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Influence of ocean-atmospheric oscillations on lake ice phenology in eastern North America

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Abstract Our results reveal long-term trends in ice out dates (1836-2013) for twelve lakes in Maine, New Brunswick and New Hampshire, in eastern North America. The trends are remarkably coherent between lakes (r_s = 0.462-0.933, p<0.01) and correlate closely with the March-April (MA) instrumental temperature records from the region (r_s = 0.488-0.816, p<0.01). This correlation permits use of ice out dates as a proxy to extend the shorter MA instrumental record (1876-2013). Mean ice out dates trended progressively earlier during the recovery from the Little Ice Age through to the 1940s, and gradually became later again through to the late 1970s, when ice out dates had returned to values more typical of the late 19th century. Post-1970's ice out dates resumed trending toward earlier dates, with the 21st century being characterized by the earliest ice out dates on record. Spectral and wavelet time series analysis indicate that ice out is influenced by several teleconnections including the Quasi-biennial Oscillation, El Niño-Southern Oscillation, North Atlantic Oscillation, as well as a significant correlation between inland lake records and the Atlantic Multidecadal Oscillation. The relative influence of these teleconnections is variable with notable shifts occurring after ~1870, ~1925, and ~1980-2000. The intermittent expression of these cycles in the ice out and MA instrumental record is not only influenced by absolute changes in the intensity of the various teleconnections and other climate drivers, but through phase interference between teleconnections, which periodically damps the various signals.

Key Words

Lake Ice Out Phenology; AMO NAO ENSO QBO Teleconnections; Climate Change; March April Temperature; Time series analysis; Eastern North America

1 Introduction

Distinguishing the relative contributions of natural climate variability from anthropogenic causes is an important focus of climate change research (Stocker et al. 2013). However the short available instrumental record presents a major difficulty to investigators (Anderson et al. 2013; Lewis and Curry 2014). Phenological information, the study of changes in the date of recurring natural phenomena, can be used as a proxy to significantly extend available instrumental data (Futter 2003). Lake ice phenology series, from mid-high latitude regions, are comprised of the calendar dates when ice forms in the fall and melts in the spring. The annual dates in the spring when winter ice cover leaves a lake has come to be known as “ice out” (Hodgkins 2013). Ice out is sometimes referred to as “ice off” (e.g. Ghanbari et al. 2009) and “ice break up” (e.g. Sharma and Magnuson 2014). Ice out records are more valuable than ice formation records as the breakup and disappearance of ice from a lake in the spring can occur very quickly (<24 hrs), whereas fall freeze-up may take many days, and may be punctuated by several freeze-thaw cycles before ice finally settles in for the winter (Robertson et al. 1992). Ice out dates for lakes correlate most strongly with local, late winter air temperatures and thus provide an important quantitative and annually-resolved source of hydrologic data for late-winter/early-spring climate change (Futter 2003; Hodgkins 2010; Hodgkins et al. 2002; Livingstone and Adrian 2009; Shuter et al. 2013). These data have been compiled primarily by amateur citizen scientists for a variety of purposes, including determining fishing seasons, estimating the spring opening of ferry boat routes, community contests, and general curiosity (Futter 2003; Hodgkins et al. 2002;). Many ice out records extend well back into the 19th century, and are spread throughout the northern hemisphere (e.g. Magnuson et al. 2005). As such these records provide an important proxy for late-winter/early-spring climate in eastern North America, which extends beyond data available from instrumental climate stations. Temporal change in ice out dates is thus a useful proxy in temperature reconstruction as earlier (later) ice up breakup is indicative of warmer (cooler) spring temperatures (Assel and Robertson 1995). In some areas records of sufficient length are common enough that both temporal trends and spatial patterns have been analyzed (e.g. Benson et al. 2012; Duguay et al. 2006; Magnuson et al. 2000), particularly in Finland (Korhonen 2006; Kuusisto 1987; Kuusisto and Elo 2000), Sweden (Weyhenmeyer et al. 2004), New England (Hodgkins et al. 2002), Southern Ontario (Futter 2003) and the Great Lakes region of North America (Magnuson et al. 2005). Coherency analysis and Moran Eigenvector Maps (MEM) are two examples of analytical approaches used previously to quantify the influence of climate cycles and trends on ice out throughout the northern Hemisphere, including New England (e.g. Magnuson et al., 2004; Magnuson et al., 2005; Ghanbari et al. 2009; Sharma et al. 2013; Sharma and Magnuson, 2014). In ice out compilations from New England in eastern North America, the oldest known record in the region extends back to AD1807 at Sebago Lake, Maine (Hodgkins 2010) with many other documented records spanning at least the past 150 years. Of three previously unpublished ice out records from adjacent New Brunswick the oldest available is a 138-year record from Oromocto Lake that extends to 1876. Previous research on ice out records from New England has recognized that there has been a significant shortening of the ice cover season from the late 19th century to the early

21st century at a rate of, to 0.6 days/decade through the last 125 years (Hodgkins 2013; Hodgkins et al. 2002; Huntington et al. 2003). A similar trend has been observed elsewhere in the northern hemisphere (e.g. Benson et al. 2012, Futter 2003; Ghanbari et al. 2009; Magnuson et al. 2000; Prowse et al. 2011).

The aquatic ecosystem services contributed by the 1000s of lakes in eastern North America play an integral role in the lives of the people who live there. These lakes support the economic wellbeing of entire communities and provide an important recreational resource, clean drinking water, water storage to offset the impact of droughts and a means to preserve wildlife biodiversity and habitat, in addition to their natural aesthetic beauty (Environment and Local Government, New Brunswick 2014; Maine Dept of Environmental Protection 2013). Changes in ice out dates have a significant influence on the hydroecology of lakes. For example, earlier ice out dates result in warmer spring water temperatures as well as increased light availability and changes to circulation patterns (Hodgkins 2013). Resultant changes in spring and summer patterns and mechanisms of phytoplankton and zooplankton dynamics significantly alter the trophic structure of lake ecosystems (Arhonditis et al. 2004; Blenckner et al. 2002). Understanding the dynamics of ongoing changes in ice out dates thus has important implications for determining the impact of climate change on hydrology, terrestrial and aquatic ecosystems, and the economy of this region.

The Maine-New Brunswick-New Hampshire ice out data set analyzed in this study provides a unique opportunity to assess the relationship between the various late winter climatic influences in the region from AD 1836-2013, comparing between lakes and against instrumental data. In many cases the available ice out data reaches many decades further into the past than the available instrumental record. In particular we will: 1) demonstrate the temporal coherence of spatial patterns in ice out data in 12 lakes from New Hampshire, Maine and New Brunswick (Fig. 1); 2) document changes in ice out for the region during the late 19th century recovery from the Little Ice Age, and impact of possible anthropogenic influence on ice out during the late 20th – early 21st century; and 3) use spectral and wavelet time series analysis techniques to recognize trends and cycles in the climate drivers that impact the region.

2 Methods

2.1 Lake Ice out and climate station data

Lake ice out records from NH (three lakes), ME (seven lakes), and NB (three lakes), with near continuous, long-term ice out records ranging from as far back as 1836 were selected for analysis (Sup. Table 1). Although Sebago Lake, ME has ice out records dating back to 1807 (Hodgkins 2010) it was not used in this study, as significant gaps in that record unfortunately precluded time series analysis, a prerequisite of lakes chosen for this study. Lake Utopia (1937-2013) and Skiff Lake (1933-2013) in NB had shorter records than the other lakes but were included to extend coverage further eastward. The 2008 and earlier NH and ME ice out dates were obtained from the compilation of Hodgkins (2010) with later ME ice out dates obtained from an online data repository maintained by the Maine Department of Agriculture, Conservation and Forestry (Appendix 1). Post-2008 records for NH and all NB records were obtained from websites hosted by local lake associations (Appendix 1). With the exception of Lake

Auburn all lakes are located in remote or rural settings.

Changes in lake morphology (e.g. depth and surface area) generally do not impact the temporal coherence of ice out dates (Wynne et al. 1996) and in any case most lakes in the study area have undergone little morphological change. Ice out criteria differ between the lakes (Appendix 1) but have for the most part been consistently applied as observers changed over time, resulting in negligible impact on reported ice out dates (Hodgkins et al. 2002; Sup Fig. 1). Following past practice, Julian calendar ice out dates (including inclusion of leap years) were used in all analyses (Sup. Table 1). Using a calendar date rather than using timing relative to vernal equinox introduced a small bias (e.g. a maximum of 0.8 days for ice out dates spanning AD 1900-2000) (Sagarin 2001).

