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Persistence of coherence of ice-off dates for inland lakes across the Laurentian Great Lakes region

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Introduction

Ice phenologies, dates of ice-on and ice-off on lakes and rivers, provide information on climate change and variability. These long-term records indicate that lakes and rivers are sensitive to climatic change and variability. A symposium on ice phenologies of lakes as a climate indicator was held at the 27th Congress of the International Association of Theoretical and Applied Limnology in Dublin and published in the Verhandlungen (MAGNUSON et al. 2000b). Ice records have been especially useful because they can be long, over 150 years in length, and occur broadly around the Northern Hemisphere. In some areas, such as Finland (KUUSISTO & ELO 2000), Sweden (WEYHENMEYER et al. 2004), and the Great Lakes region of North America (MAGNUSON et al. 2005a, b), lakes with records of moderate length are common enough so that spatial patterns in dynamics can be analyzed. In some cases, records are sufficient to examine global, or at least intercontinental, trends (MAGNUSON et al. 2000a) and dynamics (LIVINGSTONE 2000, MAGNUSON et al. 2004).

Our purpose here is to examine the spatial patterns of temporal coherence or synchrony in time series of ice-off dates between lakes in the Laurentian Great Lakes region. In particular, we (1) compare the coherence within and between four states and one province bordering the Great Lakes, (2) describe the persistence and decline of coherence between lakes with increasing latitudinal and longitudinal distances between them, and (3) suggest explanations for the observed pattern of coherence at multiple spatial scales. Coherence, as quantified here, is the shared variance between two time series. Discussions of coherent dynamics between lakes are reviewed in MAGNUSON & KRATZ (2000) and MAGNUSON et al. (2005b).

Key words: climatic variability, ice phenology, spatial statistics, time series, common variance

Data and analyses

The authors of this paper updated and aggregated time series of ice-off dates for a large number of lakes in the states of Minnesota, Wisconsin, Michigan, and New York, and the province of Ontario based largely on data from the Lake Ice Analysis Group (MAGNUSON 2000b). A subset of 83 lakes was chosen for analysis that had a record of at least 17 years for breakup in the springs of 1977 through 2002 (Fig. 1). The number of years per lake ranged from 17–26 and averaged 23. Records of this length appear to provide good estimates of coherence; coherences with shorter time series than 17 years in ice-off dates increase with the length of the time series (MAGNUSON et al. 2004). Any remaining bias owing to the short length of these series would tend to be a slight underestimation of coherence.

Coherence was calculated as r^2, that is, the proportion of shared variance between two time series of ice-off dates for a pair of lakes. Only a few of the coherence values were from a negative correlation coefficient and those were tiny in magnitude. We have not indicated which r^2 values came from negative correlation coefficients.

Distances between a lake pair in latitude and longitude were calculated as the absolute values of their differences in latitude and their differences in longitude. These differences were calculated for each lake pairing to produce 3,403 lake pairs, each with a latitude distance in decimal degrees and a longitude distance in decimal degrees, and a coherence value (r^2) expressed as a proportion.

To facilitate comparison of North-South and East-West patterns, distances in decimal degrees were converted to kilometers. This conversion was necessary, because a degree of longitude is shorter than a degree of latitude. The length of a degree of latitude was calculated using the conversion of a degree latitude = 111 km. The length of a degree of longitude was calculated using a conversion of a degree longitude = 78.5 km, based on the length of a degree of

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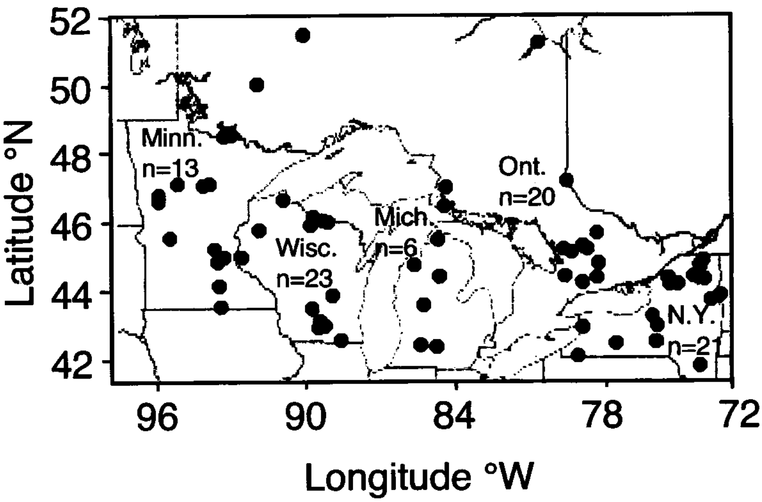

