Climatic Forcing of Multidecadal Variation in Lake Sediment Characteristics: Teleconnections Spanning 1,700 Kilometers of North America from Michigan to New York

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Sediment cores from Fourth Lake, New York record the past ~340 years. One core had been ^{210}Pb dated, and its age model and long-term trends in sediment characteristics discussed in Kanfoush (2013) and Robinson and Kanfoush (2017). Here, its age model was transferred onto a nearby core by stratigraphic correlation of peaks in bulk density and shorter-term variations examined. The %clay shows multidecadal variations superimposed upon a longer-term up-core trend toward less clay.

The Fourth Lake record resembles published pollen-inferred annual precipitation and summer temperature from Lake of the Clouds, Michigan (Gajewski, 1988), with each on their independently-derived age models, implying existence of a common control on the lakes despite their separation distance. Human influences likely varied spatially and temporally, consequently the similarity of changes within the widely-separated lakes suggests a response to broad climate drivers influencing the 1,700 kilometers span of these geographically-distant lakes.

Shorter multidecadal fluctuations toward lower %clay at Fourth Lake coincide with reduced precipitation and higher temperatures at Lake of the Clouds. Due to chronological limitations, duration of %clay variations remains uncertain. However, their estimated maximum duration (~21-yr) makes the North Atlantic Oscillation (NAO) a candidate, and many minima in %clay at Fourth Lake coincide with positive NAO values. In longer multidecadal variations, Fourth Lake %carbonate maxima coincide with minima in the Atlantic Multidecadal Oscillation (AMO). Fluctuating intensity of zonal and meridonal winds and associated storm tracks accompanying the NAO and AMO could explain similarity of inferred climate records and responses from geographically remote lakes. *Key Words: climate cycles, multidecadal, paleolimnology, grain size, loss-on-ignition, carbonate*

Over the past century lakes and rivers in the northern hemisphere and specifically in New England have been freezing later in the fall and becoming ice-free earlier in the spring, changes that have been attributed to rising global temperatures (Magnuson et al., 2000; Hodgkins et al., 2002). Hewitt and others (2018) reported from 1975 to 2004, lakes thawed 6.3 days earlier and froze 9.9 days later. In conjunction with these changes, the timing of 20th century high river flows in New England occurred 1-2 weeks earlier in the spring (Hodgkins et al., 2003; Huntington, 2009). In New York State, a rise in biologically-mediated calcite in one of the Finger Lakes since the mid-20th century has been attributed to rising atmospheric carbon dioxide levels (Mullins, 1998).

In addition to a trend toward rising temperature and CO_2 over the past century, several studies have identified multidecadal and centennial variability in climate records around the globe (Appenzeller et al., 1988; Jones et al., 2001; Mann et al., 2009; Frankcombe et al., 2010). Similarly, the Northeast lake ice-out and river high flow records of Hodgkins and others (2002, 2003) display a reversal in the middle part of the past century (ca. AD 1945 to 1968) that punctuates the longer-term trend. Oxygen isotopes measured on carbonate within a 1000-year long varved record from Fayetteville Green Lake, New York display a 20-30 year cyclicity that has been attributed to changes in overlying atmospheric circulation, specifically the expansion and contraction of the winter circumpolar vortex (Kirby et al., 2001). Stager and others (2021) have suggested Atlantic sea-surface temperatures and solar variability may have influenced the two most severe droughts in the Adirondack region of the past 1,000 years at ca. A.D. 1260–1330 and ca. A.D. 1360–1390.

It is well known that contribution of greenhouse gases to the atmosphere through anthropogenic activities is a significant factor moderating Earth's present climate system (Overpeck et al., 1997). However, recognition of short-term variability in paleoclimate records occurring prior to and persisting into times of anthropogenic influences raises the question if and how natural climate variability will amplify or dampen, or perhaps mask, anthropogenic contribution to the warming trends observed within regional records. Further, spatial patterns of short-term cyclical climate influences remain unclear.

Modeling and paleoclimate studies suggest that multidecadal variability of the North Atlantic Oscillation (NAO) contributed a cooling overprint to North America climate over the last few decades that masked anthropogenic contribution to global warming, and that a recent reversal of the NAO will likely enhance anthropogenic warming for the next few decades (Hurrell, 1995; Mann et al., 1998; Delworth and Mann, 2000). Wang and others (2018) reported that positive phases of the Atlantic Multidecadal Oscillation (AMO) exerted warming in the Great Lakes region resulting in decreased lake ice cover. Of equal interest and concern is if and how anthropogenic warming will alter natural short-term climate variability. Intensity of recent El Nino events, for example, appears to be unprecedented over the past several centuries (Mann, 2001). An understanding of the role of natural variability is critical to narrowing the range of projections of future temperature rise and its potential impacts.

Included within the need to understand natural variability is a need to understand not only the direction and magnitude but also the geographic patterns of such. Across North America, for example, changes from warm to cold phase of the Atlantic Multidecadal Oscillation (AMO) result in a 40% variation in river volume entering Lake Okeechobee but only a 10% variation in Mississippi river volume (Enfield et al., 2001; Tootle et al., 2005; Stager et al., 2021).