Late winter March-April (MA) air temperature data was obtained from five climate stations that spanned the region (Appendix 2); four NOAA National Climatic Data Center (NCDC) United States Historical Climatology Network (USHCN) sites in the US [Houlton, ME (1902-2013), Orono, ME, (1894-2013), Lewiston, ME (1893-2013), Hanover NH (1894-2013), and one particularly long Environment Canada Surface Air Temperature Data site from Fredericton, NB (1874-2013). Stations were selected based on record continuity and to provide a broad coverage of MA temperatures across the region. All temperature data was subject to quality control, homogeneity testing and adjustments applied for changes in observation time, instrumentation, station location and urban heat island effects (Hodgkins et al. 2002; Vincent et al. 2012). March-April temperature data was used in this study as it has previously been demonstrated that there is a strong correlation between late-winter/early-spring air temperatures and ice out dates (Futter 2003; Hodgkins 2010; Hodgkins, et al. 2002; Livingstone and Adrian 2009; Shuter et al. 2013).

Correlations between ice out dates and instrumental data were carried out using Spearman's rank correlation, following the results from Shapiro-Wilk normality tests. To generate regional compilations, ice out and instrumental data were compiled and average annual values were calculated. Lowess smoothing functions (Cleveland, 1979, 1981) were applied to generate 1-dimensional data summaries. 95% confidence bands were estimated using bootstrapping (999 random replicates). In order to retain the structure of the interpolation, the procedure used resampling of residuals rather than resampling of original data points.

2.2 Spectral analysis

We used spectral analysis to examine the time series in the frequency domain. We used the Fortran 90 program REDFIT, which is based on Lomb-Scargle Fourier Transform. A runs test showed that a red noise model was appropriate for the ice out and instrumental data (i.e. within 5% acceptance interval). A rectangular window was used and the statistical significance of spectral peaks was tested using a parametric approach (90%, 95%, and 99% χ^2 false-alarm levels) against a realistic null hypothesis of red (auto-correlated) noise (Schulz and Stattegger 1997; Schulz and Mudelsee 2002; Schwarzacher 1993). We also used the multitaper method (MTM; Thomson, 1982), which is commonly used for annually-resolved data (e.g. Lees and Park, 1995); however, missing years, or blocks of years, meant that interpolation to annual interval was needed in places, which potentially introduced bias by enhancing the low-frequency components at the expense of high-frequency components (Schulz and Mudelsee 2002). Therefore, we decided to rely on the results of the REDFIT spectral analysis. Nevertheless, there was very good correspondence between the results of the two methods.

2.3 Wavelet analysis

Continuous wavelet transforms (CWT) were used to determine the temporal nature of continuous and discontinuous periodicities (Torrence and Compo 1998). Interpolation was carried out over any missing years and the Morlet mother wavelet was used. Cross-wavelet (XWT) and Wavelet Coherence (WTC) analyses were used to examine common features in wavelet power of two time series (Maraun and Kurths 2004). XWT illustrates regions when there is a high common power between two time series and also shows the phase relationship. WTC illustrates the local correlation between two continuous wavelet transforms (CWT) and can reveal locally phase-locked behavior (Grinsted et al. 2004). Before analysis the data were transformed into a series of percentiles, which is a simple, effective transformation for time series data, with the advantage that it does not have any outliers (Grinsted et al. 2004). A significance level of 95% against a red noise (lag-1 autoregressive) background was determined using Monte-Carlo methods (Grinsted et al., 2004). CWT, XWT and WTC analyses were carried out using PAST (Hammer et al. 2001) and the ‘Cross Wavelet’ package in Matlab v.7.12.0.635 (Grinsted et al. 2004; Maraun and Kurths 2004; Torrence and Compo 1998).

3 Results

3.1 Ice out date correlation to instrumental record

The data from this study is characterized by a strong relationship ($r^2 = 0.763$) between lake ice out dates and distance from the coast (Fig. 1). Lakes at cooler, higher elevations also tend to have later ice out dates. There is a slightly weaker, but still strong relationship between elevation and ice out dates in the data ($r^2 = 0.535$). Correlation analysis of this same data yielded similar results with there being a significant positive correlation between distance from coast and ice out dates (r_s=0.865, p<0.01), and a slightly weaker but still highly-significant positive correlation between ice out dates and elevation of lakes (r_s=0.715, p<0.01). Ice out dates across the region has changed considerably through the available 177-year ice out record (Fig. 2; Sup. Table 1). All lakes in this dataset have trended toward earlier ice out dates, although there have been decadal-scale reversals in the tendency to later ice out dates. There has also been a similar variation in MA air temperatures through the available instrumental record (Sup. Fig, 2; Sup. Table 2) with a trend toward warmer temperatures through the entire record, tempered by periodic reversals in the record that are coherent across the region. After accounting for the considerable variation in absolute ice out dates between lakes, primarily related to climate variation associated with distance from the coast and elevation, there is a strong coherence in the pattern of ice out across all lakes (Figs. 1-3; r_s = 0.462-0.933, p<0.01).

Lake ice out data and mean MA air temperature data from selected climate stations across the region (Sup. Table 2) were analyzed using Spearman's rank correlation (Sup. Table 3). The correlation between all lakes was significant (r_s = 0.462-0.933, p<0.01), and despite there being a significant climate gradient between the five climate stations used in the study there was significant correlation (r_s = 0.704-0.926, p<0.01) between all climate stations. The correlation analysis indicated that there was also a strong correlation between MA air temperatures at all climate stations and spring ice out dates that was significant (r_s = 0.488-0.816, p<0.01; Sup. Table 3). The strong correlation between the lake ice out dates and climate stations indicates that ice out data can be used as a proxy for MA temperature for 19th century ice out records predating the thermometer record.

Locally weighted scatterplot smoothing (LOWESS) of both ice out data and thermometer data provide further confirmation of the close correlation between the two records (Fig. 2). The LOWESS plot in Fig. 2a, showing the trends for the entire data set post-1876, after which time complete records for all of the lakes become available. Coastal lakes dominated the pre-1876 record and inclusion of earlier ice out dates of these lakes [Auburn (from 1836); Damariscotta (from 1837); Cobbosseecontee (from 1840)] would have skewed the results in favor of the typically milder conditions at the coast. To determine the relative change in ice out dates for pre-1876, a separate LOWESS plot for the record from Auburn, Damarsiscotta and Cobbosseecontee lakes is included (Fig. 2b). The close correlation between the trends in Figs. 2a and 2b highlight the coherence of the trend data, despite absolute value differences ice out dates between lakes in different climate zones. The LOWESS plot of MA temperatures (Fig. 2c) is restricted to the post-1893 record when complete temperature records for the 5 thermometer stations became available. Inclusion of the 1874-1893 record from Fredericton NB where MA temperatures are generally cooler than stations to the south, would have skewed the trend data to lower temperatures.

The LOWESS ice out plots provide an overall indication of the trend of ice out dates and late winter climate from 1836 to 2013. The interval of the record spanning 1836-1876 derived from the ice out records from Auburn, Damariscotta and Cobbosseecontee lakes was characterized by progressively later ice out dates, indicating cooling MA conditions (Fig. 2b). Across the region the interval from 1876 to 1953 was characterized by progressively earlier mean ice out dates, punctuated by decadal scale reversals of the trend from 1902-1917 and 1936-1944 (Fig. 2a,b,c). The 25-year interval spanning 1953-1978 was characterized by progressively later ice out dates, temporarily returning to general MA conditions that last prevailed in the 1890s, although not as cold as earlier in the 19th century (Fig. 2a,b,c). The latter part of the 20th century was characterized by a return to progressively earlier ice out dates with the early 21st century being characterized by the earliest ice out dates of the entire record (Fig. 2a,b,c).

As discussed above ice out results correlate closely with the mean MA temperature records from the five climate stations used in the study. This similarity is further clearly demonstrated by a CWT comparison between the available MA temperature record at Lewiston and truncated ice out records from adjacent Lake Auburn, and nearby lakes Cobboseecontee and Damarisotta (Fig. 4). Correlation analysis between the Lewiston temperature record and the ice out data from the three lakes indicates that there is generally a strong correlation between the instrumental and ice out records in the three lakes (r_s = 0.783-0.926, p<0.01; Sup. Table 3; Fig. 4c).

3.2 Spectral and wavelet time series analysis

Spectral and CWT analysis identified statistically significant cycles in the ice out data from each lake (>95% false alarm level). Spectral analysis detected strong periodicity at 2.1 and/or 2.3-2.4 years in all lakes, with the exception of Lake Winnipesaukee, NH where the same 2.1 and 2.4 year cycles were still evident but less significant (>90% false alarm level) (Fig. 5; Sup. Table 4). These cycles match well with a 2.1-2.3 year signal recognized in the MA air temperature records from all climate stations from the region (Sup. Table 4; Fig. 6). This cycle is discontinuous, being strong in available ice out records prior to the mid-1850s, nearly disappearing until the early 1870s, becoming quite strong again until the early 1890s, when it disappeared again until ~1910 (Fig. 3). The signal then oscillated at a pentennial-scale through the balance of the record with the exception of a few lakes (e.g. Moosehead, Rangeley, Sebec, Sunapee), which show evidence of some weakening from the late 1940s through 1970s (Fig. 2). A similar pattern is observed in wavelet analysis of the available MA temperature record (Fig. 7). A weakening of the 2.1-2.3 year cycle in the 1890-1910 interval is particularly evident in wavelet analysis of the longer instrumental record available from Fredericton, where the strengthening of the signal again in 1910 is visible. This strengthening is also evident in analysis of the records from Hanover, Lewiston and Orono, which had become established by this time. The available instrumental record from Houlton was too short for recognition of cycles from the earliest years of the 20th century.

