MJ, Hirota I, Horinouchi T. 2001. The quasi-biennial oscillation. *Reviews of Geophysics* **39(2)**:179–229 DOI 10.1029/1999RG000073.

Barbosa S, Silva ME, Fernandes MJ. 2006. Wavelet analysis of the Lisbon and Gibraltar North Atlantic Oscillation winter indices. *International Journal of Climatology: A Journal of the Royal Meteorological Society* **26(5)**:581–593 DOI 10.1002/joc.1263.

Becker S, Hartmann H, Coulibaly M, Zhang Q, Jiang T. 2008. Quasi periodicities of extreme precipitation events in the Yangtze River basin, China. *Theoretical and Applied Climatology* **94(3–4)**:139–152 DOI 10.1007/s00704-007-0357-6.

Benson BJ, Magnuson JJ, Jensen OP, Card VM, Hodgkins G, Korhonen J, Livingstone DM, Stewart KM, Weyhenmeyer GA, Granin NG. 2012. Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855–2005). *Climatic Change* **112(2)**:299–323 DOI 10.1007/s10584-011-0212-8.

Blenckner T, Adrian R, Livingstone DM, Jennings E, Weyhenmeyer GA, George DG, Jankowski T, Järvinen M, Aonghusa CN, Noges T. 2007. Large-scale climatic signatures in lakes across Europe: a meta-analysis. *Global Change Biology* **13(7)**:1314–1326 DOI 10.1111/j.1365-2486.2007.01364.x.

Blenckner T, Omstedt A, Rummukainen M. 2002. A Swedish case study of contemporary and possible future consequences of climate change on lake function. *Aquatic Sciences* **64(2)**:171–184 DOI 10.1007/s00027-002-8065-x.

Bonsal BR, Prowse TD, Duguay CR, Lacroix MP. 2006. Impacts of large-scale teleconnections on freshwater-ice break/freeze-up dates over Canada. *Journal of Hydrology* **330(1–2)**:340–353 DOI 10.1016/j.jhydrol.2006.03.022.

Bonsal B, Shabbar A. 2011. *Large-scale climate oscillations influencing Canada, 1900–2008.* Montreal, QC, Canada: Canadian Councils of Resource Ministers.

Chattopadhyay J, Bhatla R. 2002. Possible influence of QBO on teleconnections relating Indian summer monsoon rainfall and sea-surface temperature anomalies across the equatorial pacific. *International Journal of Climatology* **22(1)**:121–127 DOI 10.1002/joc.661.

Cherenkova EA, Bardin MY, Zolotokrylin AN. 2015. The statistics of precipitation and droughts during opposite phases of the quasi-biennial oscillation of atmospheric processes and its relation to the yield in the European part of Russia. *Russian Meteorology and Hydrology* **40(3)**:160–169 DOI 10.3103/S1068373915030024.

Cleveland WS. 1979. Robust locally weighted regression and smoothing scatterplots. *Journal of the American Statistical Association* **74(368)**:829–836 DOI 10.1080/01621459.1979.10481038.

Cleveland WS. 1981. LOWESS: a program for smoothing scatterplots by robust locally weighted regression. *American Statistician* **35(1)**:54.

Cohen J, Barlow M. 2005. The NAO, the AO, and global warming: how closely related? *Journal of Climate* **18(21)**:4498–4513 DOI 10.1175/JCLI3530.1.

Colombo F, Magazù S, Caccamo MT. 2018. Wavelet analysis as a tool for characterizing trends in climatic data. In: Burgess J, ed. *Wavelets: principles, analysis and applications.* Hauppauge, New York: Nova Science Publishers, 55–76.

Couture R-M, De Wit HA, Tominaga K, Kiuru P, Markelov I. 2015. Oxygen dynamics in a boreal lake responds to long-term changes in climate, ice phenology, and DOC inputs. *Journal of Geophysical Research: Biogeosciences* **120(11)**:2441–2456 DOI 10.1002/2015JG003065.

Currie RG. 1993. Luni-solar 18.6-and solar cycle 10–11-year signals in USA air temperature records. *International Journal of Climatology* **13(1)**:31–50 DOI 10.1002/joc.3370130103.

