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Patterns of coherent dynamics within and between lake districts at local to intercontinental scales

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Spatial patterns of coherent inter-annual dynamics between lakes occur within and between lake districts at regional, continental, and even intercontinental scales. Climatic variability and change are external drivers of lake dynamics but individual lake ecosystems differentially filter these signals and alter their expression. When related to landscape position spatial patterns in coherence can be uniform, unstructured, or structured. A structured pattern emerges for chemical responses to drought in a lake district dominated by groundwater while a more uniform pattern emerges in a stream-flow dominated lake district. Near-surface water temperatures and ice dates have a uniform pattern within and even between some lake districts; near-bottom water temperatures have an unstructured pattern; water levels have a complex pattern. Coherence in ice dates declines with latitudinal distance between lakes, but some coherence persists even at intercontinental scales that appears related to long-term climate change and common large-scale climate drivers.

Introduction

The long-term dynamics of lakes in the landscape provides an appropriate set of temporal and spatial scales to study climate change for lake ecosystems. Traditionally, limnologists have focused on understanding and predicting the status of a lake and on understanding the in-lake or catchment processes determining that status, or we have conducted broad surveys of many lakes in single years or at best for a few years to learn from inter-lake comparisons. Being able to treat time (long-term inter-annual dynamics) and space (multiple lakes of different character across a landscape) simultaneously provides a worthwhile challenge in our field. The challenges are both practical, in terms of obtaining resources for research, and they are scientific, in terms of developing concepts for spatial scales larger than a lake and its catchment. The value of a long-term landscape approach to understanding the interaction between lakes and climate change and variability comes from the realizations that not all lakes respond to climate change and variability differentially, and that we are just beginning to learn what determines whether lakes have similar or dissimilar dynamics. Climate change and variability have a broad footprint spatially and generally are best understood by taking long-term approaches. Without a broad, long-term view we will be constrained by approaches that place us, to use a metaphor, in the "Invisible Present" (Magnuson 1990) and the "Invisible Place" (Swanson and Sparks 1990). We will be blind to the dynamics and spatial setting that are so important to understanding.

Several quotes from North American thinkers from the 1800s, while not unique, make the point: "Time is but the stream I go a-fishing in." (Thoreau 1854). "The field cannot be well seen from within the field." (Ralph Waldo Emerson 1841, *Essay X — Circles*, from *Essays: First Series*). "A fundamental characteristic of complex human systems: 'cause' and 'effect' are not close in time and space." The problem is that "most of us assume, most of the time, that cause and effect are close in time and space." (Senge 1990). Quotes from Senge can be readily transferred from complex human systems to complex ecological systems.

For us at the Center for Limnology at the University of Wisconsin-Madison, the practical opportunity to conduct limnological studies at longer temporal and broader spatial scales has been provided by the Long-term Ecological Research (LTER) Program of the US National Science Foundation (Callahan 1984, Franklin *et al*. 1990, Hobbie *et al*. 2003). Our site, the North Temperate Lakes LTER, NTL-LTER, (http://lter.limnology.wisc.edu/) began in 1980 and is presently funded in six-year grants through 2006.

We began with seven lakes in a forested lake district surrounding Trout Lake in northern Wisconsin. In 1994, we added four more lakes in an urban and agricultural lake district in southern Wisconsin in the Madison vicinity. In each location, the lakes lie in the same hydrological flow system except for one lake in the southern set. The flow systems are dominated by groundwater in northern Wisconsin and stream flow in southern Wisconsin. This difference in hydrological connectivity would be expected to influence some aspects of coherent dynamics between lakes.

Our purpose here is to present ideas and results relevant to climate change and variability from a lake ecology perspective. Our focus is on the coherent inter-annual dynamics of lakes from a lake district to an intercontinental scale.

Coherent inter-annual dynamics

From the start of our program in 1980, we were interested in describing and understanding inter-annual dynamics in lake districts. During the first few years, of course, we had only a few years of data; statistical approaches for analyzing time series were not appropriate for the short length of the record. We chose to approach the emerging time series in two ways. First, we began to analyze the coherence or synchrony between lake pairs using correlation coefficients (r) or shared variance (r^2) with only seven years of data (Magnuson *et al*. 1990) and soon after with 13 years of data (Kratz *et al*. 1998). The second approach was to analyze inter-annual variance in variables at our site and at other LTER sites (Kratz *et al*. 1991, Magnuson *et al*. 1991, Kratz *et al*. 1995).