Discontinuous cycles (>95% false alarm level) ranging from 2.7-3.0, 3.2-4.2 and 5.5-6.4 years were variably developed in spectral analyses of ice out records from most lakes (Fig. 5; Sup Table 4), although they were entirely absent or statistically weak in the easternmost lakes including Skiff Lake, Lake Utopia and West Grand Lake. Similar cycles in the 2.8-3.0, 3.4-4.2, and 5.3-5.6 year range were variably developed in the spectral analysis of the MA thermometer record, although some signals in these ranges were either absent, or only >90% false alarm level, at some stations (Fig. 6). CWT analysis revealed that cycles in these frequencies oscillated on a decadal scale through much of the record with notable weakening from the 1840s-1860s observed in the long ice out record from Lake Damariscotta, and from ~1890-1910 in many lakes, particularly Oromocto Lake (Fig. 3). Cycles at these frequencies were also particularly strong in many lakes from the mid-1930s through the 1940s, particularly in Rangely, Moosehead, Sebec, Cobbosseecontee, Damariscotta, Auburn, Sunapee, Winnipesaukee and Oromocto lakes (Fig. 3). The latter part of the wavelet analysis record, particularly from the early 1990s onward is also characterized by a relatively strong signal in the 2.8-3.0, 3.4-4.2, and 5.3-5.6 bandwidths. CWT analysis of the MA thermometer records revealed similar decadal-scale intensification and weakening of cycles at these frequencies (Fig. 7). In particularly, the long thermometer record from Fredericton is characterized by a significantly weaker signal at these frequencies from the 1880s through to ~1910, similar to the pattern observed in nearby Oromocto Lake. The strong signal at these return times detected in the ice out record, which began the 1930s, is also strong in the thermometer records from all stations (Fig. 7).

An interesting 16.2-16.7 year cycle (>90% false alarm level) was observed in spectral analyses of several inland lakes (Oromocto, West Grand, Sebec, and Moosehead; Fig. 5). This frequency shows up even more strongly in the wavelet analysis results for these same four lakes (Fig. 3 Sup. Table 4). These cycles may be related to a 34-year signal (>99% false alarm level) observed in the Lake Utopia record, which may represent a signal harmonic. With the exception of a 32-year cycle (>99% false alarm level) observed in the Orono instrumental record, this pattern was otherwise absent from spectral analysis of the MA thermometer records (Fig. 6; Sup. Table 4).

Spectral analysis also identified a 25.3-26.8 year signal in five lakes; >95% false alarm level in Sebec, Skiff, and West Grand lakes, and >90% false alarm level in Auburn and Rangely lakes (Fig. 5; Sup Table 4). No corresponding patterns were observed in spectral analysis of the MA instrumental data.

4 Discussion and Conclusions

4.1 Regional ice out trends

There are some notable variations in absolute ice out dates in the lakes used in this study that relate to the geography of eastern North America. For example, the winter climate of New England and the Maritimes is characterized by typically milder conditions at the coast, where the Atlantic Ocean influence moderates temperatures, and colder more continental conditions further inland (Trewartha and Horn 1980). Analysis of ice out dates in Sweden spanning 55.7°-68.4°N demonstrated that the relationship between the timing of ice out and air temperature was non-linear and could be described by an arc cosine function (Weyhenmeyer et al. 2004). We found no such relationship across the lower latitude, and narrower latitudinal range (43.4°-45.8°N) spanned by the lakes examined in this study. As has been observed elsewhere in the Northern Hemisphere there has also been a general shortening of the ice cover season in eastern North America over the last century as the region recovered from the Little Ice Age (Fagan 2001) with further shortening occurring in the late 20th-early 21st century (Benson, et al. 2012; Hodgkins 2013).

4.2 Teleconnections derived from time series analysis

The network of ice out data presented in this research provides a long duration, regionally coherent and statistically verified proxy of annual to decadal-scale eastern North America late-winter/early-spring climate variability. The climate of this region is influenced by a complex interaction of continental and atmospheric-ocean coupled circulation patterns that through teleconnections (Zielinski and Keim, 2003) have a significant impact on lake ice distribution and seasonal ice duration, all of which have an influence on late winter MA temperatures and ultimately ice out dates. Among the most significant influences are several teleconnections including the Quasi-biennial Oscillation (QBO), El Niño-Southern Oscillation (ENSO), North Atlantic Oscillations/Atlantic Oscillation (NAO/AO), and the Atlantic Multidecadal Oscillation

(AMO). NAO, and to a lesser extent, AMO, have previously been demonstrated to have the most significant overall impact on winter climate in eastern North America (Burakowski et al. 2010; Hubeny et al. 2006). AMO had a particularly significant influence on climate, at least in inland regions, during the early 20th century, as described below. In addition, other superimposed influences on climate variability include periodic heightened volcanic activity (e.g. Gennaretti, et al. 2014), changes in solar insolation (e.g. Gray et al. 2010), and in recent decades anthropogenically-influenced climate change (e.g. IPCC 2013).

4.2.1 Quasi-Biennial Oscillation (QBO)

Spectral analysis of the Julian calendar ice out dates for the 12 lakes used in this study revealed prominent cycles that were coherent across the region and can be traced back as far as 1836. These cycles correlated well with the spectral analysis results derived from the shorter MA thermometer records. The 2.1 and 2.3-2.4 cycles identified in the ice out record and the 2.1-2.3 year cycles identified in the MA temperature records are most likely attributable to the QBO. The QBO annual record is characterized by 2.1-2.2 and 2.3-2.4 cycles, while the QBO Winter (DJFM) signal is characterized by similar 2.1 and 2.3-2.4 year cycles (Fig. 8). The QBO describes a quasi-periodic 2.3-2.4 year oscillation between westerlies and easterlies in the tropical stratosphere. The QBO impacts stratospheric circulation during northern hemisphere winters. In particular, westward phases of the QBO often coincide with abrupt stratospheric warming and cold winters in Northern Europe and eastern North America (Baldwin et al. 2001).

CWT analysis results for the 12 lakes indicate that QBO has had a late winter influence on ice out through the entire 1836-2013 record, and pulses on an approximately pentennial scale, particularly in southern, more coastal lakes (e.g. Auburn, Cobbosseecontee, Damariscotta; Fig. 3). Sharma and Magnuson (2014) analyzed ice out data from 13 lakes spread throughout the northern hemisphere, including Auburn, Cobbosseecontee, Damariscotta, and Moosehead lakes, and also observed that ice out throughout the northern hemisphere seems to be influenced by QBO, explaining up to 17.9% of the variance in their data. Our analysis indicates that although the role of QBO on ice out is important, there seem to be multidecadal intervals in several inland lakes when the QBO signal disappears entirely (e.g. ~1850-1870 in Moosehead Lake; late 1870s-~1905 in Moosehead, Oromocto, Rangeley, Sebec, and West Grand Lake; late 1940s-~1970 in Moosehead, Rangeley, Sebec, West Grand Lake, and in Sunapee and Winnipesaukee, NH). This intermittent oscillatory behavior has been observed in time series datasets elsewhere [e.g. Northeast Pacific (Patterson et al. 2013); southern New England (Hubeny et al. 2006); Greenland (Appenzeller et al. 1998)], where similar patterns been interpreted as the phase interference of competing teleconnections. During intervals when the QBO signal is not expressed in the wavelets, particularly with the observed regular pentennial pattern here, other teleconnections (e.g. NAO, AMO, ENSO) and other climate drivers (e.g. volcanism, solar influences) swamp the QBO signal and it becomes indistinguishable from background noise. This does not preclude the additional influence of stochastic processes on the observed time series.

4.2.2 North Atlantic Oscillation (NAO) and El Niño-Southern Oscillation (ENSO)

The 2.7-3.0, 3.2-4.2, 5.5-6.4, and 7.6-8.0 year cycles identified in the ice out records (Fig. 4), and the 2.8-3.0, 3.4-4.2, 5.3-5.6, and 7.8-9 year cycles recognized in the MA temperature records (Fig. 6) are difficult to correlate against a specific teleconnection as they contain cycles that can be attributed to both ENSO and NAO. The influence of NAO is significantly more prevalent in this region though (Burakowski et al. 2010; Zielinski and Keim 2003; Fig. 8). Comparison of CWT analysis results for the MA thermometer record from Lewiston and ice out data from three nearby lakes (Auburn, Cobbosseecontee, Damariscotta) indicate that the influence of cycles in the 3-5.5-year ENSO-NAO frequency range were particularly significant during the 1920's and again in the 1940s (Fig. 4a,b), which correspond with intervals characterized by significant NAO excursions (Hurrell, 2014). These same cycles are similarly prominent in the XWT analysis results (Fig. 4d).