Currie RG, O'Brien DP. 1988. Periodic 18.6-year and cyclic 10 to 11 year signals in northeastern United States precipitation data. *Journal of Climatology* **8(3)**:255–281 DOI 10.1002/joc.3370080304.

Deser C. 2000. On the teleconnectivity of the Arctic Oscillation. *Geophysical Research Letters* **27(6)**:779–782 DOI 10.1029/1999GL010945.

Deser C, Trenberth K, National Center for Atmospheric Research Staff (NCAR) (eds.) 2016. The climate data guide: Pacific Decadal Oscillation (PDO): definition and indices. *Available at https://climatedataguide.ucar.edu/climate-data/pacific-decadal-oscillation-pdo-definition-and-indices*.

Dima M, Lohmann G. 2007. A hemispheric mechanism for the Atlantic Multidecadal Oscillation. *Journal of Climate* **20(11)**:2706–2719 DOI 10.1175/JCLI4174.1.

D'Orgeville M, Peltier WR. 2007. On the Pacific decadal oscillation and the Atlantic multidecadal oscillation: might they be related? *Geophysical Research Letters* **34(23)**:L23705.

Dorothée . 2020. Red noise confidence levels (https://www.mathworks.com/matlabcentral/fileexchange/45539-rednoise_confidencelevels). MATLAB central file exchange. (accessed on 11 February 2020).

Dunkerton TJ. 1997. The role of gravity waves in the quasi-biennial oscillation. *Journal of Geophysical Research: Atmospheres* **102(D22)**:26053–26076 DOI 10.1029/96JD02999.

Enfield DB, Mestas-Nuñez AM, Trimble PJ. 2001. The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental US. *Geophysical Research Letters* **28(10)**:2077–2080 DOI 10.1029/2000GL012745.

Ewing HA, Weathers KC, Cottingham KL, Leavitt PR, Greer ML, Carey CC, Steele BG, Fiorillo AU, Sowles JP. 2020. ''New'' cyanobacterial blooms are not new: two centuries of lake production are related to ice cover and land use. *Ecosphere* **11(6)**:e03170.

Feng S, Hu Q, Oglesby RJ. 2011. Influence of Atlantic sea surface temperatures on persistent drought in North America. *Climate Dynamics* **37(3–4)**:569–586 DOI 10.1007/s00382-010-0835-x.

Fischer P, Tung KK. 2008. A reexamination of the QBO period modulation by the solar cycle. *Journal of Geophysical Research: Atmospheres* **113(D7)**:D07114.

Fu C, Yao H. 2015. Trends of ice breakup date in south-central Ontario. *Journal of Geophysical Research: Atmospheres* **120(18)**:9220–9236 DOI 10.1002/2015JD023370.

Futter MN. 2003. Patterns and trends in Southern Ontario lake ice phenology. *Environmental Monitoring and Assessment* **88(1)**:431–444 DOI 10.1023/A:1025549913965.

Ghanbari RN, Bravo HR, Magnuson JJ, Hyzer WG, Benson BJ. 2009. Coherence between lake ice cover, local climate and teleconnections (Lake Mendota, Wisconsin). *Journal of Hydrology* **374(3–4)**:282–293 DOI 10.1016/j.jhydrol.2009.06.024.

Gray LJ, Anstey JA, Kawatani Y, Lu H, Osprey S, Schenzinger V. 2018. Surface impacts of the quasi biennial oscillation. *Atmospheric Chemistry and Physics* **18(11)**:8227–8247 DOI 10.5194/acp-18-8227-2018.

Grinsted A, Moore JC, Jevrejeva S. 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics* **11(5/6)**:561–566 DOI 10.5194/npg-11-561-2004.

Hamilton K. 2002. On the quasi-decadal modulation of the stratospheric QBO period. *Journal of Climate* **15(17)**:2562–2565 DOI 10.1175/1520-0442(2002)015<2562:OTQDMO>2.0.CO;2.

Hare SR, Mantua NJ. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* **47(2–4)**:103–145 DOI 10.1016/S0079-6611(00)00033-1.

Hathaway DH. 2015. The solar cycle. *Living Reviews in Solar Physics* **12(1)**:4 DOI 10.1007/lrsp-2015-4.