Here we will review and expand on the analyses of coherence. To quantify the magnitude of inter-annual coherence between two lakes, we first calculated annual values (often by averaging) for the variable of interest for each lake. Then we calculated the correlation coefficient for the time series of annual values between the two lakes. We use the square of the correlation coefficient r^2 to express the amount of shared variance between the two lakes.

The average coherence between northern Wisconsin LTER lakes, even between adjacent lakes, was very low when physical, chemical, and biological variables were considered together. The overall coherence averaged only $r^2 = 0.10$ among all pairings of the seven lakes for 15 variables over seven years (Magnuson *et al*. 1990) and $r^2 = 0.07$ for 61 variables over 13 years (Kratz *et al*. 1998). More than 90% of the inter-annual variation was lake-specific, suggesting that the lakes behaved largely independently of each other.

One explanation of the low overall coherence could derive from the complexity of lake ecosystems in their response to external drivers. We conceptualized external drivers, here exemplified by climatic drivers, as signals imparting their dynamics to the lake (Fig. 1). The lake then is a receptor, but one that has several levels of filters, that could impart a more unique

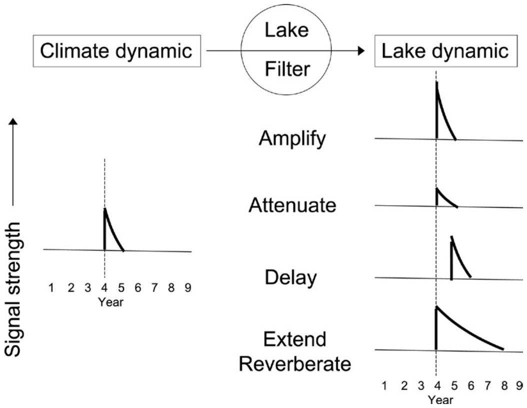

Fig. 1. Diagram of a climate signal and the lake filters that could modify the strength and timing of the lake response to that climate signal. Here we show a pulse or event type of signal; more gradual or oscillatory signals could also be envisioned in the same way. With multiple signals of various forms, interference and other interactions could further complicate the response leading to low coherence of lake responses.

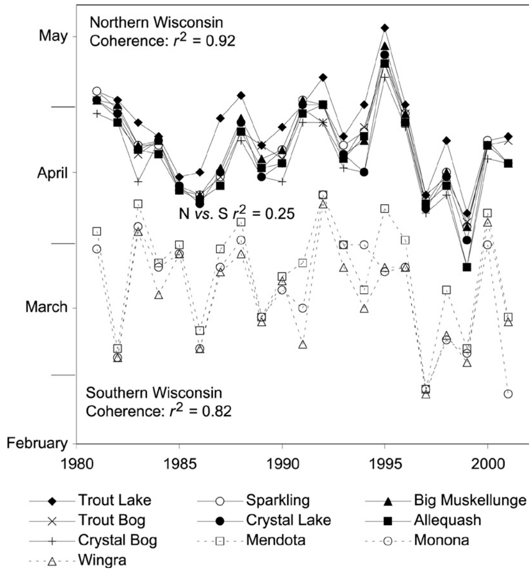

Fig. 2. Coherence in ice-off time series for the LTER lakes from 1981–2001, excluding Fish Lake. The average coherences are measured as r^2 between pairs of northern LTER lakes, pairs of southern LTER lakes, and pairs of southern and northern LTER lakes.

dynamic to the lake properties. The influence of these filters would be expected to vary among lakes depending on the morphometry, chemistry, hydrology, and biology of the individual lake ecosystems. The filters associated with these lake properties could amplify, attenuate, delay, and extend the realization of the climate signal in the lake. For example, a strong storm event would impart greater mixing to a lake with a large fetch than to a lake with a small fetch; the large lake might amplify the signal while the small lake would certainly attenuate the storm signal. For another example, if a warm summer resulted in the formation of a strong year class of a particular piscivorous fish found only in some of the lakes, that long-lived species would impart its predation rates on food web structure in some of the lakes over a number of years. The effect of this year class would be expected to be greatest several years after the warm summer. This example depicts a signal having a delayed and an extended influence on the lake ecosystem. Clearly, these complexities would reduce a coherent response between lakes even if the lake dynamics were driven by an external climatic signal.