El Niño is characterized by a pool of anomalously warm water that develops off the west coast of South America. Through teleconnections it influences global climate. La Niña, the counterpart of El Niño is characterized by cold-water conditions in the Eastern Pacific. Variation in water temperatures of the tropical eastern Pacific (El Niño and La Niña) that become coupled with air surface temperatures in the tropical western Pacific are known as ENSO. This anomaly typically persists for nine months to two years with an irregular return time of two to seven years (average approximately five years; Philander 1990). Not all ENSO events impact eastern North America, but strong El Niño events are typically characterized by warmer than normal winter conditions. In contrast, La Niña generally has little impact on winter weather in the region (Chiodi & Harrison 2013).

The NAO is a measure of the difference in the atmospheric pressure at sea level between the Icelandic Low and Azores High. The oscillation between these semi-permanent atmospheric features controls the direction of westerly winds and storm tracks across the North Atlantic (Olsen et al. 2012). During a +NAO the Icelandic low pressure system deepens, leading to colder winters in northern Canada and warmer temperatures in Europe. During a –NAO the anomaly is reversed with winters in New England and Maritimes being characterized by periodic significant cold air outbreaks, which are often slow to move away due to a blocking high in the mid-Atlantic (Zielinski and Keim 2003). In addition, the highly meridional 500-mb pattern associated with the –NAO phase favors the development of frequent low-pressure systems along the eastern seaboard, which often brings large storms to the region (Grenci and Nese 2010). The NAO is part of the AO and can potentially switch from one phase to another several times through a single season. The NAO is also associated with longer quasi-periodicities that have been measured by the instrumental record at 3-6 and 7-8-years, with ~20, 50-70, ~170 and ~300 year periodicities observed in the geologic record (Appenzeller et al. 1998; Hubeny et al. 2006; Olsen et al. 2012). The CWT analysis results presented here suggests that NAO, and periodically ENSO, has been a significant contributor to controlling ice out across the region throughout the entire record. However, as discussed in the context of QBO above, the influence has been discontinuous (Fig. 3). Sharma and Magnuson (2014) similarly recognized the possible influence of NAO and ENSO on ice out in Auburn, Cobbosseecontee, Damariscotta and Moosehead lakes, which explained from 1.9-10% of the total variance in their data. A similar influence at NOA and ENSO frequencies has been observed in other lakes throughout the northern hemisphere (Livingstone 2000; Sharma and Magnuson 2014). In an analysis of the varying influence of local climate and teleconnections on lake ice cover on Lake Mendota, Wisconsin, Ghanbari et al. (2009) concluded that the Pacific Decadal Oscillation and NAO were the most significant influences on ice cover. They observed that the influence of NAO was primarily transmitted through snow cover, and as observed in this study, temperature.

4.2.3 Atlantic Multidecadal Oscillation (AMO)

The AMO has been characterized by a quasi-periodic ~64 year cycle through the last 450 years (Fortin and Lamoureux 2009; Fig. 8), which has a duration of about 30-35 years per phase (Knudsen et al. 2011). Modeling results suggest that the AMO may be derived from an oscillatory component in the strength of North Atlantic thermohaline circulation (Dima and Lohmann, 2007) and is characterized by a coherent pattern of sea surface temperature variability between “warm” and “cold” phases in the North Atlantic with any linear trends removed (Schlesinger and Ramankutty 1994; Fig. 3). The highly significant 34-year spectral analysis signal recognized in the Lake Utopia record (Fig. 5) and 32-year cycle recognized in the MA thermometer record from Orono (Fig. 6; Sup. Table 4) may be recording the influence of individual AMO phases. Spectral analysis also revealed a 16.2.-16.7-year cycle in several inland lake ice out records (Oromocto, Moosehead, Sebec, West Grand), which may represent AMO harmonic signals (Fig. 5). Harmonic signals are common features of climate cycles and are generally characterized by component frequencies of the fundamental frequency that is an integer multiple or fraction of the fundamental frequency (Burroughs 2007). In this case the observed 16.2-16.7 year cycles would be a second subharmonic of the primary AMO multidecadal signal. This hypothesis is supported by Ruiz-Barradas et al. (2013) who reported a similar 16-24 year harmonic within the AMO. The expression of the ~16-year cycle observed in these four lakes lakes is slightly different though. While in Sebec Lake a 16.2 year CWT cycle is found through the entire record, in Oromocto, West Grand and Moosehead lakes the pattern only develops after ~1925 (Fig. 3, Sup. Fig. 3). The expression of AMO on ice out in inland lakes and not coastal sites is supported by previous research that found the imprint of AMO on continental hydroclimate was significantly greater inland in this region than along the coast (Fortin and Lamoureux 2009).

The 25.3-29-year cycles found in the records from six of the lakes in the study are difficult to interpret as they are slightly too short to correlate with AMO phases and slightly too long to represent the 16-24-year AMO harmonic.

4.3 Climate drivers of ice out data

In the ice out record presented here there are two periods of rapidly changing ice out trends, one occurring in the late 19th century to early 20th century and the second beginning in the late 20th century and continuing to the present. The late 19th century-early 20th century ice out dates in these lakes were ~six days earlier than the earliest part of the ice out record. This shift occurred during the thermal recovery from Little Ice Age (Bradley and Jones 1993; Fagan 2001), and has been demonstrated in other climate records, (and thus probably applicable to ice out dates) to be strongly influenced by an increase in solar insolation (Gray et al. 2010). Since the late 1970s ice out trends in the lakes studied here have trended earlier than at any time since record keeping began in AD1836 (Fig. 2; Sup. Table 1). In the late 20th century-early 21st century it has been suggested that solar insolation has had significantly less influence on climate, particularly since the early 1980s (Rind et al. 2014). The significant increase in anthropogenically-produced atmospheric CO_2 concentrations through the 20th century is often invoked to explain late 20th century temperature increase (IPCC 2013). There is a strong statistical correlation between the ice out records presented in this research and atmospheric CO_2 levels (Sup. Table 3). Ice out dates also correlated strongly with the AMO Index, particularly for the more continental climate regime inland lakes of the study (Sup. Table 3). A shift to a +AMO phase developed in the mid 1990s (Fortin and Lamoureux 2009; Kavvada et al. 2013), which corresponds well with the continued trend to earlier ice out dates. The subsequent development of negative Pacific Decadal Oscillation by 2000, amplified the impact of the +AMO, significantly impacting the climate of this region (McCabe et al. 2004; Rowe and Derry 2012; Wyatt et al. 2012). This shift accelerated the trend toward even warmer MA temperatures (Knight et al. 2006; Ning and Bradley 2014; Sutton and Hodson 2005) and resultant earlier ice out dates. Additional research is required to elucidate the long-term trends in ice out, and the relative impacts of anthropogenic climate change and other long-term cycles such as AMO.

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Figures in Text

Fig. 1 Location map showing position of lakes and climate stations used. Vertical bars adjacent to lakes provide relative indication of average Julian Day ice out dates for two 30-year climate periods (1952-1982, left; 1983-2013, right). Scatter plots are for mean "ice out" dates for inland (red dots) and southern/coastal lakes (blue dots) versus distance from the coast, and elevation above mean sea level.

Fig. 2. A,B. Julian Day ice out dates plotted against calendar year for the lakes uses in study (Auburn (AUB), Cobbosseecontee (COB), Damariscotta (DAM), Moosehead (MOO), Oromocto (ORO), Rangeley (RAN), Sebec (SEB), Skiff (SKI), Sunapee (SUN), Utopia (UTO), West Grand (WGL), Winnipesaukee (WIN)). A. Smoothed (LOWESS, span – 0.1 +/- 95%) plots for compilation of available annual data for all lakes from 1876-2013. LOWESS smoothing was not provided for earlier ice out data in the series, as it is dominated by records from typically warmer MA southern coastal lakes with longer ice out records, which would give the illusion that ice out dates were later in the mid-19th century. B. Smoothed (LOWESS, span – 0.1 +/- 95%) plots for compilation of available data for southern coastal lakes AUB, COB and DAM from 1836-2013. Post 1876 results in B closely match the results for all lakes (A). C. Average March-April air temperature data from climatological stations in Fredericton (FRE), Hanover (HAN), Houlton (HOU), Lewiston (LEW) and Orono (ORO). Smoothed (LOWESS, span – 0.1 +/- 95%) plots for compilation of available data for year included for 1893-2013. LOWESS smoothing was not provided for earlier March-April temperature data in the series, as it is comprised exclusively by the generally

cooler MA records from FRE in the northern part of the region. If this dataset were included it would have given the inaccurate result that the climate recovery from the Little Ice Age across the region was more dramatic than in reality.