Hewitt BA, Lopez LS, Gaibisels KM, Murdoch A, Higgins SN, Magnuson JJ, Paterson AM, Rusak JA, Yao H, Sharma S. 2018. Historical trends, drivers, and future projections of ice phenology in small north temperate lakes in the Laurentian Great Lakes Region. *Water* **10(1)**:70 DOI 10.3390/w10010070.

Hodgkins GA. 2013. The importance of record length in estimating the magnitude of climatic changes: an example using 175 years of lake ice-out dates in New England. *Climatic Change* **119(3)**:705–718 DOI 10.1007/s10584-013-0766-8.

Hodgkins GA, James IC, Huntington TG. 2002. Historical changes in lake ice-out dates as indicators of climate change in New England, 1850–2000. *International Journal of Climatology: A Journal of the Royal Meteorological Society* **22(15)**:1819–1827 DOI 10.1002/joc.857.

Holton JR, Tan H-C. 1980. The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. *Journal of Atmospheric Sciences* **37(10)**:2200–2208 DOI 10.1175/1520-0469(1980)037<2200:TIOTEQ>2.0.CO;2.

Hu Q, Feng S. 2012. AMO-and ENSO-driven summertime circulation and precipitation variations in North America. *Journal of Climate* **25(19)**:6477–6495 DOI 10.1175/JCLI-D-11-00520.1.

Hurrell JW. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* **269(5224)**:676–679 DOI 10.1126/science.269.5224.676.

Hurrell JW, Kushnir Y, Ottersen G, Visbeck M. 2003. An overview of the North Atlantic oscillation. *Geophysical Monograph-American Geophysical Union* **134**:1–36.

Hurrell JW, Kushnir Y, Visbeck M. 2001. The North Atlantic Oscillation. *Science* **291(5504)**:603–605 DOI 10.1126/science.1058761.

Hurrell J, National Center for Atmospheric Research Staff (NCAR) (ed.) 2020. The climate data guide: hurrell North Atlantic Oscillation (NAO) index (station-based). *Available at* https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based.

Husson D, Thibault N, Galbrun B, Gardin S, Minoletti F, Sageman B, Huret E. 2014. Lower Maastrichtian cyclostratigraphy of the Bidart section (Basque Country, SW France): a remarkable record of precessional forcing. *Palaeogeography, Palaeoclimatology, Palaeoecology* **395**:176–197 DOI 10.1016/j.palaeo.2013.12.008.
Imrit MA, Sharma S. 2021. Climate change is contributing to faster rates of lake ice loss in lakes around the Northern Hemisphere. *Journal of Geophysical Research: Biogeosciences* **126**(7):e2020JG006134.

Jacques-Coper M, Garreaud RD. 2015. Characterization of the 1970s climate shift in South America. *International Journal of Climatology* **35**(8):2164–2179 DOI 10.1002/joc.4120.

Jensen OP, Benson BJ, Magnuson JJ, Card VM, Futter MN, Soranno PA, Stewart KM. 2007. Spatial analysis of ice phenology trends across the Laurentian Great Lakes region during a recent warming period. *Limnology and Oceanography* **52**(5):2013–2026 DOI 10.4319/lo.2007.52.5.2013.

Kestin TS, Karoly DJ, Yano J-I, Rayner NA. 1998. Time–frequency variability of ENSO and stochastic simulations. *Journal of Climate* **11**(9):2258–2272 DOI 10.1175/1520-0442(1998)011<2258:TFVOEA>2.0.CO;2.

Knight JR, Folland CK, Scaife AA. 2006. Climate impacts of the Atlantic multidecadal oscillation. *Geophysical Research Letters* **33**(17):L17706.

Knudsen MF, Seidenkrantz M-S, Jacobsen BH, Kuijpers A. 2011. Tracking the Atlantic Multidecadal Oscillation through the last 8,000 years. *Nature Communications* **2**(1):1–8.

Kopp G. 2014. An assessment of the solar irradiance record for climate studies. *Journal of Space Weather and Space Climate* **4**:A14 DOI 10.1051/swsc/2014012.

Lassen K, Friis-Christensen E. 1995. Variability of the solar cycle length during the past five centuries and the apparent association with terrestrial climate. *Journal of Atmospheric and Terrestrial Physics* **57**(8):835–845 DOI 10.1016/0021-9169(94)00088-6.

Latif M, Barnett TP. 1994. Causes of decadal climate variability over the North Pacific and North America. *Science* **266**(5185):634–637 DOI 10.1126/science.266.5185.634.