Secondly, low coherence does not characterize all lake variables; generally, physical variables have higher coherences (median $r = 0.45$), chemical variables intermediate coherences (median $r = 0.2$), and biological variables have lower coherences (median coherence $r = 0.1$) (Kratz *et al.* 1998). For example, ice-out date, a lake variable that is strongly influenced by climatic drivers, has extremely high coherence both in the northern and the southern LTER lakes (for a lake pair, $r^2 > 0.30$ is statistically significant at the 0.01 level) (Fig. 2). However, even physical variables in the northern Wisconsin LTER lakes differ greatly in their inter-annual coherence, ranging from a median $r^2 = 0.92$ for ice-off dates to $r^2 = 0.07$ for near-bottom water temperatures in summer (Fig. 3). At one extreme (ice-off date), climatic variability dominates the processes that result in ice breakup and these processes affect each lake rather equally. At the other extreme (bottom temperatures in summer), climatic drivers are filtered by the individual morphometry of each lake such as differences in fetch and depth, and the influence these have on vertical mixing and heat budgets.

Low coherence can occur because short records do not incorporate as large a range of inter-annual variability in climatic drivers

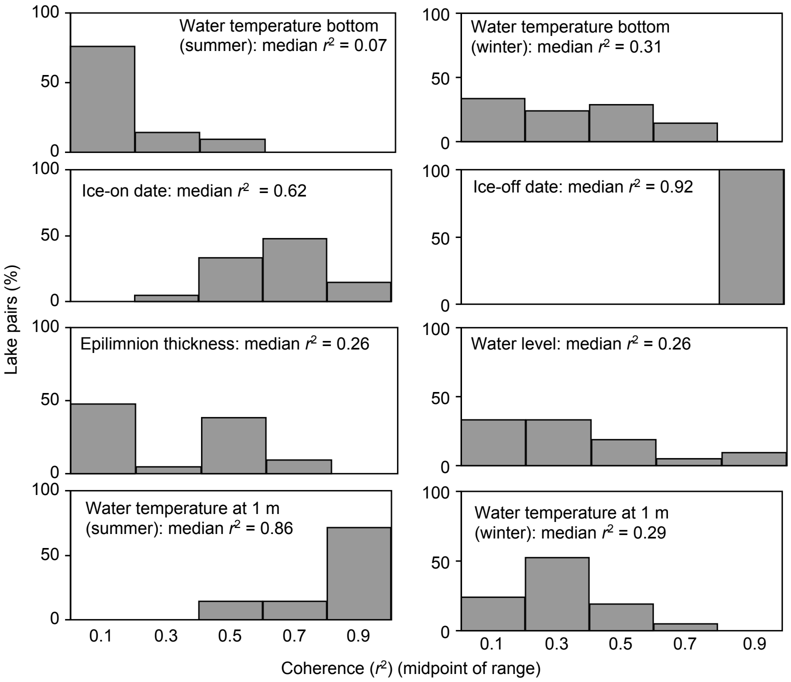

Fig. 3. Frequency distributions of the 21 coherence values between pairs of LTER lakes in northern Wisconsin for eight physical lake variables from 1981 to 2001.

as do longer records. For a 22-year record, coherences increased as the length of the record increased from three years to 19 years (Fig. 4). The increase in coherence with the length of the record occurred with a highly coherent, climate-driven variable, ice-off date, and with a variable less closely determined by climatic variability, acid neutralizing capacity (ANC). In the case of coherence in ANC between Sparkling and Trout Lakes, the increase in r^2 was dramatic, presumably because the two lakes responded similarly to the two- to three-year drought that occurred in the late 1980s. This drought would not have left its mark in the earlier analyses by Magnuson *et al.* (1990).