The Northeast is a region of very steep north-south climatic gradients, and the climate of the region has been shown to be sensitive to changes in overlying atmospheric circulation (Balling and Lawson, 1982; Cember and Wilks, 1993; Kirby et al., 2001). Stager and Martin (2002) report that instrumental weather records show the Adirondack region has exhibited climate trends in recent decades that at times differ in magnitude and direction from global, and even regional, trends. Stager and others (2021) reported that lake sediment records from the Adirondacks exhibit a different response to the Pacific Decadal Oscillation (PDO) to that of not only the Southwest but even relative to other parts of the Northeast.

The NAO, AMO, PDO, and ENSO are potential drivers of multidecadal climate variability across broad geographic areas – drivers referred to as climate teleconnections. Thus, different locations within the Northeast may potentially be simultaneously influenced by and record different climatic conditions or different magnitudes of climate change at times in the past. Here, a high-resolution paleoclimate record from a lake in the Adirondack Mountains is presented to expand coverage of climate records not only within the region but in the context of broader climate change to contribute to our understanding of past climate variation, its causes, and spatial variability as well as broad climate teleconnections as a means to improve predictability of future climate change.

Study Site

Fourth Lake is one lake in a series of nine interconnected lakes (the Fulton Chain), located at 43º44.22'N, 74º53.88'W in the southwestern Adirondack Park in northern New York State (Figure 1). It has a volume of 850×10^5 m^3 with a mean and maximum depth of 10.2m and 25.9m, respectively, and is the largest and deepest lake in the series (ALSC, 2006). It is a drainage lake, meaning it has an inflow and outflow. Within the Oswegatchie-Black Watershed Fourth Lake receives inflow at the northern end by a narrow channel from the interconnected series of Fifth, Sixth, Seventh and Eighth Lakes and discharges water at the southern end by a narrow channel to the interconnected series of Third, Second, First Lakes, and Old Forge Pond. The residence time is 1.29 years. The watershed area is 93.0 km^2, the elevation of the lake is 520 meters, and the lake sits at the base of a fault scarp formed in gneissic bedrock with northwest-dipping layers (Van Diver, 1985). The town of Inlet is situated at the northern extremity of Fourth Lake and the town of Old Forge is situated at the southern end of the Chain at Old Forge Pond

Although not considered part of the Fulton Chain, Raquette, Utowana, Eagle, Blue Mountain and Durant lakes situated at the northeast end of the Fulton Chain were also likely all interconnected and connected with the Fulton Chain following retreat of the Laurentide ice sheet as one large glacial lake that drained eastward into the Hudson (Van Diver, 1985). Now separated by drainage divides of glacial debris, only the easternmost, Lake Durant, presently drains to the east. Raquette, Utowana, Eagle and Blue Mountain lakes all drain northward into the St. Lawrence and the Fulton Chain drains westward into the Black River and then to Lake Ontario.

Fourth Lake is ~11.3 kilometers in length and ~1.6 kilometers wide at its maximum and trends northeast-southwest. It is subdivided into 3 physiographic basins; the shallowest southwestern basin is separated from the others by a large island, Alger Island. Although it was, like today, a chain of interconnected lakes prior to human modification, the water depth of the Fulton Chain was increased by construction of a dam at the southern outlet in 1798. The deepest point in the lake (presently 25.9m) occurs off-center within the central basin, nearer the southern shore off Cohassett Point. The watershed is characterized by a mixed deciduous-conifer forest. Fourth Lake lies approximately 120 kilometers northeast of the aforementioned Fayetteville Green Lake, and both lakes lie north of the mean annual position of the winter circumpolar vortex (Yarnal and Leathers, 1988).

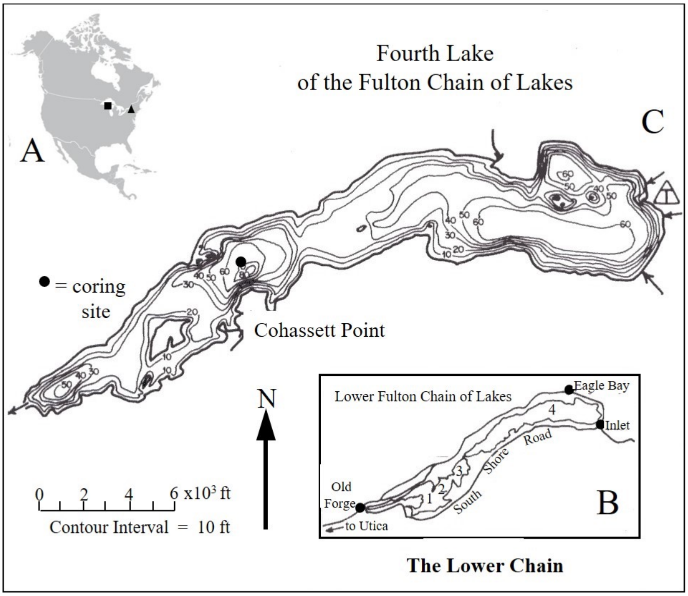

Figure 1. (A) Locations of Fourth Lake (black triangle) in the Adirondack Mountains, New York State in Eastern North America (triangle) and Lake of the Clouds (black square) in the Upper Peninsula, Michigan in the Midwest. (B) The lower Fulton Chain of Lakes, including Lakes 4-1 and Old Forge Pond. And (B) Fourth Lake of the Chain indicating collection site of Cores 1 and 2 from 13.4- and 17.7-m water depth, respectively, in the central basin, offshore Cohassett Point.