Latifovic R, Pouliot D. 2007. Analysis of climate change impacts on lake ice phenology in Canada using the historical satellite data record. *Remote Sensing of Environment* **106**(4):492–507 DOI 10.1016/j.rse.2006.09.015.

Lau K-M, Sheu PJ. 1988. Annual cycle, Quasi-Biennial Oscillation, and Southern Oscillation in global precipitation. *Journal of Geophysical Research: Atmospheres* **93**(D9):10975–10988 DOI 10.1029/JD093iD09p10975.

Laurenz L, Lüdecke H-J, Lüning S. 2019. Influence of solar activity changes on European rainfall. *Journal of Atmospheric and Solar-Terrestrial Physics* **185**:29–42 DOI 10.1016/j.jastp.2019.01.012.

Le Goff H, Flannigan MD, Bergeron Y, Girardin MP. 2007. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. *International Journal of Wildland Fire* **16**(5):607–618 DOI 10.1071/WF06151.

Li Z, Manson AH, Li Y, Meek C. 2017. Circulation characteristics of persistent cold spells in central–eastern North America. *Journal of Meteorological Research* **31**(1):250–260 DOI 10.1007/s13351-017-6146-y.

Lindzen RS, Holton JR. 1968. A theory of the quasi-biennial oscillation. *Journal of the Atmospheric Sciences* **25**(**6**):1095–1107 DOI 10.1175/1520-0469(1968)025<1095:ATOTQB>2.0.CO;2.

Litzow MA. 2006. Climate regime shifts and community reorganization in the Gulf of Alaska: how do recent shifts compare with 1976/1977? *ICES Journal of Marine Science* **63**(**8**):1386–1396 DOI 10.1016/j.icesjms.2006.06.003.

Livingstone DM. 2000. Large-scale climatic forcing detected in historical observations of lake ice break-up. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen* **27**(**5**):2775–2783.

Livingstone DM, Adrian R, Blenckner T, George G, Weyhenmeyer GA. 2010. Lake ice phenology. In: *The impact of climate change on European lakes.* Dordrecht, Netherlands: Springer, 51–61.

Lockwood M. 2012. Solar influence on global and regional climates. *Surveys in Geophysics* **33**(**3–4**):503–534 DOI 10.1007/s10712-012-9181-3.

Magnuson JJ, Benson BJ, Kratz TK. 2004. Patterns of coherent dynamics within and between lake districts at local to intercontinental scales. *Boreal Environment Research* **9**(**5**):359–369.

Mantua NJ, Hare SR. 2002. The Pacific decadal oscillation. *Journal of Oceanography* **58**(**1**):35–44 DOI 10.1023/A:1015820616384.

McCabe GJ, Palecki MA, Betancourt JL. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *Proceedings of the National Academy of Sciences of the United States of America* **101**(**12**):4136–4141 DOI 10.1073/pnas.0306738101.

Minobe S. 1997. A 50–70 year climatic oscillation over the North Pacific and North America. *Geophysical Research Letters* **24**(**6**):683–686 DOI 10.1029/97GL00504.

Minobe S. 1999. Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: Role in climatic regime shifts. *Geophysical Research Letters* **26**(**7**):855–858 DOI 10.1029/1999GL900119.

Mishra V, Cherkauer KA, Bowling LC, Huber M. 2011. Lake ice phenology of small lakes: impacts of climate variability in the Great Lakes region. *Global and Planetary Change* **76**(**3–4**):166–185 DOI 10.1016/j.gloplacha.2011.01.004.

Moy CM, Seltzer GO, Rodbell DT, Anderson DM. 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* **420**(**6912**):162–165 DOI 10.1038/nature01194.

Mudelsee M. 2012. A proxy record of winter temperatures since 1836 from ice freeze-up/breakup in lake Näsijärvi, Finland. *Climate Dynamics* **38**(**7–8**):1413–1420 DOI 10.1007/s00382-011-1046-9.

Nalley D, Adamowski J, Biswas A, Gharabaghi B, Hu W. 2019. A multiscale and multivariate analysis of precipitation and streamflow variability in relation to ENSO, NAO and PDO. *Journal of Hydrology* **574**:288–307 DOI 10.1016/j.jhydrol.2019.04.024.