Structure of coherence within a lake district

A concept we developed, about the organization of lake districts and somewhat analogous to the concept of the stream continuum (Vannote *et al.* 1980), is "the position of a lake in the landscape" (Kratz *et al.* 1997, Magnuson and Kratz 2000, Riera *et al.* 2000, Kratz *et al.* 2005). We defined a lake's position in the landscape as its position in the hydrologic flow system in a manner analogous to stream order, except we used both positive and negative orders starting from a lake with no inlet but with an outlet as order zero (Magnuson and Kratz 2000, Riera *et al.* 2000). Positive numbers were assigned progressively going downstream from this zero-order lake based on the stream order of the outlet stream; negative numbers were assigned progressively for lakes higher in the groundwater flow system from this zero order lake.

Do lakes at similar positions in the landscape have more similar inter-annual dynamics? The coherence or lack of coherence in chemical concentrations between lakes was related to the hydrologic conductivity between lakes (Webster *et al.* 2000, Magnuson *et al.* 2005). In the northern Wisconsin lakes the pattern of coherence differed between lowland and highland lakes. The upland lakes behaved incoherently, and the lowland lakes behaved coherently. This result suggests that the upland lakes behave independently because hydrological connections are weak, while the lowland lakes are more strongly connected hydrologically. In contrast, the southern Wisconsin lakes behaved coherently (Webster *et al.* 2000). For water chemistry,

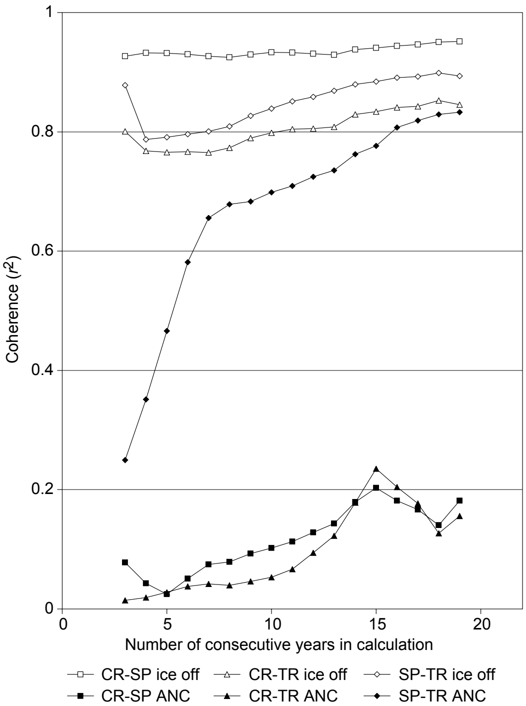

Fig. 4. Sensitivity of coherence estimates (r^2) to the number of years of observation for ice-off date and acid neutralizing capacity (ANC) of the water for pairings of Crystal (CR), Sparkling (SP), and Trout (TR) Lakes. All consecutive sets of years from three to 19 years were used. The number of values averaged ranged from 17 for 3-year sets to two for 18-year sets; the 19-year set had one value.

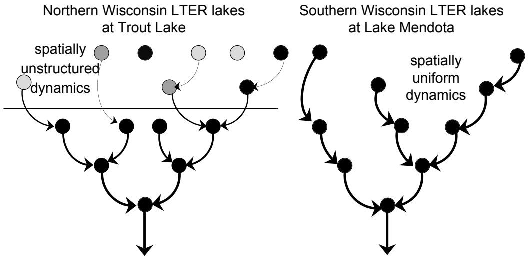

Fig. 5. Diagram of spatial structure of coherent inter-annual dynamics between lakes in the same hydrological flow systems. The same shading indicates subsets of lakes that exhibit coherent inter-annual dynamics. The occurrence of these patterns for different lake variables is in Table 1 for the northern Wisconsin LTER lakes. This figure is based on fig. 1 in Webster *et al.* (2000).

coherent behaviors are the expected consequence from precipitation-driven runoff in a surface-water dominated system such as the Madison lakes. The strength of the hydrological connection between lakes also appears to influence the coherence patterns of the late-winter dynamics of Finnish lakes either connected or not connected by streams (Järvinen *et al.* 2002). Thermal and chemical dynamics for March and April were more coherent for lakes in a chain than for other lakes.

Observed patterns in coherence among lakes can be classified as spatially uniform, spatially unstructured, and spatially structured (Webster *et al.* 2000). For the spatially uniform category, coherent dynamics occur across the entire flow system from high to low in the landscape; for the spatially unstructured category coherence differs independently of position in the landscape or all coherence values are low; for the spatially structured category, lakes occupying similar positions in the hydrologic system were coherent and lakes at different positions in the landscape were not (Fig. 5). The chemical variables discussed above (Webster *et al.* 2000) fit in both the structured and unstructured categories with lowland lakes being coherent but upland lakes being unstructured.