Materials and Methods

Using a polycarbonate tube mud-water interface gravity corer, Cores 1 and 2 with lengths of 30- and 37-cm, respectively, were recovered near Cohassett Point in the central basin from water depths of 13.4- and 17.7-cm (Figure 1). The cores were extruded vertically in the lab and sub-sampled at 1-cm intervals. Sub-samples were dried for 24 hours at 60°C and weighed to ascertain bulk density and then coarsely ground for subsequent ^{210}Pb analysis. Lead-210 analysis used to construct a chronology for the longer Core 2 was performed on core 2 using a Bicron 2" sodium-iodide well-detector and assuming a Constant Rate of Supply model (Appleby and Oldfield, 1992). Prior study of the lake showed sedimentation rates vary through time in response to anthropogenic activities in the surrounding watershed (Robinson and Kanfoush, 2017). In a comparative study of the CRS versus Constant Initial Concentration (CIC) models, Turner and Delorme (1996) showed the CRS model yielded more accurate age models where variability of sedimentation rate is high. A later study by Zhang and others (2015) reached a similar conclusion. Occurrence of a ^{137}Cs peak within the dated core coincides with the 1962 peak in above-ground nuclear weapons testing, and supports the chronology developed from the ^{210}Pb. The age model and the long-term climate changes back three centuries recorded in the lake sediments were published previously in Kanfoush (2013), and a systematic review of lower-resolution but longer-term climate of the region extending back three millennia is detailed in Marlon and others (2017).

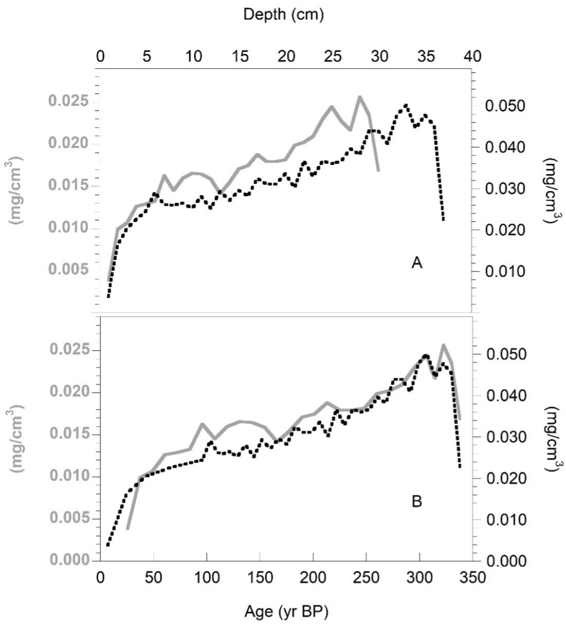

Figure 2. (A) Dry sediment bulk density is shown for both shorter Core 1 (solid gray line) and longer Core 2 (dashed black line) versus depth. In both records, bulk density increases with depth as a result of dewatering and compaction. (B) The chronology of Core 2 (Kanfoush, 2013) was then transferred to Core 1 by aligning prominent peaks in the bulk density records of the two cores.

For this study, the radiometrically-derived chronology of Core 2 reported in Kanfoush (2013) was transferred to Core 1 by aligning prominent peaks in the bulk density records of the two cores (Figure 2).

For both cores, subsamples were disaggregated in a 1% sodium metaphosphate solution and sonicated, following which sediment grain size was measured using a Malvern laser diffraction system. Magnetic susceptibility was measured using a Bartington MS2. Organic content and relative percent carbonate were inferred from loss-on-ignition (Dean, 1974). Weighed subsamples between 0.5 and 1.5 grams, depending upon sample availability, were ashed at 550°C for 4 hours and reweighed, then ashed at 950°C for an additional 2 hours and reweighed (Heiri et al., 2001). Fragments of charcoal were counted on a limited number of sub-samples following isolation of the >250micron size fraction via wet sieving.

Results

As reported in Kanfoush (2013), ^{210}Pb dating indicates the longer of the cores, Core 2, records ~340 years of sediment accumulation. The sedimentation rate averages ~1.1 mm/yr. The 1-cm sampling interval, therefore, yields an average temporal resolution of ~8.9 years/cm. Although shorter in sampled length, Core 1 as transferred onto the age model of Core 2 by stratigraphic correlation of bulk density variations had a similar basal age, sedimentation rate, and temporal resolution to Core 2 (Figure 2). This suggests the shorter length and associated higher bulk density of Core 1 may have been artifacts of compaction during the coring process. Human influences on the lake were detailed in Robinson and Kanfoush (2017) and long-term climate influences were detailed in Kanfoush (2013). Here, the focus will be on the nature and causes of recurring shorter-term variations recorded within the sediments.

Percent coarse (>250μ) sediment ranges from 0-3% and displays a series of discrete peaks that rise above baseline values near zero (Figure 3). The relative percent of clay (<3.9μ) and silt (3.0-63μ) ranges from 1.9-4.1% and 77-93%, respectively, and both parameters show variations on multi-decadal timescales. Within the limitations of the age model, the variations are estimated to average approximately 21 years. The observed variability typically occurs from one subsample to the next, suggesting the low sedimentation rate and 1-cm sampling interval did not yield high enough resolution to ascertain the precise recurrence interval. The ~21-year recurrence interval is thus likely a maximum estimate. Magnetic susceptibility also displays multidecadal variability, but the recurrence interval is less regular and frequently longer than that observed in the record of % fines (material <63μ).

