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Regional coherence of climatic and lake thermal variables of four lake districts in the Upper Great Lakes Region of North America

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SUMMARY

1. Within a region with common climatic conditions, lake thermal variables should exhibit coherent variability patterns to the extent to which they are not influenced by lake specific features such as morphometry and water clarity. We tested the degree of temporal coherence in interannual variability for climatic variables (air temperature and solar radiation) among four lake districts in the Upper Great Lakes Region. We also tested the degree of coherence of lake thermal variables (near-surface temperature, eplimnetic temperature, hypolimnetic temperature and thermocline depth) for lakes within these districts.

2. Our four lake districts included the Experimental Lakes Area in north-western Ontario, the Dorset Research Centre area north of Toronto, Ontario, the Northern Highland Lake District in northern Wisconsin, and the Yahara Lakes near Madison in southern Wisconsin. Seventeen lakes were analyzed for lake thermal variables dependent on stratification. Another five lakes were added for the analysis of near-surface temperature.

3. The analysis tested whether for monthly and summer means, the climate (air temperature and solar radiation) across the four lake districts was coherent interannually and whether variables which measure the thermal structure of the lakes were coherent interannually among lakes *within* each lake district and *across* the four lake districts.

4. Temporal coherence was estimated by the correlation between lake districts for meteorological variables and between lake pairs for lake thermal variables. Mean coherence and the percentage of correlations exceeding the 5% significance level were derived both within and between lake districts for lake thermal variables.

5. Across the four lake districts, summer mean air temperature was highly coherent while summer solar radiation was less coherent. Approximately 60–80% of the interannual variation in mean summer air temperature at a site occurred across the entire region. Less than 45% of the variation in solar radiation occurred across sites.

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6. Epilimnetic temperature and the near-surface temperature were highly coherent both within and between lake districts. The coherence of thermocline depth within and between lake districts was weaker. Hypolimnetic temperature was not coherent between lake districts for most lake pairs. It was coherent among lakes within some lake districts.
7. The influences of local weather and differences among lakes in water clarity are discussed in the context of differences in levels of coherence among lake thermal variables and among lake pairs for a given variable.

Keywords: coherence, lake districts, lake thermal structure, regional climate, regional limnology, temporal variability

Introduction

Lake ecosystems respond strongly to climatic conditions (Arnell *et al*., 1996; Magnuson *et al*., 1997). Within a limited geographic range (< 10 km), neighboring lakes have exhibited synchronous interannual variation, or temporal coherence, for a number of variables directly linked to climate such as ice cover, water level, and water temperature (Magnuson *et al*., 1990; Kratz *et al*., 1998; Baines *et al*., 2000). However, the spatial extent over which lakes vary coherently among years is poorly understood.

Here we expand the spatial scale of previous investigations of lake coherence. If climate is coherent across a geographic region, lake variables driven in part by climate could also be expected to be coherent across the region. However, lake thermal variables could be expected to exhibit varied responses to climatic conditions. Lake features such as morphometry and water clarity seem likely to modify lake responses to climatic variation (Fee *et al*., 1996). We examined the degree of coherence for climatic variables across four lake districts in the Upper Great Lakes Region during 1982–93. We then examined patterns of coherence in lake thermal variables that might be expected to be driven directly by climatic conditions.

Data on air temperature and solar radiation were available at all four lake districts and this availability dictated our choice of climatic variables for the analysis. We analyzed air temperature and solar radiation on both a monthly and a seasonal (summer) time scale. The degree of coherence among sites for these climate variables might provide an approximate upper bound on any climate driven coherence that could be expected for lake variables. Both air temperature and water temperature respond to a complex set of climate drivers that influence the heat budget of the atmosphere and lakes. This paper does not attempt to identify the most significant climate driver of lake thermal variables but rather explores the spatial pattern of climatically influenced properties of the lower atmosphere and lakes.

As measures of the lakes' responses to climatic conditions, we examined the near-surface water temperature, epilimnetic temperature, hypolimnetic temperature, and the depth of the thermocline. These thermal variables are all potentially linked to climatic variation but they differ in the directness of their link to climatic forcing. We anticipated a range of responses in the coherence of lake thermal variables that would reflect the varying degrees of lake-specific vs. regional control.