Fig. 1. Locations of the 83 lake sites across the Laurentian Great Lakes region used in the analyses of coherence in ice-off dates. Except for three bays or shorelines on the Great Lakes themselves, all sites were inland lakes.

longitude at 45°N latitude (the approximate central latitude of the lakes considered in this study). The converted distances are referred to as delta Northing (distance between pairs of points in the north-south direction) and delta Easting (distance between pairs of points in the east-west direction).

Although r^2 is an intuitive measure of coherence, r^2 values are not normally distributed. The FISHER (1915) transformation

$$z = 0.5 \cdot \ln\left(\frac{1+r}{1-r}\right)$$

of the correlation coefficient was used to convert r^2 to z, which is normally distributed. All statistical analyses in respect to latitude and longitude were conducted on z and back-transformed to r^2 for display. We did not test for statistical significance in any of our analyses because the values of r^2 are not statistically independent; each lake appears in 82 pairings.

Comparison within and between areas

The coherences within and between areas, that is Minnesota, Wisconsin, Michigan, New York, and Ontario, were highest within an area and decreased progressively with the distance between the areas; note that the one exception is Michigan, where Michigan compared with Wisconsin is only 0.01 r^2 units higher than for comparisons within Michigan (Table 1). Coherence of pairs of sites within areas averaged r^2 = 0.46 and ranged from r^2 = 0.39 to 0.55. Comparison of lake pairs from adjacent and more distant areas revealed a decline, but even the two most distant states, Minnesota and New York, had an average coherence of r^2 = 0.19. Some adjacent states had similar levels of coherence between each other as they had within their own boundaries, for example, Michigan x Wisconsin and Minnesota x Wisconsin. Ontario and Michigan had the lowest within-area coherence, r^2 = 0.39. For Ontario the lakes were more geographically dispersed than for each of the four states; most Ontario sites were in the southeast part of the province, but a few were in the far west or north. For Michigan, no explanation is apparent, but the sample size is low, with only six sites.

Within an area, the r^2 values of 0.39 to 0.55 suggest that at this scale much of the interannual variability in ice-out dates has a common driver. The driver of coherent dynamics is most certainly large-scale interannual climatic variability and climatic change. The between-area comparison suggests a decay in coherence, but with some coherence, r^2 = 0.19, persisting even between the most distant states of Minnesota and New York.

While a perhaps surprising proportion of the interannual dynamics in ice-off dates is coherent across the Laurentian Great Lakes region, an even larger proportion, $1-r^2$, is incoherent and represents independent interannual variability. Within areas, incoherent dynamics between lake pairs is similar or only slightly greater than the proportion of coherent dynamics. In the most distant comparison, Minnesota and New York, about 80 percent of the variability is incoherent, that is, independent of the dynamics in the other area.

Spatial persistence in coherence

Actual geographic distances between pairs of lakes provide a finer scale of analysis that might explain differences among the lakes in the temporal coherence of their ice-off dates. States and provinces, on

Table 1. Average coherence (r^2) within areas and between areas presented as a comparison from the vantage of each of the areas. Areas are arranged from west to east and a set of values is presented for each area. Averages between areas appear twice. Averages within areas (bold) appear only once. Arithmetic averages of untransformed coherence values are presented.