Even in the same lake district, different limnological variables fit into different categories (Table 1). In northern Wisconsin, the uniform pattern of inter-annual dynamics characterized the entire set of LTER lakes for date of ice on and ice off and for surface water temperatures. For these physical variables, the lakes were responding in the same way to climate variability regardless of position in the landscape. The unstructured pattern of inter-annual dynamics characterized bottom water temperature; none of the lake pairs exhibited high coherence. Inter-annual dynamics of lake levels also were unstructured at the scale of upland versus lowland lakes, but more complex structure was apparent. Average coherence between all lake pairs was moderate, $r^2 = 0.30$, but ranged from $r^2 = 0.04$ to $r^2 = 0.94$. Eight of the lake pairings had relatively low coherence and 11 pairings had relatively high coherence. For lake levels, the differences between individual lake pairs do make sense with closer examination (Magnuson *et al.* 2005). Although both low and high coherence values occurred in comparisons of lakes at similar and different positions in the landscape, the three lakes with greatest coherence all were of lake order –1. This result suggests that landscape position can be important in influencing coherence of water level between lake-pairs.

The differences in status (average condition) of the lakes in relation to landscape position (Riera *et al*. 2000) were more consistent among lakes than were their patterns of inter-annual dynamics. The status patterns are clear even though a great deal of variability in the limnological properties existed among lakes of a similar order. In northern Wisconsin, lake area and shape varied from smaller and rounder lakes high in the landscape, to larger and more complex shaped lakes lower in the landscape. The lakes highest in the landscape tended to be more brown colored than those lower in the landscape. Chemical concentrations (conductivity, pH, calcium, acid neutralizing capacity, chloride, Kjeldahl nitrogen, and silica) were less for lakes high in the landscape and greater for lakes lower in the landscape. Chlorophyll, crayfish abundance, and fish species richness were greater for lakes lower in the landscape. Even human settlement was related to lake order with upland lakes having fewer cottages and resorts per unit shoreline than did lowland lakes. These differences in status associated with lake order appear to be largely, but not entirely, consistent for a number of lake districts (Soranno *et al*. 1999, Quinlan *et al*. 2003).

As we have stated before (Magnuson and Kratz 2000, Riera *et al*. 2000, Kratz *et al*. 2005), landscape position is a geomorphic legacy from continental glaciation; it is the spatial context over which the operation of hydrologic, geochemical, and biological processes play out their influences. The strength and dynamics of these processes clearly differ across the gradients of landscape position and influence the patterns of both coherence and status.

Coherence among lake districts

Climate and inter-annual climatic variability have a large spatial footprint in terms of their influence on lakes (Benson *et al*. 2000a, Magnuson *et al*. 2005). Near-surface summer water temperatures had strong coherence between pairs of lakes from different lake districts among four lake districts in the Western Great Lakes region (Wisconsin–northern and southern LTER lakes, and Ontario–Experimental Lakes Area and the Dorset Lakes). Mean coherences between lake districts ranged from $r = 0.75$ to 0.84 (Benson *et al*. 2000a). Not surprisingly, the coherence between lake districts was usually less than the coherence within a lake district where means ranged from $r = 0.86$ to 0.92.

To examine the spatial extent of coherence between lake districts at greater distances we computed coherence between pairs of seven lakes around the northern hemisphere. A criterion for lake and variable choice was that a long time series existed. Coherence in ice-on and ice-off dates between the 28 lake pairings was calculated over a 45-year period from 1951 to 1995 and over a 151-year period from 1855 to

Table 1. Structure of inter-annual variability in the seven northern Wisconsin lakes based on definitions of spatially structured, inter-annual variability in Webster *et al.* (2000). The lakes used by Webster *et al.* (2000) included some of the LTER lakes as well as other nearby upland lakes; upland and lowland were determined by differences in conductivity (ion concentration); none of the lakes were dystrophic bog lakes. The lakes on which we present information in this paper were the LTER lakes that ranged in lake order from –3 to +2 and included several dystrophic bog lakes, several clear water seepage lakes, and several drainage lakes.