National Center for Atmospheric Research Staff (NCAR). 2013. The climate data guide: QBO: Quasi-Biennial Oscillation). *Available at* https://climatedataguide.ucar.edu/climate-data/qbo-quasi-biennial-oscillation.

National Center for Atmospheric Research Staff (NCAR). 2020. The climate data guide: hurrell wintertime SLP-based Northern Annular Mode (NAM) index. *Available at* https://climatedataguide.ucar.edu/climate-data/hurrell-wintertime-slp-based-northern-annular-mode-nam-index.

Ng EKW, Chan JCL. 2012. Geophysical applications of partial wavelet coherence and multiple wavelet coherence. *Journal of Atmospheric and Oceanic Technology* **29(12)**:1845–1853 DOI 10.1175/JTECH-D-12-00056.1.

Ogunjo ST, Fuwape IA. 2020. Nonlinear characterization and interaction in teleconnection patterns. *Advances in Space Research* **65(12)**:2723–2732 DOI 10.1016/j.asr.2020.03.023.

Ogurtsov MG, Raspopov OM, Helama S, Oinonen M, Lindholm M, Jungner H, Meriläinen J. 2008. Climatic variability along a north–south transect of Finland over the last 500 years: signature of solar influence or internal climate oscillations? *Geografiska Annaler: Series A, Physical Geography* **90(2)**:141–150 DOI 10.1111/j.1468-0459.2008.00160.x.

Olsen J, Anderson NJ, Knudsen MF. 2012. Variability of the North Atlantic Oscillation over the past 5,200 years. *Nature Geoscience* **5(11)**:808–812 DOI 10.1038/ngeo1589.

Overland JE, Wang M. 2019. Impact of the winter polar vortex on greater North America. *International Journal of Climatology* **39(15)**:5815–5821 DOI 10.1002/joc.6174.

Patterson RT, Swindles GT. 2015. Influence of ocean–atmospheric oscillations on lake ice phenology in eastern North America. *Climate Dynamics* **45(9–10)**:2293–2308 DOI 10.1007/s00382-014-2415-y.

Philander SG. 1989. El Niño, La Niña, and the southern oscillation. *International Geophysics Series* **46**:X-289.

Philander SGH. 1983. El Nino southern oscillation phenomena. *Nature* **302(5906)**:295–301 DOI 10.1038/302295a0.

Pozo-Vázquez D, Esteban-Parra MJ, Rodrigo FS, Castro-Díez Y. 2001. A study of NAO variability and its possible non-linear influences on European surface temperature. *Climate Dynamics* **17(9)**:701–715 DOI 10.1007/s003820000137.

Quiroz RS. 1981. Period modulation of the stratospheric Quasi-Biennial Oscillation. *Monthly Weather Review* **109(3)**:665–674 DOI 10.1175/1520-0493(1981)109<0665:PMOTSQ>2.0.CO;2.

Rasmusson EM, Carpenter TH. 1982. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Monthly Weather Review* **110(5)**:354–384 DOI 10.1175/1520-0493(1982)110<0354:VITSST>2.0.CO;2.

Rind D, Lean J, Lerner J, Lonergan P, Leboissitier A. 2008. Exploring the stratospheric/tropospheric response to solar forcing. *Journal of Geophysical Research: Atmospheres* **113(D24)**:D24103.

Rogers J, McHugh M. 2002. On the separability of the North Atlantic oscillation and Arctic oscillation. *Climate Dynamics* **19(7)**:599–608 DOI 10.1007/s00382-002-0247-7.

Ropelewski CF, Halpert MS. 1986. North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO). *Monthly Weather Review* **114(12)**:2352–2362 DOI 10.1175/1520-0493(1986)114<2352:NAPATP>2.0.CO;2.

Ruiz-Barradas A, Nigam S, Kavvada A. 2013. The Atlantic Multidecadal Oscillation in twentieth century climate simulations: uneven progress from CMIP3 to CMIP5. *Climate Dynamics* **41(11–12)**:3301–3315 DOI 10.1007/s00382-013-1810-0.

Scheffer M, Carpenter S, Foley JA, Folke C, Walker B. 2001. Catastrophic shifts in ecosystems. *Nature* **413(6856)**:591–596 DOI 10.1038/35098000.