Coherence with Minnesota				
Minnesota	Wisconsin	Michigan	Ontario	New York
0.48	0.43	0.30	0.28	0.19
Coherence with Wisconsin				
Minnesota	Wisconsin	Michigan	Ontario	New York
0.43	**0.55**	0.40	0.28	0.22
Coherence with Michigan				
Minnesota	Wisconsin	Michigan	Ontario	New York
0.30	0.40	**0.39**	0.20	0.30
Coherence with Ontario				
Minnesota	Wisconsin	Michigan	Ontario	New York
0.28	0.28	0.20	**0.39**	0.29
Coherence with New York				
Minnesota	Wisconsin	Michigan	Ontario	New York
0.19	0.22	0.30	0.29	**0.49**

the other hand, are large enough areas to include significant climatic gradients from north to south and east to west. Each lake pair can be characterized by differences in latitude and longitude. Here we compare the magnitude of coherence in the ice-off dynamics with the differences in latitude and longitude between lake pairs expressed in kilometers.

Average coherence in ice-off dynamics declines with increasing distance in the north-south direction (Fig. 2 top) and east-west direction (Fig. 2 bottom). Declines in the Fisher transformed coherence (z) are approximately linear over the first 1000 km along both the delta Northing and delta Easting axes, with a greater rate of decline in the north-south axes (linear slope coefficient = –0.0022) than east-west direction (linear slope coefficient = –0.0009). Distance along the north-south axis also explains a greater proportion of the variation in coherence among lake pairs than does longitude distance, $r^2 = 0.43$ for the north-south model versus $r^2 = 0.26$ for the east-west model.

The most striking feature of the two graphs (Fig. 2) depicting the decline in coherence with distance between lake pairs would appear to be the high variability in coherence for any particular latitude or longitude distance. Some lakes that are close to each other in either latitude or longitude have coherence values just below $r^2 = 1.0$ while other lakes close in latitude or longitude have coherence values close to zero. As distance increases, the high coherence values are lost; low values persist across the entire range of distances. Because these graphs do not include both latitude and longitude simultaneously, two lakes close in either longitude or latitude could be up to 150 km distant in the other geographic dimension; this range may partially explain the wide variation in coherence at any given distance in delta Northing or delta Easting. However, both graphs also suggest that between-lake coherence in lake-ice temporal dynamics includes both large-scale climatic drivers and local influences.

Clearly the changes in coherence with latitude and longitude should be examined together (Fig. 3). The pattern of changes in mean coherence in both latitude and longitude in each of the three dimensional presentations reveals some of the same features as the single axes graphs. Coherence is greater for lakes that are close together and declines with between-lake distance in both latitude and longitude. As in Fig. 2, the decline in coherence is steeper and reaches a lower level for latitude distance (delta Northing) than for longitude distance (delta Easting). Even lakes 1500 km distant in longitude, have coherences averaging near $r^2 = 0.2$; this level of coherence persists along distance gradient in latitude to 700 km (Fig. 3 top, bottom). The graphs also make clear why two lakes with the same longitude distance could differ greatly in coherence owing to difference in latitude or vice versa for the same latitude, even when they are within 150 km in the other dimension. The graphs also make apparent that part of the explanation for only moderate coherence within a state or provincial area (Table 1) results because mean coherence changes rapidly with latitude and longitude over distances that occur within a single state or province.

The 97 lake pairs within about 30 km north and south and 20 km east and west of each other are high-