The ~21-year variability is superimposed upon a longer-term up-core trend toward lower % fine sediment. Expressed in terms of volume, magnetic susceptibility appears to parallel this trend as it displays a decrease from ~1.3x10^{-6} to values approaching zero (Figure 4). Taking into account downcore increases in bulk density and expressing magnetic susceptibility in terms of mass rather than volume, however, removes nearly all the apparent trend. Like the % fines record, the record of percent organics displays a long-term up-core trend spanning the length of the record, increasing from less than 4% to more than 6%.

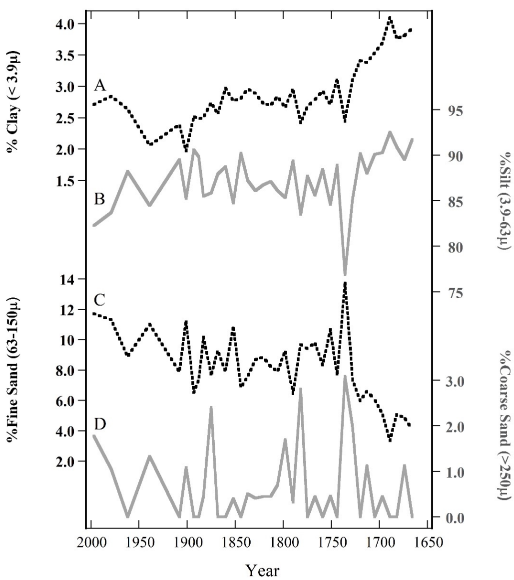

Figure 3. Relative percent of individual sediment size fractions is shown. The relative percent of fine-grained material clay (< 3.9μ) (A) and silt (3.9-63μ) (B) ranges from 2 to 4% and 77 to 93%, respectively, and shows variations on multi-decadal timescales averaging approximately 21 years. (D) Percent coarse sand (>250 μ) sediment ranges from 0-3% and displays a series of discrete peaks that rise above baseline values near zero. (C) Downcore variations displayed by the fine sand (63-150μ) size fraction is largely the inverse of the pattern displayed by the fine-grained material.

Percent carbonate results show neither the ~21-year variability nor the longer-term trend. Values of % carbonate range from ~3.3-4.6% and show two prominent peaks centered at the 14- and 5-cm horizons, at ca. AD 1825 and AD 1925, respectively (Figure 4a). These peaks are the highest values of the entire record (~4.6% in each case) and are separated by values lower than those recorded at any other time within the record (~3.3%). Percent organic content also displays two prominent peaks that occur very near in time to those observed in the carbonate record (Figure 4b).

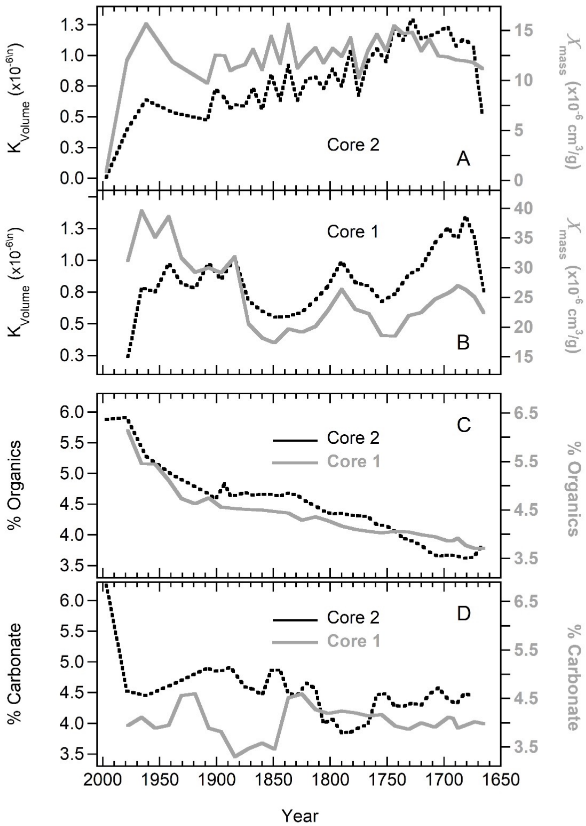

Figure 4. Magnetic susceptibility of Core 2 (A) and Core 1 (B) is expressed here as both Kvolume (solid gray line) and Kmass (dashed black line). Like the % clay, magnetic susceptibility also displays multidecadal variability, although the recurrence interval is somewhat less regular. (C) Percent organic content of Core 2 (solid gray line) and Core 1 (dashed black line) displays a long-term up-core trend, increasing from less than 4% to more than 6%, with almost no higher-frequency superimposed variations. (D) Percent carbonate of Core 2 (solid gray line) ranges from ~3.8-6.2%, with the lowest value occurring at ca. AD 1785. It displays a long-term up-core trend toward higher values and shows some multidecadal variability, although of longer duration than the ~21-year variability observed in the % clay record. Values of %carbonate in Core 1 range from ~3.3-4.6% and show two prominent maxima centered at the 14- and 5-cm horizons, at ca. AD 1825 and AD 1925, respectively.