Fig. 3 Absolute and smoothed (LOWESS, span = 0.1) plots of Julian Calendar ice out dates for each lake used in study, as well as ice out wavelet scalograms in the time domain for each lake. Orange and yellow areas in plots indicate high wavelet coefficients (high spectral power), and blue color indicates low wavelet coefficients (low spectral power) at specific wavelengths at specific locations in time. Muted color regions bounded by thin white line delineate the cone of influence, which is the region of the wavelet spectrum where edge effects become important. White text corresponds to peaks above 95% false alarm level identified in the spectral analysis (see Fig. 5).

Fig. 4 Wavelet scalograms in the time domain for (a) March-April (MA) data from the climate station at Lewiston, ME, and (b) ice out data from lakes Auburn, Cobbosseecontee, and Damariscotta. Relative phase relationships are shown as in-phase arrows pointing right, anti-phase pointing left, variable 1 leading variable 2 pointing up and variable 2 leading variable 1 pointing down. The out of phase relationship indicated corresponds to later ice out dates (higher values) corresponding to lower mean instrumental temperature (lower values) and vice versa. (c) Wavelet coherence analysis and (d) cross-wavelet transformation results in the time domain between the MA instrumental record from Lewiston (variable 1) and the lakes (variable 2; Auburn, Cobbosseecontee, and Damariscotta). Relative phase relationships as indicated by arrows are explained and defined in Figure 8 caption. White text corresponds to peaks above 95% false alarm level identified in the spectral analysis (see Figs. 5,6).

Fig. 5 Spectral analysis for Auburn, Cobbosseecontee, Damariscotta, Moosehead, Oromocto, Rangeley, Sebec, Skiff, Sunapee, Utopia, West Grand, and Winnipesaukee lakes. The AR1 and false alarm levels are shown on the diagrams. Peaks above 90% false alarm level are considered statistically robust.

Fig. 6 Spectral analysis for climate stations in Fredericton, NB; Hanover, NH; Houlton, ME; Lewiston, ME; and Orono. ME. The AR1 and false alarm levels are shown on the diagrams. Peaks above 90% false alarm level are considered statistically robust.

Fig. 7 Wavelet scalograms in the time domain for each climate station used in the study. See Figure 3 for detailed description of components of wavelet plots. White text corresponds to peaks above 90% false alarm level identified in the spectral analysis (see Fig. 6).

Fig. 8 Spectral analysis for the Quasi-biennial Oscillation (QBO, annual and winter (DJFM), Southern Oscillation Index (SOI, annual and winter), North Atlantic

Oscillation - Climatic Research Unit (NAO CRU, annual and winter (DJFM), and Atlantic Multidecadal Oscillation - Climatic Research Unit (AMO CRU, annual and winter (DJFM). The AR1 and false alarm levels are shown on the diagrams. Peaks above the 90% false alarm level are considered statistically robust.

Supplementary Figures

Supplementary Fig. 1 View of Oromocto Lake, New Brunswick, from one of the farms along the western margin of the Lake. Citizen scientist Clayton Piercy, pictured in the lower right photo, lives in a house that overlooks the lake, and has documented ice out dates since 1944. Ice out dates to as far back as 1876 were variously gleaned from barn doors, dairy cow stalls, woodshed walls and cellarways from farms around the lake. Since record keeping began ice out dates for Oromocto Lake have been consistently determined to be the date when the various coves of the lake are open to navigation, which may be several days later than when the main body of the lake is open to navigation. See Appendix 1 for list of observers and criteria used to determine ice out for each lake.

Supplementary Fig. 2 Absolute and smoothed (LOWESS, span = 0.05) plots of mean March-April temperatures for the five climate stations used in the study. Station details are provided in Appendix 2.

Supplementary Fig. 3 a) Wavelet scalograms in the time domain for (a) annual Atlantic Multidecadal Oscillation - Climatic Research Unit (AMO CRU) Index and (c) Sebec Lake ice out data. See Figure 3 for detailed description of components of wavelet plots. (b) Plot of annual AMO-CRU Index. Red shaded areas represent positive anomalies while blue shaded areas represent negative anomalies. (d) Coherence analysis and (e) cross-wavelet transformation results in the time domain between the Annual AMO-CRU Index (variable 1) and Sebec Lake ice out data (variable 2). Relative phase relationships are shown as in-phase arrows pointing right, anti-phase pointing left, variable 1 leading variable 2 pointing up and variable 2 leading variable 1 pointing down. The out of phase relationship indicated corresponds to later ice out dates (higher values) corresponding to lower mean instrumental temperature (lower values) and vice versa.

Supplementary Tables

Supplementary Table 1. Julian calendar ice out dates for the 12 lakes from New Hampshire, Maine and New Brunswick used in the study.

Supplementary Table 2. Mean March-April temperatures for five climate stations used in study. Specific details for each station is provided in Appendix 2.

Supplementary Table 3. Spearman rank correlations of ice-out data, instrumental records for March-April and possible forcing mechanisms. All instrumental MA and ice-out records are significantly correlated to each other at the p<0.01 level. There is a significant correlation between atmospheric CO_2 concentrations and the ice-out records as well as a correlation between annual Atlantic Multidecadal Oscillation records and ice out records from inland lakes.

Supplementary Table 4. Summary of the cycles recognized in spectral analysis of the Ice data, mean March-April temperatures for five climate stations used in study, and climate forcing indexes for the Quasi-biennial Oscillation (mean and December, January, February, March (DJFM), El Niño-Southern Oscillation (ENSO; mean and DJFM); North Atlantic Oscillation – Climate Research Unit (NAO-CRU; mean and DJFM), and Atlantic Multidecadal Oscillation (mean, DJFM). Specific details for each lake and climate station are provided in Appendix 2.

1

Appendices

Appendix 1. List of lakes used in study, including lake location, elevation of lake above mean sea-level, duration of ice-out record, and observers. For some lakes the criteria for determining ice dates are included.

Appendix 2. List of climate stations used in study, including geographic location, elevation of station above mean sea-level, and duration of March-April temperature record.

Figure 1

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Figure 1

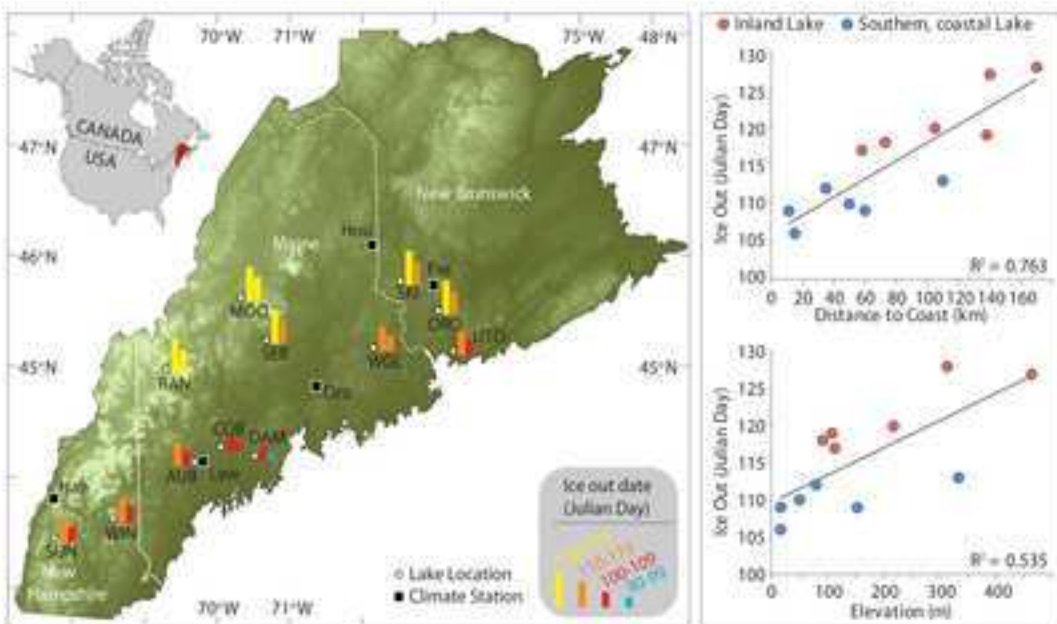

Fig. 1 Location map showing position of lakes and climate stations used. Vertical bars adjacent to lakes provide relative indication of average Julian Day ice out dates for two 30-year climate periods (1952-1982, left; 1983-2013, right). Scatter plots are for mean "ice out" dates for inland (red dots) and southern/coastal lakes (blue dots) versus distance from the coast, and elevation above mean sea level.