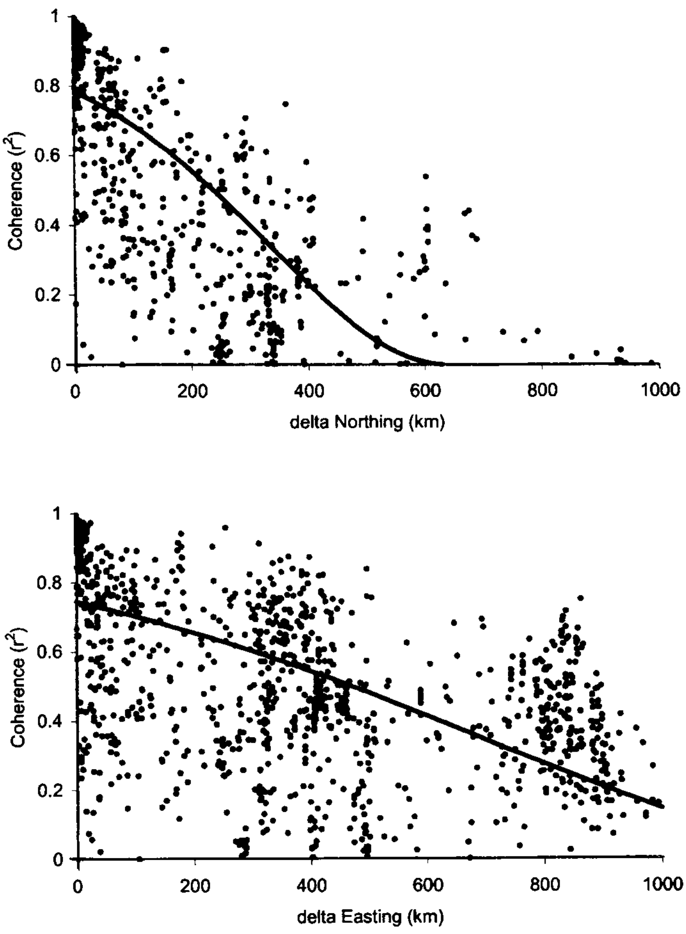

Fig. 2. Coherence (r^2) plotted against the distance (km) between pairs of lakes in the north-south direction (delta Northing) and in the east-west direction (delta Easting) in the Laurentian Great Lakes region from 1977 through 2002. Lake subsets used for each plot were selected to be within 150 km in the other distance dimension. The fitted lines are from the back-transformed linear model: $z = \beta_0 + \beta_1$ distance where z is the FISHER (1915) transformed correlation coefficient (r). Top: The least-squares parameter estimates are: $\beta_0 = 1.401$, $\beta_1 = -0.0022$ (delta Northing). The model r^2 value is 0.43. Not shown is that the line extends below the x axis. Bottom: The least-squares parameter estimates are: $\beta_0 = 1.305$, $\beta_1 = -0.0009$ (delta Easting). The model r^2 value is 0.26.

ly coherent, averaging $r^2 = 0.92$. The decline in coherence is most rapid in the first 100–200 km in latitude and the first 100–400 km in longitude (Fig. 3 top, bottom). By 500 km distances, coherences are 0.5 or less.

Variability in the residuals from the trend surface (Fig. 3 middle) was further analyzed using geostatistical techniques (CRESSIE 1993). Although these methods are typically applied to raw data such as ice-off dates for individual lakes, they can be applied to examine patterns in coherence. A variogram of the residuals (Fig. 3 bottom, insert) is strongly autocorrelated to a lag distance of approximately 45 km, indicating that pairs of residuals separated by less than 45 km in delta Easting and delta Northing space are correlated. Note that a pair of lakes with a similar lag distance as another pair of lakes may occur in different areas of the Great Lakes region, for example Wisconsin and New York. Nevertheless, the presence of strong spatial autocorrelation in the residuals suggests that spatial-temporal modeling tools may prove useful in future analysis of lake ice data.

Some small-scale variability that was smoothed over in the trend surface (Fig. 3 middle) is added back to the trend surface in the kriged surface of the model residuals (Fig. 3 bottom). The kriged surface corrects some of the oversimplifications of the trend surface. For example, the kriged surface does not drop below zero, but rather reflects the fact that coherence declines to relatively low, but positive, values as distance between pairs of lakes increases.

The pattern of variation in coherence with distances in latitude and longitude between lakes does not appear to be a smoothly declining surface from near to far as modeled in Fig. 3 middle. Instead hills and valleys are observed over latitude and longitude distances (Fig. 3 top, bottom). This hilly terrain may indicate other spatial patterns of large-scale climatic and small-scale local influences but could be a sampling artifact from the opportunistic rather than planned distribution of lake-ice sites (Fig. 1). The sites are clustered geographically, and large areas do not have sites. Regardless, the irregular pattern is interesting and raises unanswered questions.

General discussion

The rich spatial pattern of temporal coherence in ice-off dates across the Great Lakes region results from the interplay between the spatial patterns of various climatic drivers and landscape patterns at multiple spatial scales. Here we discuss (1) factors influencing the magnitude of coherence and (2) changes in coherence at increasing spatial scales. At the smallest spatial scale, what is the likely influence of lake specific filters of climate signals in lowering coherence? Over a few 100 km what might cause the rapid decline in coherence? Over the Great Lakes region (1000 km north-south and 1700 km east-west) what determines the greater persistence in coherence with delta Easting than with delta Northing? Across the areas denoted by Great Lakes states and Ontario what likely explains differences and similarities in coherence?