Discussion

As shown in Kanfoush (2013), comparison of the record of Fourth Lake sediment characteristics with a pollen-inferred climate record from Clear Pond in northeastern New York State reveals general similarity (Gajewski, 1988). This suggests the up-core trend toward lower % fines at Fourth Lake coincides with a long-term trend toward reduced precipitation and higher summer temperatures over the past 340 years. This is consistent with other evidence of warming in New York and New England (Mullins, 1998; Magnuson et al., 2000; Hodgkins et al. 2002; Hodgkins et al., 2003).

Interestingly, on their independently-derived chronologies, the Fourth Lake record bears an even stronger resemblance to a second, much higher-resolution, record of inferred annual precipitation and summer temperature reported by Gajewski (1988) from Lake of the Clouds, Michigan (Figure 5a). The similarity to this site suggests that over the length of the records there existed a common control on the climate of much of the eastern and central United States.

Short-Term Multidecadal Variability

Within the observed ~21-year variability, fluctuations toward higher % fines in Fourth Lake coincide with similar duration increases in inferred annual precipitation and decreases in inferred summer temperature at Lake of the Clouds. The simplest explanation of this relationship is that more fine-grained terrigenous material is washed into the lake basin by increased amounts of surface runoff during wet climate conditions. Such a relationship was inferred by Gushulak and others (2021) for northeastern Canadian lakes over the middle and late Holocene in response to the NAO whereby less terrestrial material was washed into the lakes at times of cool conditions in the North Atlantic.

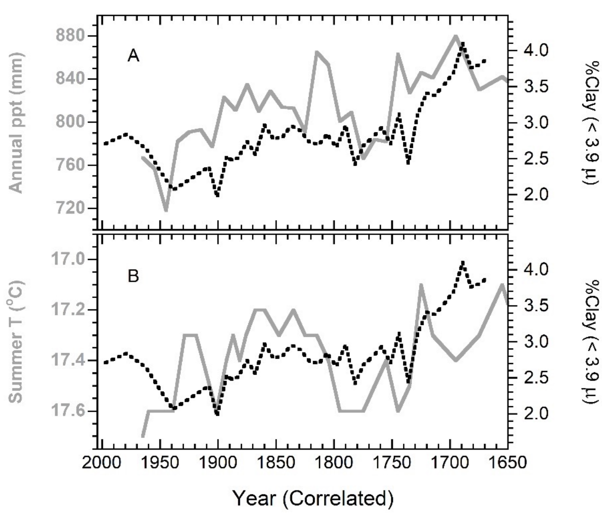

Figure 5. With each on their independent chronologies, the record of clay (% <3.9-63µ; dashed black line) from Fourth Lake is plotted against (A) the record of inferred annual precipitation from Lake of the Clouds, Michigan (solid gray line; Gajewski, 1988) and against (B) the record of inferred summer temperature from Lake of the Clouds, Michigan (solid gray line).

However, although comparison of the % fines with magnetic susceptibility reveals some similarities it also reveals some differences between the two records providing some evidence there may be additional or alternate controls. Because grain size analysis was performed on raw sample without prior removal of biogenic materials, an alternate possibility is that the increase in % fines reflects in part increased abundance of small-diameter biota. Such a change would be consistent with increased precipitation because increased runoff would likely cause attendant delivery of nutrients and an increase in primary productivity. If changes in % fines reflect in part changes in biota, the fact that the record of % fines does not exhibit similarity to the % carbonate record suggests such changes are dominated by siliceous microfossils, diatoms.

Yet another potential explanation of the observed relationship between sediment grain size and inferred temperature and precipitation is that times of increased temperature and decreased precipitation (in severe cases, droughts) increase the frequency of forest fires. Resulting loss of vegetation, and thus loss of the flow impedance and anchoring effect of plant roots, would likely facilitate increased erosion and delivery of coarse-grained terrigenous material to the lake. High percentage of material >250μ as measured by laser diffraction does in many but not all coincide with times of inferred low precipitation. However, there seems to be little correspondence between clay and charcoal on these timescales. This could be because the charcoal counts were conducted at a coarser temporal resolution.

Precise watershed and internal controls on multidecadal variations in sedimentation in Fourth Lake are not fully understood. Nonetheless, the duration of the short-term variations makes the North Atlantic Oscillation a candidate. Whereas the NAO is cited to display dominantly subdecadal periodicity (Hurrell, 1995; Hurrell and Van Loon, 1997), additional NAO variability ranging from ~20 to 25 years has been reported (Rogers, 1984; Cook et al., 1998; Luterbacher et al., 1999; Cullen et al., 2001). Many records of central European temperature exhibit variability with periodicities ranging from 23-25 years for which the NAO has been implicated as a potential forcing mechanism (Folland, 1983; Stocker and Mysak, 1992; Baliunas et al., 1997; Benner, 1999). Similarly sea-ice coverage of the western Baltic, also affected by the NAO, displays variability at ~19-year recurrence, near that observed in the Fourth Lake record (Loewe and Koslowski, 1998). The Fourth Lake records showed little resemblance to the records of ENSO or PDO indices.