Figure 2
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Figure 2

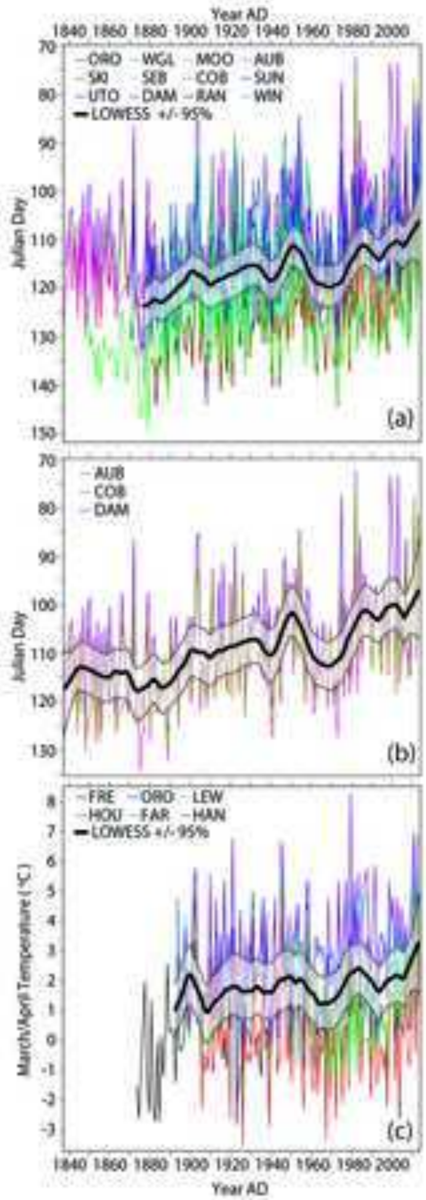

Fig. 2. A,B. Julian Day ice out dates plotted against calendar year for the lakes uses in study (Auburn (AUB), Cobbosseecontee (COB), Damariscotta (DAM), Moosehead (MOO), Oromocto (ORO), Rangeley (RAN), Sebec (SEB), Skiff (SKI), Sunapee (SUN), Utopia (UTO), West Grand (WGL), Winnipesaukee (WIN)). A. Smoothed (LOWESS, span – 0.1 +/- 95%) plots for compilation of available annual data for all lakes from 1876 onward. LOWESS smoothing was not provided for earlier ice out data in the series, as it is dominated by records from coastal lakes to the south, which would give the illusion that ice out dates were later in the mid-19th century. B. Smoothed (LOWESS, span – 0.1 +/- 95%) plots for compilation of available data for southern coastal lakes AUB, COB and DAM from 1836 onward. Post 1876 results in B closely match the results for all lakes (A). C. Average March-April air temperature data from climatological stations in Fredericton (FRE), Hanover (HAN), Houlton (HOU), Lewiston (LEW) and Orono (ORO). Smoothed (LOWESS, span – 0.1 +/- 95%) plots for compilation of available data for year included for 1893 onward. LOWESS smoothing was not provided for earlier March-April temperature data in the series, as it is comprised exclusively by the generally cooler records from FRE in the northern part of the region. If this dataset were included it would have given the inaccurate result that the climate recovery from the Little Ice Age across the region was more dramatic than in reality.

Figure 3
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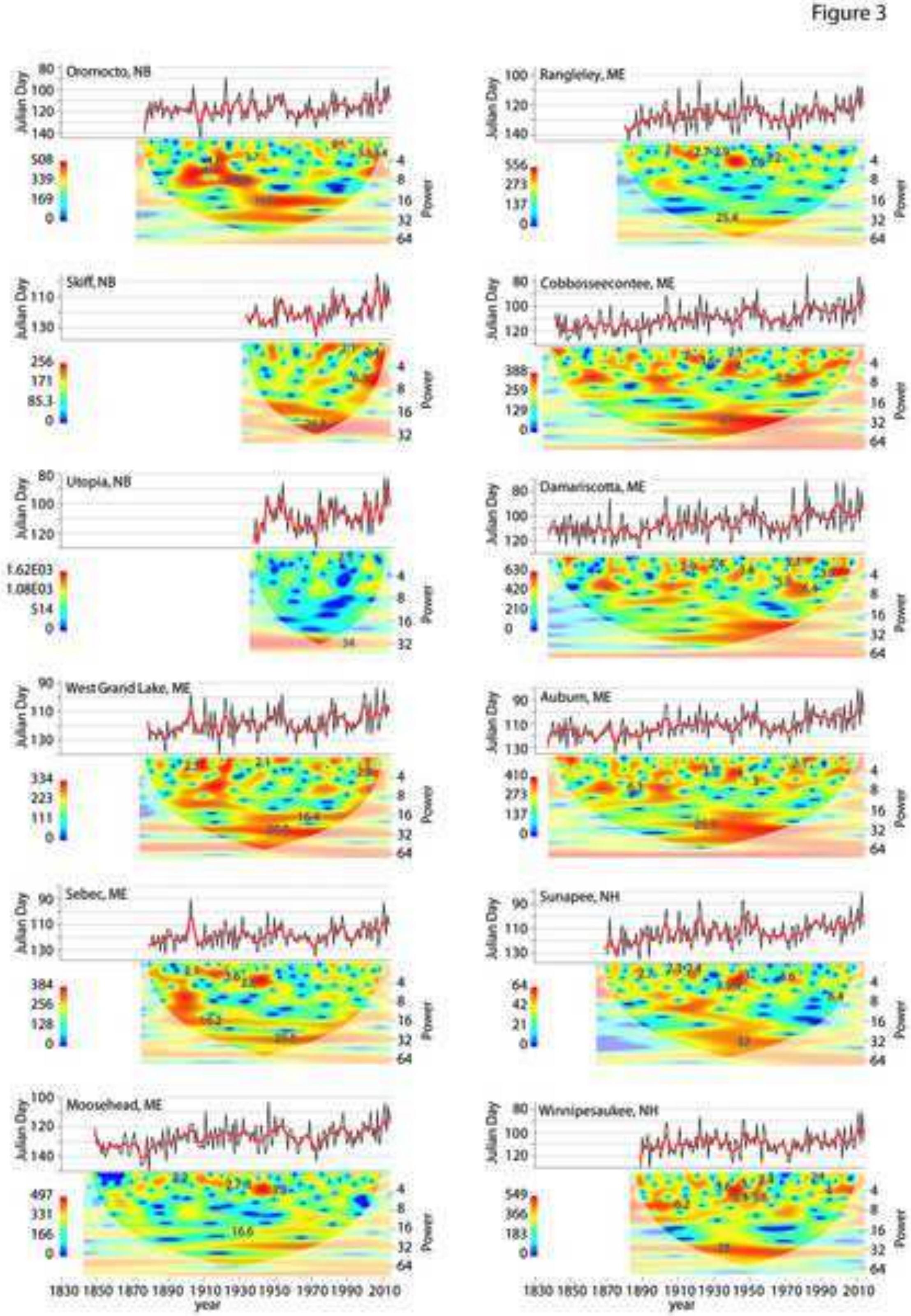

Fig. 3 Absolute and smoothed (LOWESS, span = 0.1) plots of Julian Calendar ice out dates for each lake used in study, as well as ice out wavelet scalograms in the time domain for each lake. Scalogram axes represent the logarithmic scaled period (wavelength). Orange and yellow areas in plots indicate high wavelet coefficients (high spectral power or amplitude), and blue color indicates low wavelet coefficients (low spectral power or absent amplitude) at specific wavelengths at specific locations. Muted color regions bounded by thin white line delineate the cone of influence, which is the region of the wavelet spectrum where edge effects become important. White text in the margin on the right edge of the wavelet plots correspond to peaks above 95% confidence identified identified using REDFIT spectral analysis (see Fig. 5).