Variables	Overall	High in landscape	Low in landscape	Source
Water chemistry	Mixed	Unstructured	Structured	Webster *et al.* (2000)
Water level	Unstructured			LTER database 1981–2001
Ice-on date	Uniform			LTER database 1981–2001
Ice-off date	Uniform			LTER database 1981–2001
Surface (1 m) temperature	Uniform			LTER database 1981–2001
Bottom (1 m) temperature	Unstructured			LTER database 1981–2001

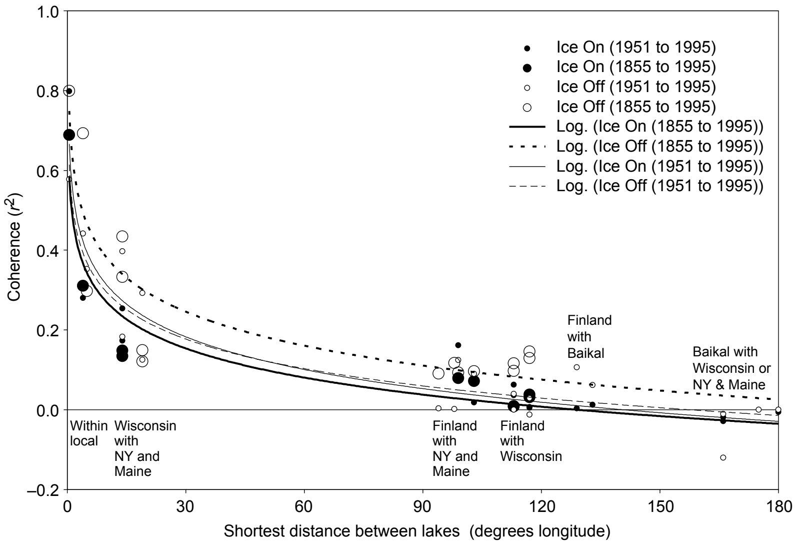

Fig. 6. Inter-annual coherence between lakes in ice-on and ice-off dates in relation to the longitudinal distance between lakes around the northern hemisphere. Values of r^2 are plotted as negative if they were calculated from a negative correlation coefficient. For the longer time series an $r^2 > 0.02$ is significant at $p \leq 0.05$ in a two-tailed test. For the shorter time series an r^2 of 0.08 is significant at $p \leq 0.05$. Lines relating coherence to latitudinal distance between lakes were fit using the log of the coherences (r^2). The lakes are Lakes Mendota and Monona in Wisconsin, Lake Otsego in New York and Moosehead Lake in Maine, lakes Kallevesi and Näsijärvi in Finland, and Lake Baikal in Russia.

1995; for the long series Baikal had a 128-year period from 1868 to 1995 owing to the length of the record. Ice-on data were not available for Moosehead Lake.

The coherence was greatest between pairs of lakes within a location and declined with increasing distance between the lakes (Fig. 6). For a given distance between lakes, the coherence of ice-off dates for the longer time series was more coherent than for the ice-on dates and for the shorter series of ice-off dates. For this longer series, coherences between Wisconsin and New York and Maine averaged $r^2 = 0.26$; thus, about 25 percent of the variability was shared over distances of 1200 to 1600 km. The coherence persisted, but at lower levels, between North America and Europe. Coherence between Finland versus Wisconsin or New York and Maine averaged $r^2 = 0.11$; about 10 percent of the variability was shared even over distances of 6000 to 7000 km.

This common variance over such continental and intercontinental scales suggests that common drivers control part of the inter-annual variability even at great distances between sites. The major components of inter-annual dynamics would be coherent dynamics from long-term trends of climate change, coherent dynamics from common large-scale climatic drivers, and incoherent dynamics from more local considerations such as differences in lake filters, landscape position, alternate large-scale climatic drivers, and stochastic variability. We assumed that, for the same type of lake district, the importance of local filters would remain the same regardless of distance between lake districts. We hypothesized that for the strength of between lake coherences the influence of long-term global trends and local filters would not change with increasing distances, but that the influence of common large-scale drivers would decrease because these drivers have a spatial footprint at regional, not global scales (Fig. 7).