First we consider lake-specific filters at the smallest scales. Variability in ice-off dates may be largely independent of climatic filtering by lake-specific factors such as lake morphometry and trophic status (MAGNUSON et al. 2005 a, b).

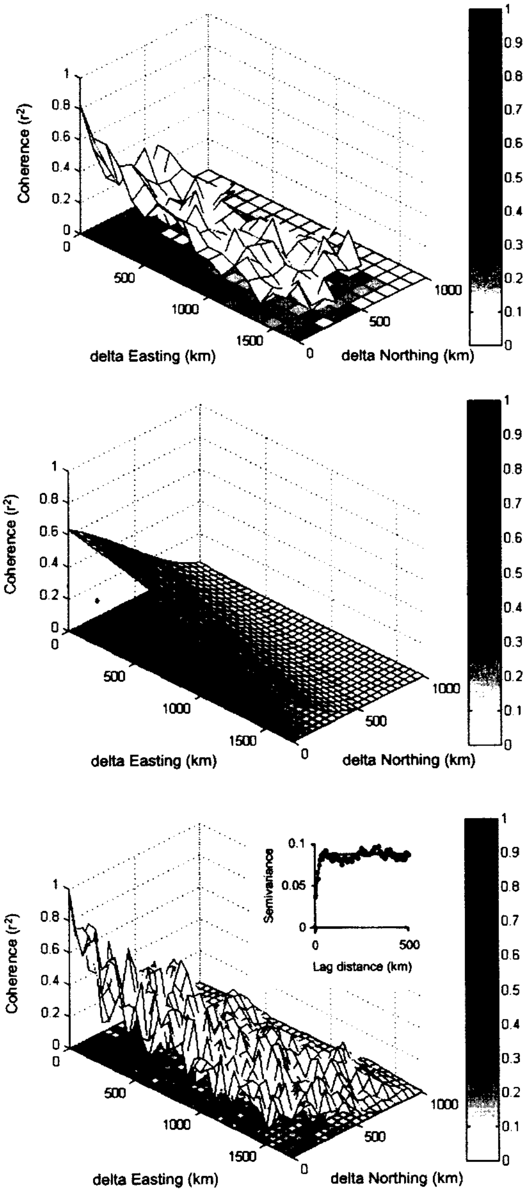

Fig. 3. Patterns in coherence (r^2) in ice-off dates versus latitude distances and longitude distances expressed in km. Data are from the pairing of 83 sites in the Laurentian Great Lakes Region from 1977 through 2002. Top: Average coherence (r^2) in 100 km bins calculated from z-transformed coherences between lake ice-off date time series versus latitude and longitude distances. Middle: Trend surface of coherence (r^2) between pairs of lakes from the back-transformed linear model: $z = \beta_0 + \beta_1$ (delta Easting) + β_2 (delta Northing), where z is the Fisher (1915) transformed correlation coefficient (r), delta Easting is the distance between pairs of lakes in the east-west direction, and delta Northing is the distance between pairs of lakes in the north-south direction. The least-squares parameter estimates are: $\beta_0 = 1.088$, $\beta_1 = -0.00031$, $\beta_2 = -0.00094$. The model r^2 value is 0.35. Not shown is that the modeled surface extends below the x-y plane. Bottom: Kriged surface of coherence (r^2) versus latitude and longitude distance in 50 km cells. Ordinary kriging (CRESSIE 1993) was conducted on the residuals from the trend surface (Fig. 3 middle) based on a kriging neighborhood of 5 to 25 points within 25 km. The surface of kriged residuals was then added to the trend surface. The inset depicts the variogram of residuals from the trend surface and a spherical variogram model (nugget = 0.034, sill = 0.085, range = 43.3 km).