Figure 4
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Figure 4

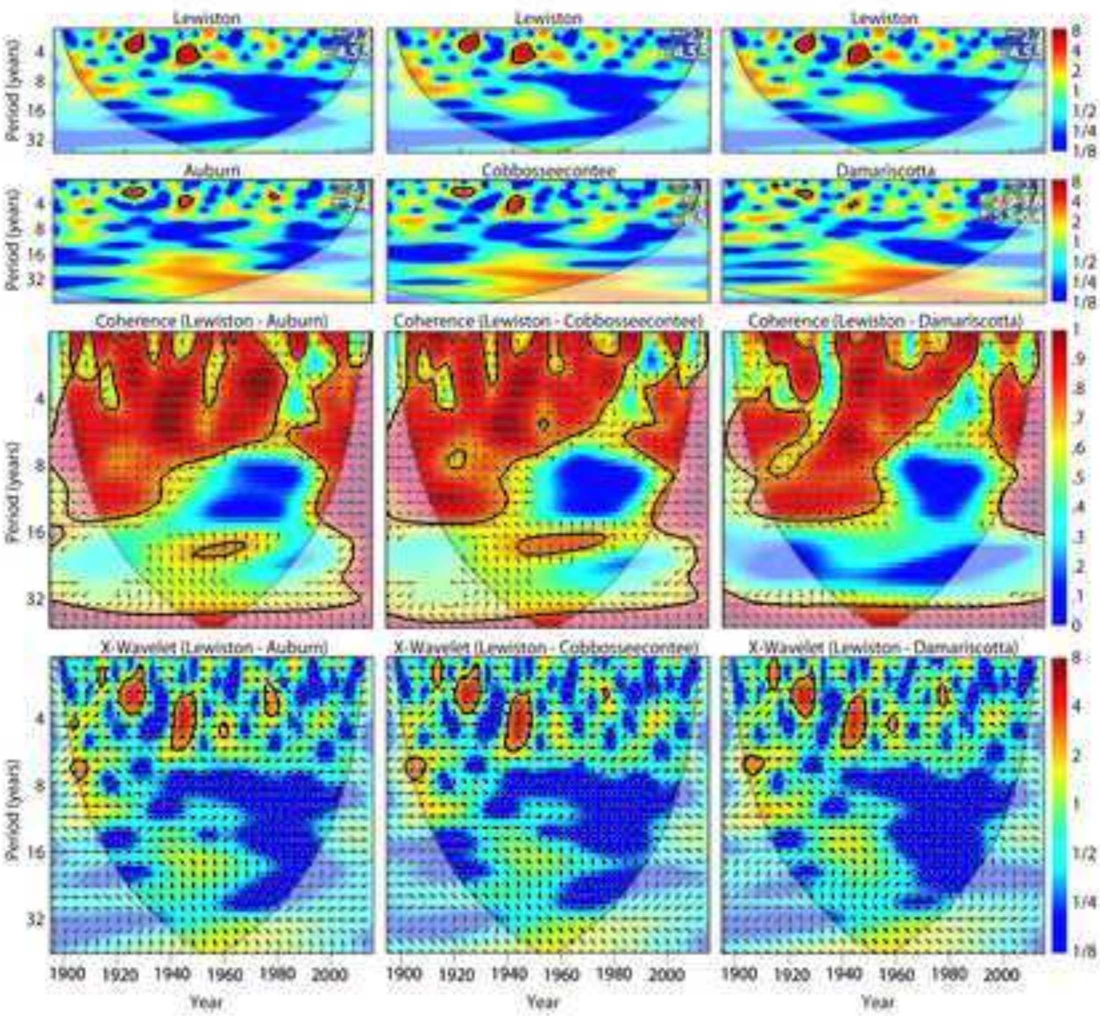

Fig. 4 Wavelet scalograms in the time domain for (a) March-April (MA) data from the climate station at Lewiston, ME, and (b) ice out data from lakes Auburn, Cobbosseecontee, and Damariscotta. Relative phase relationships are shown as in-phase arrows pointing right, anti-phase pointing left, variable 1 leading variable 2 pointing up and variable 2 leading variable 1 pointing down. The out of phase relationship indicated corresponds to later ice out dates (higher values) corresponding to lower mean instrumental temperature (lower values) and visa versa. Scalogram axes represent the logarithmic scaled period (wavelength). (c) Coherence analysis and (d) cross-wavelet transformation results in the time domain between the MA instrumental record from Lewiston (variable 1) and the lakes (variable 2; Auburn, Cobbosseecontee, and Damariscotta). Relative phase relationships as indicated by arrows are explained and defined in Figure 8 caption. Scalogram axes represent the logarithmic scaled period (wavelength). White text in the margin on the right edge of the wavelet plots correspond to peaks above 95% confidence identified using REDFIT spectral analysis (see Figs. 5,6).

Figure 5
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Figure 5

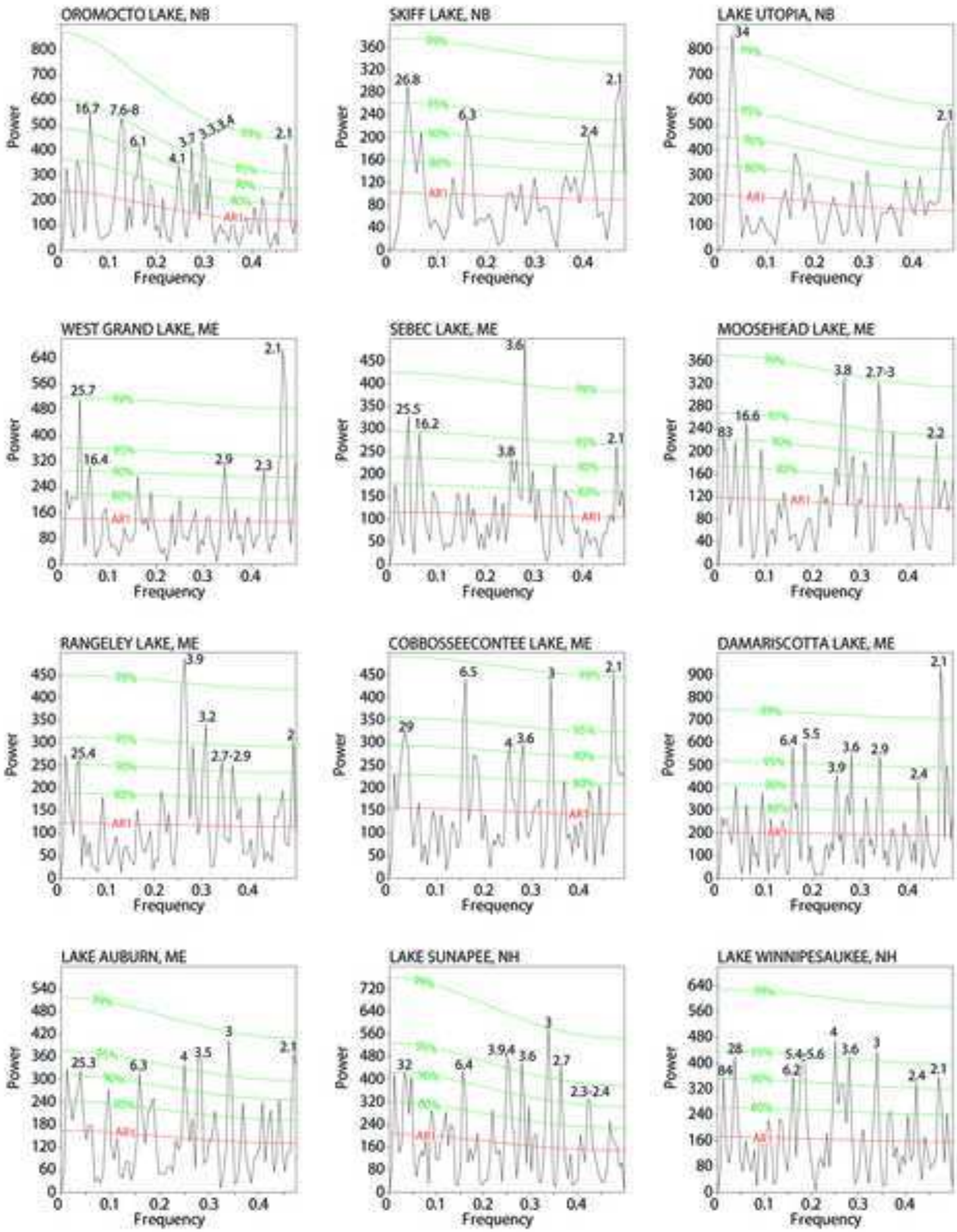

Fig. 5 REDFIT spectral analysis for Auburn, Cobbosseecontee, Damariscotta, Moosehead, Oromocto, Rangeley, Sebec, Skiff, Sunapee, Utopia, West Grand, and Winnipesaukee lakes. The AR1 and confidence intervals are shown on the diagrams. Peaks above 90% confidence interval are considered statistically robust.