Schlesinger ME, Ramankutty N. 1994. An oscillation in the global climate system of period 65–70 years. *Nature* **367(6465)**:723–726 DOI 10.1038/367723a0.

Schulz M, Mudelsee M. 2002. REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimatic time series. *Computers & Geosciences* **28(3)**:421–426 DOI 10.1016/S0098-3004(01)00044-9.

Seager R, Kushnir Y, Nakamura J, Ting M, Naik N. 2010. Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. *Geophysical Research Letters* **37(14)**:102036.

Setoh T, Imawaki S, Ostrovskii A, Umatani S-I. 1999. Interdecadal variations of ENSO signals and annual cycles revealed by wavelet analysis. *Journal of Oceanography* **55(3)**:385–394 DOI 10.1023/A:1007854415983.

Shabbar A. 2006. The impact of El Niño-Southern Oscillation on the Canadian climate. *Advances in Geosciences* **6**:149–153 DOI 10.5194/adgeo-6-149-2006.

Shabbar A, Bonsal B, Khandekar M. 1997. Canadian precipitation patterns associated with the Southern Oscillation. *Journal of Climate* **10(12)**:3016–3027 DOI 10.1175/1520-0442(1997)010<3016:CPPAWT>2.0.CO;2.

Sharma S, Magnuson JJ. 2014. Oscillatory dynamics do not mask linear trends in the timing of ice breakup for Northern Hemisphere lakes from 1855 to 2004. *Climatic Change* **124(4)**:835–847 DOI 10.1007/s10584-014-1125-0.

Sharma S, Magnuson JJ, Mendoza G, Carpenter SR. 2013. Influences of local weather, large-scale climatic drivers, and the ca. 11 year solar cycle on lake ice breakup dates; 1905–2004. *Climatic Change* **118(3)**:857–870 DOI 10.1007/s10584-012-0670-7.

Sivarajah B, Simmatis B, Favot EJ, Palmer MJ, Smol JP. 2021. Eutrophication and climatic changes lead to unprecedented cyanobacterial blooms in a Canadian sub-Arctic landscape. *Harmful Algae* **105**:102036 DOI 10.1016/j.hal.2021.102036.

Sunspot Index and Long Term Solar Observations (SILSO). 2021. *Total sunspot number*. Brussels: Royal Observatory of Belgium *Available at* http://www.sidc.be/silso.

Tan Z, Yao H, Zhuang Q. 2018. A small temperate lake in the 21st century: dynamics of water temperature, ice phenology, dissolved oxygen, and chlorophyll a. *Water Resources Research* **54(7)**:4681–4699 DOI 10.1029/2017WR022334.

Thompson DWJ, Lorenz DJ. 2004. The signature of the annular modes in the tropical troposphere. *Journal of Climate* **17(22)**:4330–4342 DOI 10.1175/3193.1.

Thompson DWJ, Wallace JM. 1998. The Arctic Oscillation signature in the winter-time geopotential height and temperature fields. *Geophysical Research Letters* **25(9)**:1297–1300 DOI 10.1029/98GL00950.

Thomson DJ. 1982. Spectrum estimation and harmonic analysis. *Proceedings of the IEEE* **70(9)**:1055–1096 DOI 10.1109/PROC.1982.12433.

Toniazzo T, Scaife AA. 2006. The influence of ENSO on winter North Atlantic climate. *Geophysical Research Letters* **33(24)**.

Torrence C, Compo GP. 1998. A practical guide to wavelet analysis. *Bulletin of the American Meteorological society* **79(1)**:61–78 DOI 10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2.

Trenberth KE. 1990. Recent observed interdecadal climate changes in the Northern Hemisphere. *Bulletin of the American Meteorological Society* **71(7)**:988–993 DOI 10.1175/1520-0477(1990)071<0988:ROICCI>2.0.CO;2.

Trenberth K, National Center for Atmospheric Research Staff (NCAR) (ed.) 2020. The climate data guide: nino SST indices (Nino 1 + 2, 3, 3.4, 4; ONI and TNI). *Available at* https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni.

Trenberth K, Zhang R, National Center for Atmospheric Research Staff (NCAR) (eds.) 2021. The Climate Data Guide: Atlantic Multi-decadal Oscillation (AMO). *Available at* https://climatedataguide.ucar.edu/climate-data/atlantic-multi-decadal-oscillation-amo.