The high average coherence ($r^2 = 0.92$) for lakes within 10s of km of each other, supports this idea. For ice-off timing, many climatic interactions with ice-covered lakes would appear to be more related to per unit surface area than to total lake area or volume. For example, the influence of solar radiation, the thermal conduction of heat, and snow depth on ice breakup would function largely on a per unit area basis. However, lake factors related to the heat budget are not entirely independent of the morphometry of individual lakes. For example, larger lakes tend to have colder water beneath the ice than do smaller lakes, owing to the delayed ice-on date and longer mixing period in early winter that larger lakes experience. Also, more of the snow blows off larger lakes than smaller lakes with a variety of consequences on breakup (VAVRUS et al. 1996, WYNNE et al. 1998). The impact of storm-event wind on the exact date of ice breakup would be greater for large than for small lakes as well. However, these potential effects did not reduce greatly the average coherence of adjacent lakes in our data set.

The rapid decline in coherence in the first few hundred kilometers suggests that small-scale differences in local climatic factors and perhaps land cover are important. For example, weather and the paths of individual storms may have a footprint small enough that lakes are influenced differentially over a few hundred kilometers. Patterns of snow cover could be important. Snow cover delays ice-out date (VAVRUS et al. 1996, WYNNE et al. 1998). Because lake-effect snow from the Great Lakes accumulates on lakes down weather from the Great Lakes, those lakes should have a delay in ice-off compared with lakes farther from the lake, even if they experienced the same temperature conditions in the spring. Many of the Great Lake states and Ontario experience lake-effect snow in relatively localized down-weather locations. Differences in land use and land cover, stream inflows, urbanization, and altitude are local factors that might alter the influence at these smaller scales of a few hundred kilometers.

The slower decline in coherence with east to west distances than with north to south distances may be influenced by the general pattern of weather movement across the Great Lakes region. Weather fronts typically move rather rapidly from west to east, less often from north to south or south to north. The jet stream also has a dominant west to east vector. The faster decline in coherence in the north to south direction is influenced by the fact that lakes farther north breakup at a later date than those in the south while those at the same latitude tend to break up on more similar dates. Latitude is a major explanatory variable in models of lake ice phenology in the western Great Lakes region (WYNNE et al. 1996); average ice-off dates would differ by 1.5 months from the most southern to the most northern lake in our lake set based on the Wynne et al. model. Thus, differences in weather in different months and the differences in the strength of the large-scale climatic drivers in different months are more likely to differentially influence lakes that differ in latitude rather than longitude.

Even across broad geographic areas (four states and Ontario) coherence persists. Such broad patterns of coherence in ice-off dates may occur because (1) common weather patterns move rapidly across the Great Lakes region, (2) many large-scale drivers of climatic variability such as the Pacific/North American pattern (PNA) and the Western Pacific pattern (WP) have a broad footprint across the Great Lakes region (BENSON et al. 2000), and (3) global climatic change has a footprint that extends across the region (MAGNUSON et al. 2000a; MAGNUSON 2004). Areas closer together, such as Minnesota and Wisconsin, have higher coherence between their lakes than do more distant areas such as Minnesota and New York. At this meso scale of state and provincial areas, coherence can decline owing to heterogeneous patterns of influence by broad-scale drivers across the region. From 1950 to 1995 ice-off dates in Wisconsin were correlated more closely with the Southern Ocean Index (SOI) than were ice-off dates in New York; the converse was the case for the North Atlantic Oscillation (NAO) index (MAGNUSON et al. 2004). Such differences can exist within areas as well. In Wisconsin, ice dynamics are correlated more closely with SOI in the southern part of the state than the northern part (ANDERSON et al. 1996), because the SOI signal is more intense during the month when ice off occurs in the southern lakes than later in the spring when ice off occurs in the northern lakes.

In summary, the levels of coherent dynamics in ice-off dates within areas and across the Great Lakes region indicate that large-scale climatic phenomena are influential and pervasive. Conversely, the levels of incoherent dynamics also indicate that more local conditions influence these dynamics. The large-scale and the local conditions interact to produce the spatial pattern of ice-off dynamics, but neither erases or masks the role of the other in the comparisons above. Obtaining a better understanding of the mechanisms and the influences of these large-scale and small-scale determinants of coherence in lake ice dynamics is a worthy challenge.

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