Figure 6
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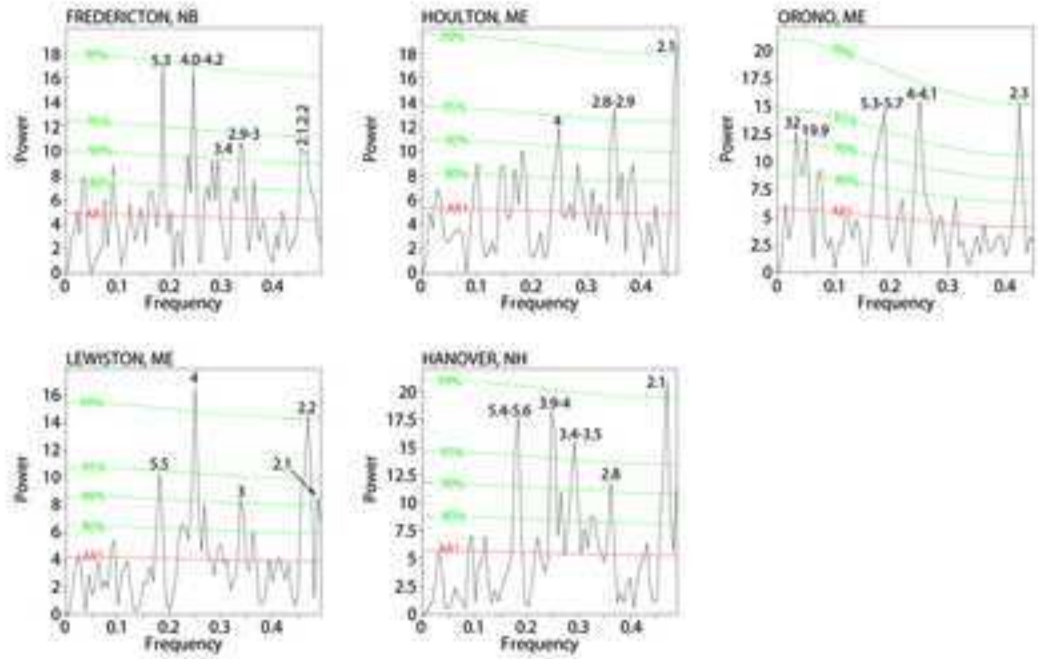

Fig. 6 REDFIT spectral analysis for climate stations in Fredericton, NB; Hanover, NH; Houlton, ME; Lewiston, ME; and Orono, ME. The AR1 and confidence intervals are shown on the diagrams. Peaks above 90% confidence interval are considered statistically robust.

Figure 7
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Figure 7

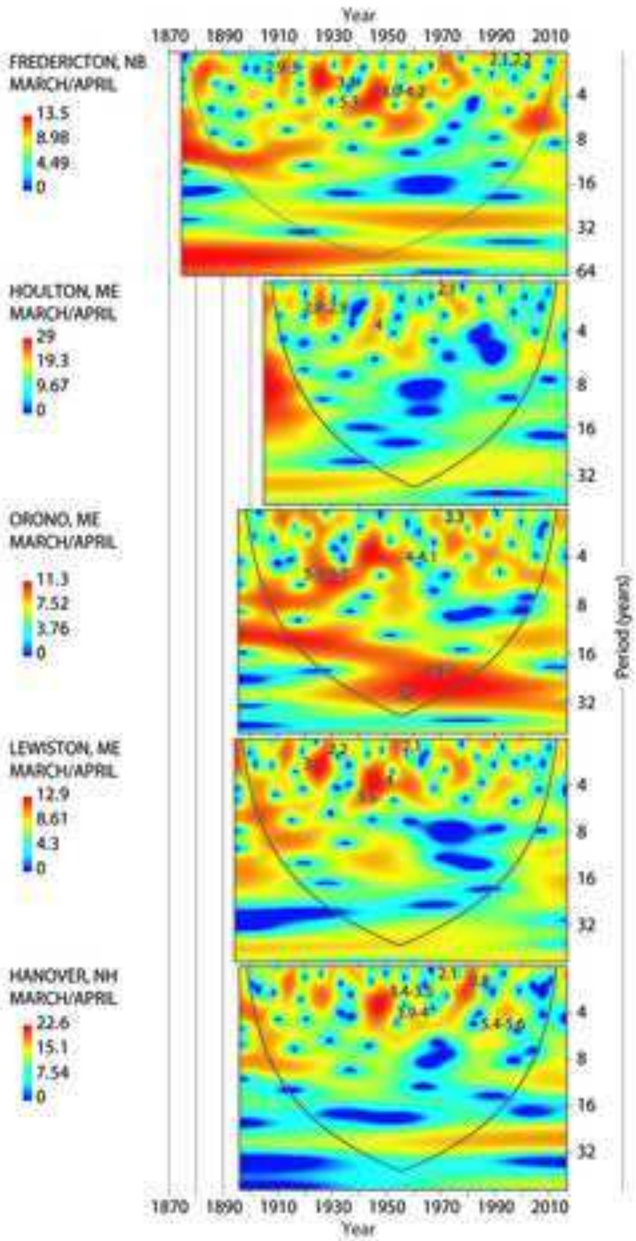

Fig. 7 Wavelet scalograms in the time domain for each climate station used in the study. See Figure 3 for detailed description of components of wavelet plots. Scalogram axes represent the logarithmic scaled period (wavelength). White text in the margin on the right edge of the wavelet plots correspond to peaks above 90% confidence identified identified using REDFIT spectral analysis (see Fig. 6).

Figure 8

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Figure 8

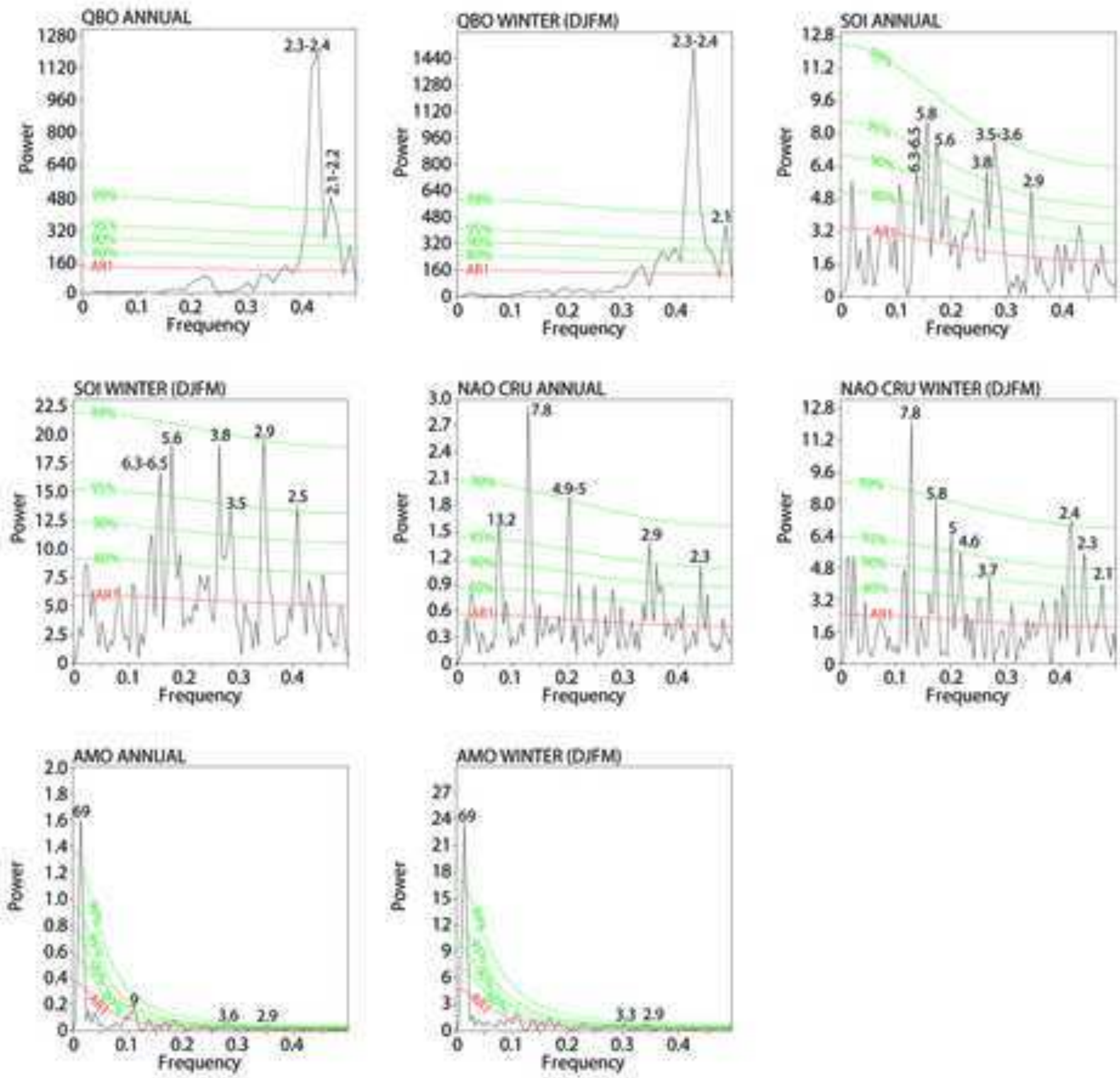

Fig. 8 REDFIT spectral analysis for the Quasi-biennial Oscillation (QBO, annual and winter (DJFM), Southern Oscillation Index (SOI, annual and winter), North Atlantic Oscillation - Climatic Research Unit (NAO CRU, annual and winter (DJFM), and Atlantic Multidecadal Oscillation - Climatic Research Unit (AMO CRU, annual and winter (DJFM). The AR1 and confidence intervals are shown on the diagrams. Peaks above 90% confidence interval are considered statistically robust.

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Sup Fig 2

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Appendix 1

Appendix 2
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