Van Loon H, Shea DJ. 1999. A probable signal of the 11-year solar cycle in the troposphere of the Northern Hemisphere. *Geophysical Research Letters* **26(18)**:2893–2896 DOI 10.1029/1999GL900596.

Vines RG. 1984. Rainfall patterns in the eastern United States. *Climatic Change* **6(1)**:79–98 DOI 10.1007/BF00141669.

Walsh CR, Patterson RT. 2022. Precipitation and temperature trends and cycles derived from historical 1890–2019 weather data for the city of Ottawa, Ontario, Canada. *Environments* **9(3)**:35 DOI 10.3390/environments9030035.

Walsh CR, Patterson RT. 2022. Attribution of observed periodicity in extreme weather events in eastern North America. *Earth and Space Science* **9**:e2022EA002359 DOI 10.1029/2022EA002359.

Walsh SE, Vavrus SJ, Foley JA, Fisher VA, Wynne RH, Lenters JD. 1998. Global patterns of lake ice phenology and climate: model simulations and observations. *Journal of Geophysical Research: Atmospheres* **103(D22)**:28825–28837 DOI 10.1029/98JD02275.

Walter K, Graf H-F. 2005. The North Atlantic variability structure, storm tracks, and precipitation depending on the polar vortex strength. *Atmospheric Chemistry and Physics* **5(1)**:239–248 DOI 10.5194/acp-5-239-2005.

Wang J, Bai X, Hu H, Clites A, Colton M, Lofgren B. 2012. Temporal and spatial variability of Great Lakes ice cover, 1973–2010. *Journal of Climate* **25**(4):1318–1329 DOI 10.1175/2011JCLI4066.1.

Wang J, Bai X, Leshkevich G, Colton M, Clites A, Lofgren B. 2010. Severe ice cover on Great Lakes during winter 2008–2009. *Eos, Transactions American Geophysical Union* **91**(5):41–42 DOI 10.1029/2010EO050001.

Wang J, Kessler J, Bai X, Clites A, Lofgren B, Assuncao A, Bratton J, Chu P, Leshkevich G. 2018. Decadal variability of Great Lakes ice cover in response to AMO and PDO, 1963–2017. *Journal of Climate* **31**(18):7249–7268 DOI 10.1175/JCLI-D-17-0283.1.

Wang X, Li Z, Ma K. 2014. Decreased sensitivity of tree growth to temperature in Southeast China after the 1976/77 regime shift in Pacific climate. *Sains Malaysiana* **43**(1):9–19.

Wu S, Liu Z, Zhang R, Delworth TL. 2011. On the observed relationship between the Pacific Decadal Oscillation and the Atlantic Multi-decadal Oscillation. *Journal of Oceanography* **67**(1):27–35 DOI 10.1007/s10872-011-0003-x.

Yang R, Cao J, Huang W, Nian A. 2010. Cross wavelet analysis of the relationship between total solar irradiance and sunspot number. *Chinese Science Bulletin* **55**(20):2126–2130 DOI 10.1007/s11434-010-3269-2.

Zanchettin D, Franks SW, Traverso P, Tomasino M. 2008. On ENSO impacts on European wintertime rainfalls and their modulation by the NAO and the Pacific multi-decadal variability described through the PDO index. *International Journal of Climatology: A Journal of the Royal Meteorological Society* **28**(8):995–1006 DOI 10.1002/joc.1601.

Zhang W, Mei X, Geng X, Turner AG, Jin F-F. 2019. A nonstationary ENSO–NAO relationship due to AMO modulation. *Journal of Climate* **32**(1):33–43 DOI 10.1175/JCLI-D-18-0365.1.

Zhang G, Zeng G, Li C, Yang X. 2020. Impact of PDO and AMO on interdecadal variability in extreme high temperatures in North China over the most recent 40-year period. *Climate Dynamics* **54**(5):3003–3020 DOI 10.1007/s00382-020-05155-z.

Zhao H, Higuchi K, Waller J, Auld H, Mote T. 2013. The impacts of the PNA and NAO on annual maximum snowpack over southern Canada during 1979–2009. *International Journal of Climatology* **33**(2):388–395 DOI 10.1002/joc.3431.