Ice-date time series around the northern hemisphere have trends towards later ice on and earlier ice off in the longer time series (Magnuson *et al.* 2000). The coherences owing to the long-term trends were similar at these different scales; $r^2 = 0.03$ for local comparisons, $r^2 = 0.06$ for Wisconsin versus New York and Maine, and

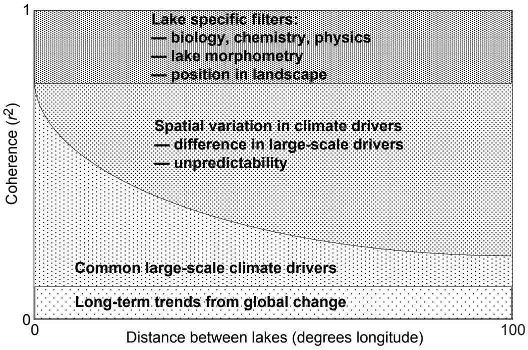

Fig. 7. Diagram of the contributions of lake filters, different large-scale climate drivers, common large-scale drivers, and long-term global trends to coherence between lakes separated by different distances around the northern hemisphere.

$r^2 = 0.06$ for comparisons between Wisconsin or New York and Maine with Finland.

To evaluate the changing influence of large scale drivers with distance, we removed the linear trends and, excluding Lake Baikal, we redid the coherence analysis using the residuals for ice dates. Indeed while the coherence owing to long-term trends was relatively invariant with distance, that owing to large-scale drivers declined. The detrended coherences declined dramatically from $r^2 = 0.56$ at the local level, to $r^2 = 0.20$ between Wisconsin versus New York and Maine, and to $r^2 = 0.05$ for comparisons between North America and Finland. Thus, the relative importance of long-term trends to coherence increases with distance between lakes while the relative importance of large-scale climatic drivers decreases with distance between lakes. In other words, the importance of incoherent dynamics owing to the influence of different large-scale climatic drivers increases with distance.

Common large-scale climatic drivers seem a likely explanation for the coherence in detrended inter-annual variability. Statistical relations between ice dates and large-scale drivers have been documented (Livingstone 1999, 2000, Benson *et al.* 2000b, Robertson *et al.* 2000, Magnuson 2002, Todd and Mackay 2003). An examination of the common variance between ice dates and large-scale climatic drivers such as the North Atlantic Oscillation (NAO), the Southern Ocean Index (SOI), the North Pacific Index (NP) and the Pacific Decadal Oscillation (PDO) provides additional evidence for the role of large-scale climatic drivers to coherent lake dynamics over large regions (Fig. 8). For the analyses we used the October through December index with ice-on dates and January through March index with the ice-off dates. Ice-on and ice-off dates were associated with NAO around the northern hemisphere based on these seven lakes with long-term ice dates.

Except for the relation between ice-off dates and SOI in the Wisconsin lakes over the shorter series (*see* also Robertson 1989, Anderson *et al.* 1996, Livingstone 2000, Robertson *et al.* 2000), the relation of ice dates to NAO is stronger than with any other driver both for the shorter and the longer time series. Some of these relationships, especially from the two Finnish lakes, are quite strong (Fig. 8, bottom left).

Coherence in the ice dates between distant lakes can be strong at the continental scale and even can persist to the intercontinental scale for some comparisons. The relation fades more rapidly with distance for ice-on dates than for ice-off dates; this result may be related to the fact that ice-on dates are less coherent than ice-off dates (Fig. 3). Lake Baikal had no apparent coherence with the Finnish or North American lakes even though all the lakes appeared to be related to the NAO index and have had long-term trends in ice dates.

Conclusion

A rich set of spatial processes, gradients, and drivers at scales from individual lakes, to lake districts, to regions, and to the globe determine long-term and inter-annual dynamics of lakes. Understanding temporal coherence of lakes at multiple spatial scales can provide important insights into these factors influencing dynamics of lakes. Coherence among lakes tends to be high when external drivers strongly influence the variable of interest and act over a spatial scale encompassing the locations of the lakes being analyzed. Complex spatial patterns of coherence arise as influenced by various filters that alter the strength and timing of an external driver, a lake's landscape position, its lake-district's hydrologic setting, and the influence of large-scale regional