Alternate increases and decreases in the sea-level pressure difference between the Icelandic low pressure center and the Azores high define the NAO and cause attendant strengthening and weakening of cold westerly winds that blow from Canada over the Labrador Sea (Hurrell, 1995). This extracts heat from the surface waters of the North Atlantic, causing them to become more dense and sink, and intensifies northward flow of warm equatorial surface waters (Broecker, 1997; Kerr, 2000; Hurrell et al., 2001). Thus, a steepened Iceland-Azores pressure gradient and enhanced Westerlies are associated with warm sea-surface temperatures (SST) in the North Atlantic.

Figure 6 shows a comparison of the relative percent of clay (% <3.9μ) sediment within Fourth Lake and the NAO index (Cook et al., 1998). Many, but not all, of the short-term (~21-year) maxima and minima appear to coincide, suggesting the NAO affected climate and thus lake and watershed processes of Fourth Lake. The two records display an inverse relationship whereby Fourth Lake % clay is low at times when values of the NAO index are high. If % clay is controlled largely by precipitation then Fourth Lake, like much of North America, experiences

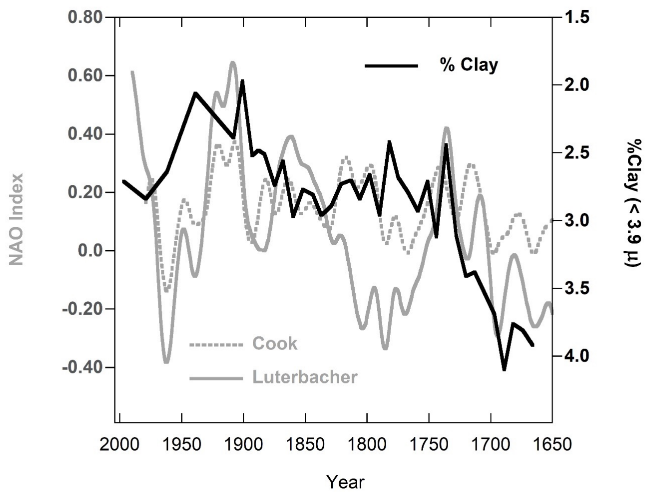

Figure 6. Comparison of the record of %clay at Fourth Lake (black line) with the NAO indices (gray lines) of (A) Luterbacher and others (1999) and (B) Cook and others (1998). The record of NAO index by Luterbacher and others (1999) describes only the winter NAO signal; the NAO index of Cook and others (1998) encompasses the annual NAO signal. The relationship between the variables is generally of an inverse nature, whereby % clay at Fourth Lake is low when the NAO index is positive. Intervals during which % clay at Fourth Lake displays lesser similarity include the late 1700's, near 1900, and in the mid-1900's. Each are times of high sunspot activity (WDC-STP, 2006).

low precipitation during positive short-term NAO phases (Enfield et al., 2001; Cook et al 2005). No proxy temperature record is available from Fourth Lake, but the similarity of its record of % fines with Lake of the Clouds inferred climate suggests Fourth Lake in the Adirondacks experiences warm, dry climate during positive NAO phases and cool, wet climate during negative NAO phases. A similar relationship is observed between the NAO index and temperatures of Europe and eastern North America (Deser et al., 2017; Chartrand and Pausata, 2020).

Longer-Term Multidecadal-to-Centennial Variability

Duration of the NAO varies substantially, and the ocean responds notably to the longer, multidecadal swings of the NAO (Schlesinger and Ramankutty, 1994). These longer-scale oceanic events known as the Atlantic Multidecadal Oscillation (AMO) involve substantially enhanced northward flow of warm equatorial waters into the high-latitude North Atlantic and have been reported to recur at intervals ranging from ~50-90 years (Schlesinger and Ramankutty, 1994; Kerr, 2000; O'Sullivan et al., 2002). As with the NAO, during AMO positive phases much of North America experiences warm, dry climate and during AMO negative phases much of North America experiences cold, wet climate (Enfield et al., 2001; McCabe et al., 2004; Cook et al 2005). Figure 8 shows a comparison of the relative percent of coarse (>63 and log percent > 250µ) sediment within Fourth Lake and the AMO index (Gray et al., 2004). Many, but not all, multidecadal maxima in coarse sediment coincide with maxima in AMO index (Figure 7). As suggested previously,

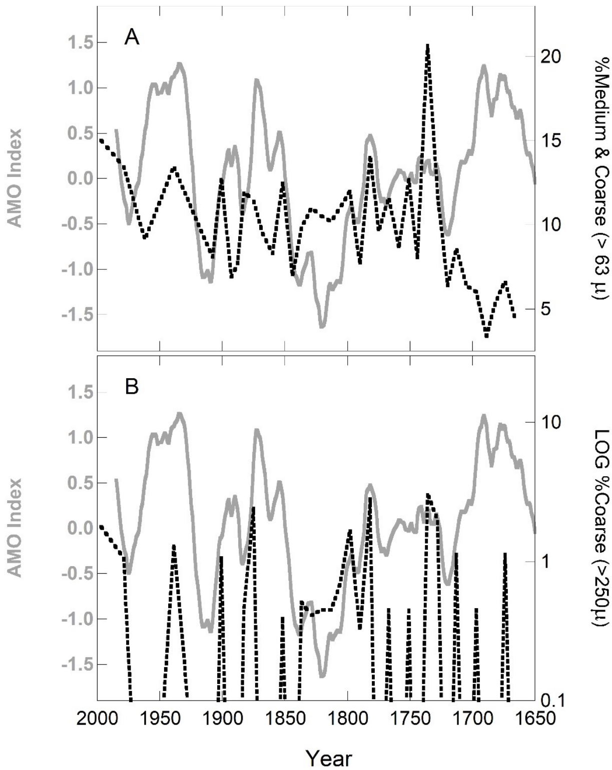

Figure 7. Comparison of the (A) percent >63 μ size (medium and coarse sediment) fraction and (B) log percent >250 μ size (coarse) fraction at Fourth Lake with the AMO index of Gray and others (2004) reveals that peaks in coarse-grained material in the lake sediments coincide with times of positive AMO values. If peaks in coarse sediments are due to enhanced erosion associated with increased wildfire frequency, this suggests that Fourth Lake warm, dry climate at times of positive AMO index.

association of coarse sediment influx with warm intervals is consistent with increased fire frequency. Unfortunately, although plausible, this remains speculative as the charcoal counts were conducted only back to 1810 and at lower resolution.

Irregular multidecadal-to-centennial variation is exhibited by carbonate in both Cores 2 and 1, including prominent peaks at ca. AD 1825 and AD 1925 (Figure 8). Fluctuations in %$CaCO_3$ within Cores 1 and 2 display an inverse relationship with inferred temperatures at Lake of the Clouds. A similar relationship is seen between %$CaCO_3$ and the AMO. Within chronological uncertainties, the two prominent maxima in %$CaCO_3$ in Core 1 collected from Fourth Lake begin within the strongest negative AMO phases of the past 340 years. These carbonate maxima are also associated with lows in sunspot number (WDC-STP, 2006). Both negative AMO values and low sunspot activity are suggestive of climatic cooling.

In other New York lakes, such as Ontario and Cayuga, high calcite precipitation occurs at times of high temperature (Schelske and Hodell, 1991; Mullins, 1998). Higher temperatures cause onset of thermal

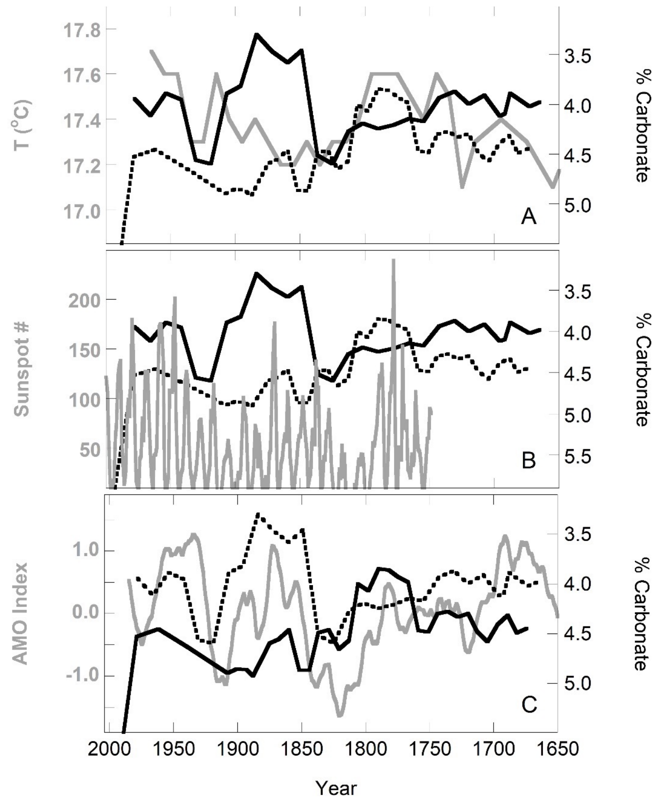

Figure 8. Comparison of %$CaCO_3$ at Fourth Lake (black lines; Core 1 solid, Core 2 dashed) with (A) inferred summer temperature at Lake of the Clouds (gray line), (B) May sunspot numbers (gray line; WDC-STP, 2006), and (C) the AMO Index (gray line; Gray et al., 2004). A notable mismatch is observed between inferred Lake of the Clouds summer temperature and Fourth Lake %$CaCO_3$ in the late 19th and into the early 20th century, suggesting the climate of the two geographically remote lakes differed at this time. This interval of low %$CaCO_3$ at Fourth Lake, however, does coincide with high sunspot number and displays striking similarity with the AMO at this time. This suggests that the climate at Fourth Lake during this interval was influenced by the AMO and to a lesser amount solar variability.

stratification earlier in the spring, lengthening primary production of picoplankton, and reduce calcite solubility (Hodell et al., 1998). The apparent association of high %$CaCO_3$ in Fourth Lake with cool conditions is therefore contrary to patterns observed in other New York State lakes. It is possible that biologically-mediated calcite precipitation was triggered by increased nutrient influx to the lake caused by wet conditions accompanying the cooling in the region of Fourth Lake. Comparison of Fourth Lake %$CaCO_3$ and inferred precipitation at Lake of the Clouds, with each on their independent chronologies, reveals a somewhat inconsistent relationship, with a notable mismatch in the late 19th century and into the early 20th century (Figure 9). However, it is possible that orographic effects may have contributed to differing precipitation patterns among such widely separated lakes. In contrast, the comparison of Fourth Lake %$CaCO_3$ and the AMO reveals good agreement in this