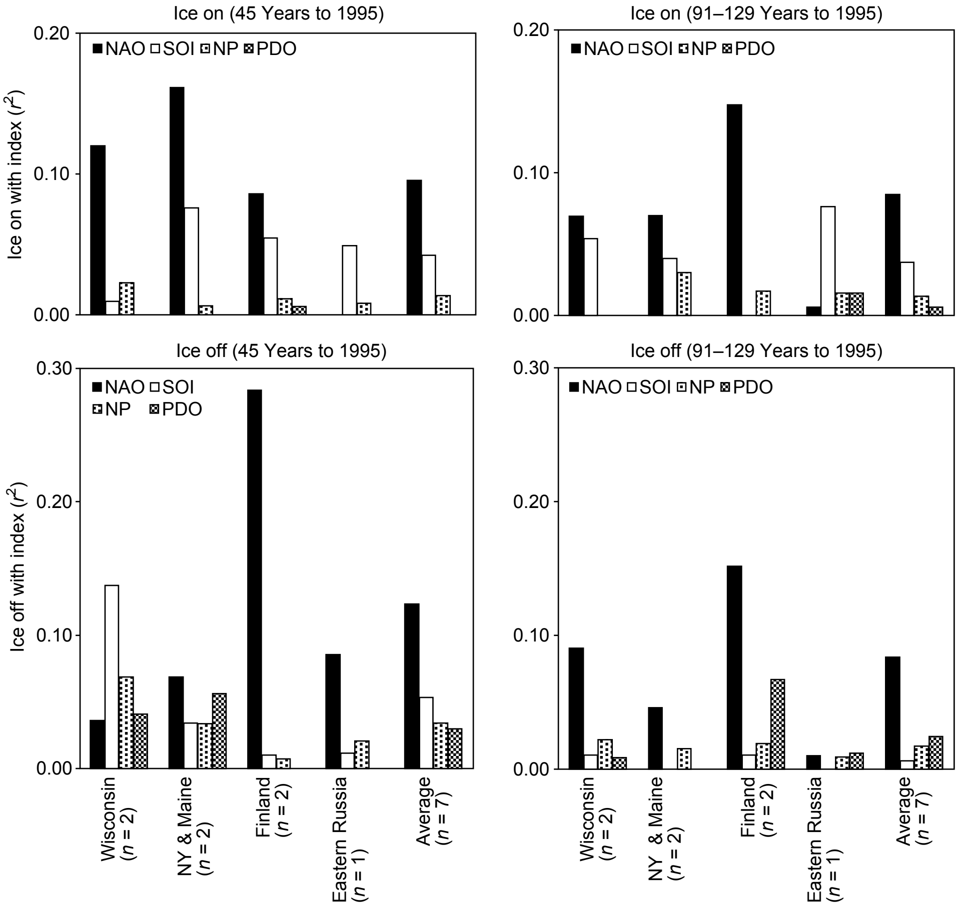

Fig. 8. Relation between ice-on and ice-off dates and large-scale regional climatic drivers, that is, the North Atlantic Oscillation (NAO), the Southern Ocean Index (SOI), the North Pacific Index (NP), and the Pacific Decadal Oscillation (PDO). The number of lakes for New York and Maine is 2 for ice-off dates and 1 for ice-on dates. The r^2 values represent the strength of the relationship, not the direction of the relationship. The direction differs among indices, locations, and ice response. For example, in Finland NAO is positively related to ice-on date, but negatively related to ice-off date. The relations of the ice date time series to large scale climate drivers are statistically significant with two-tailed tests with $r^2 > 0.08$ at $p = 0.05$ for $n = 45$ years and with $r^2 > 0.04$ or 0.03 for $n = 91$ or 129 years. The long time series begins in 1865 for the relation with NAO and SOI, and in 1899 for the PDO. In the average each lake is given equal weight. The time series for the indices used were at the following web sites: NAO at http://www.cgd.ucar.edu/~jhurrell/nao.html; SOI at http://www.cru.uea.ac.uk/ftpdata/soi.dat; NP at http://www.cgd.ucar.edu/~jhurrell/np.html and represents the strength of the Aleutian Low; and PDO at ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest.

climatic drivers such as the NAO or SOI. Having knowledge of the variables and drivers that lead to coherent and incoherent dynamics of lakes over various spatial scales will increase our ability to forecast lake responses to changes in external drivers such as climate or land use.

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