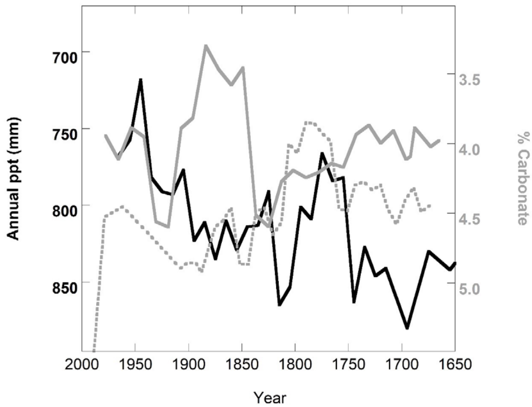

Figure 9. Comparison of $\%CaCO_3$ at Fourth Lake (gray lines) with inferred annual precipitation at Lake of the Clouds (black line; Gajewski, 1988) on their independent chronologies. As with the inferred summer temperature, comparison of Fourth Lake $\%CaCO_3$ and inferred precipitation at Lake of the Clouds reveals a somewhat inconsistent relationship, with a notable mismatch in the late 19th century and into the early 20th century (Figure 10). It is possible that orographic effects may have contributed to differing precipitation patterns among such widely separated lakes. The good agreement in this interval between the records of Fourth Lake $\%CaCO_3$ and the AMO suggests that at this time the AMO is a dominant control on carbonate precipitation through its impact on climate.

interval, suggesting that at that time the AMO is a dominant control on climate and carbonate precipitation.

The carbonate records of Cores 1 and 2 appear to differ somewhat, and the prominent peaks at ca. AD 1825 and AD 1925 are much less obvious in Core 2. Differences between the two cores may be a consequence of their differing collection sites. The Core 2 site is deeper and more centrally located whereas the Core 1 site is shallower and closer to shore. Thus, alternative explanations of the differing prominence of these carbonate maxima within the two cores potentially include slumping, sediment focusing, or differential dissolution.

In summary, Fourth Lake appears to have experienced cool, wet climate during negative AMO phases associated with the carbonate peaks—a response to the AMO at this time like much of North America. Their association with low sunspot number, and thus lows in solar irradiance, provides evidence that the response of the Adirondack region to potential AMO forcing, like NAO forcing, may be dependent to some extent upon solar activity (Gimeno et al., 2003).

The Longer-Term Trend

As detailed in Kanfoush (2013), a longer-term up-core trend is also seen between grain size and climatic variables that spans the length of the record. From the Maunder Minimum in sunspot activity in the late 17th and into the early 18th century, a time of low inferred temperature at Lake of the Clouds and globally, inferred precipitation at Lake of the Clouds decreases notably from the highest values seen within the record (Lean, 2000; Shindell et al., 2001). Across the length of the 340-year record from Fourth Lake, % fines and % organic carbon similarly decrease from the time of the Maunder Minimum solar irradiance low. It is likely that a trend toward warmer, drier conditions reduced surface runoff and attendant delivery of both fine terrigenous material and nutrients to the lake, decreasing primary production and thus organic carbon content. Thus, intervals of sunspot variability and associated solar irradiance should also be considered in reconstructions of past climate.

Conclusions

Over the past 340 years, the Fourth Lake record of % fines shows variations on multidecadal timescales superimposed upon a longer-term up-core trend toward lower % fine sediment. Even on their independent chronologies, the record bears a strong resemblance to records of annual precipitation and summer temperature inferred from pollen in Lake of the Clouds, Michigan (Gajewski, 1988). Both the up-core trend toward lower % fines and the shorter-term fluctuations coincide with reduced precipitation and higher summer temperatures. The estimated maximum duration of the short-term variations (~21-yr) makes the NAO a candidate. Although the records differ over long (centennial) timeframes many, but not all, shorter-term (decadal-to-multidecadal) maxima in %fine sediments at Fourth Lake coincide with positive values of the NAO index. Many, but not all, minima in % > 63µ sediment and maxima in log % >250µ sediment also coincide with maxima in AMO index. Irregular multidecadal-to-centennial variation is exhibited by % carbonate which displays two notable maxima centered at ca. AD 1825 and AD 1925. The long-term trend and centennial variations parallel solar variability and the AMO. Fluctuations in intensity of zonal and meridonal winds that accompany the NAO and AMO could explain the similarity between the inferred climate records from geographically remote lakes.

Evidence suggests the Lake of the Clouds in Michigan and Fourth Lake in the Adirondack Mountains, New York, experience warm, dry climate during positive NAO phases and cold, wet climate during negative NAO phases. With regard to both climatic variables, this is consistent with the pattern of multidecadal climate experienced by much of eastern North America and Europe in response to the NAO (Enfield et al., 2001; Cook et al 2005). Both lakes also appear to experience warm, dry climate during positive AMO phases and cold, wet climate during negative AMO phases—again consistent with much of North America.

At some times the NAO and AMO signals appear to be influencing temperature and precipitation of the two lakes. At other times, such as during the Maunder Minimum, solar irradiance appears to be a significant influence on the lakes. This supports recent studies that have shown that on centennial timescales NAO and AMO are negatively correlated to solar activity (Kirov and Georgieva, 2002; Gimeno et al., 2003). Interestingly, the Fourth Lake record is not always in agreement with other Adirondack lakes. This points to potential confounding effects of more localized climatic or land-use influences.

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