We asked the following questions: among years how coherent are (1) monthly and summer mean air temperature and solar radiation between the four lake districts, (2) lake thermal structure variables *within* each lake district and (3) the thermal structure variables *between* the four lake districts?

Methods

Study areas

The lakes studied are from four distinct lake districts in the Upper Great Lakes region: the Northern Highland Lake District in northern Wisconsin (Trout Lake area, TLA) and four Yahara District lakes in Dane county in southern Wisconsin (Madison lake area, MLA), the Experimental lakes area in northwestern Ontario (ELA), and the Dorset Research Centre study lakes (DOR) in Ontario north of Toronto. More detailed descriptions of study sites and measurements are given elsewhere (Brunskill & Schindler, 1971; Kratz *et al*., 1986; Dillon *et al*., 1991; Lathrop *et al*., 1992; Lathrop, 1992; Dillon *et al*., 1994; Dillon & Molot, 1996; Fee *et al*., 1996). TLA and MLA lakes are primary study lakes of the North Temperate Lakes

Long-Term Ecological Research program (http://www.limnology.wisc.edu).

Within each lake district, study lakes are located closely enough to be exposed to essentially the same monthly or seasonal climate. The seven lakes from TLA (46°01′ N, 89°40′ W) in northern Wisconsin lie within 10 km of each other (Magnuson & Bowser, 1990) and have an elevation range of ≈ 10 m. The four lakes from MLA in southern Wisconsin lie within 15 km of each other in the vicinity of Madison (43°06′ N, 89°25′ W) and differ by less than 10 m in elevation. The four lakes at the ELA (49°39′–49°44′ N, 93°43′–93°47′ W) lie within 12 km of each other and differ by 32 m in elevation. The seven lakes at Dorset (45°05′–45°23′ N, 78°50′–79°07′ W) are within ≈ 43 km of each other and have an elevation range of 80 m.

We analyzed 22 lakes (Table 1). Seventeen were clearwater lakes that stratified permanently during July through August, three were too shallow to maintain stratification throughout July and August every year, and two were stained dystrophic lakes.

Table 1 Morphometry of study lakes

Lake district	Lake	Surface area (ha)	Max. depth (m)
(a) Lakes where all thermal parameters were analyzed			
DOR	Blue Chalk	52	23
	Chub	34	27
	Crosson	57	24
	Dickie	94	12
	Harp	71	37.5
	Plastic	32	16.3
ELA	224	26	27.4
	239	54	30.4
	240	44	13.1
	373	27	20.75
MLA	Lake Mendota	3985	25.3
	Lake Monona	1326	22.6
TLA	Allequash Lake	168	7.6
	Big Muskellunge Lake	396	21.4
	Crystal Lake	37	20.4
	Sparkling Lake	64	20
	Trout Lake	1608	35.7
(b) Additional lakes where only the near surface temperature was analyzed			
DOR	Heney	21	5.8
MLA	Lake Kegonsa	1299	9.8
	Lake Waubesa	843	11.6
TLA	Crystal Bog	1	2.5
	Trout Bog	2	7.5

ELA = Experimental Lakes area, DOR = Dorset lake area, MLA = Madison lake area, TLA = Trout Lake area.

Variables

For climate variables we evaluated air temperature and solar radiation. Monthly and summer means (June through August) were determined for each lake district. Monthly solar radiation was limited to May through October because ELA solar radiation data were available for only these months. Although the summer means for thermal parameters were based on the period of stable stratification (July–August) for all the lakes, the summer means for climate variables were derived for June through August because water integrates climatic variation.

For TLA monthly mean air temperature data, we used National Weather Service data from the Minocqua Dam station located about 15 km from the TLA study lakes and for MLA, we used National Weather Service monthly mean air temperature data from the Truax Field station (Madison, WI). Both of these data sets were supplied by the Wisconsin State Climatologist. For ELA and DOR, monthly mean air temperature was calculated from daily average air temperatures measured at the research sites. At DOR, we used air temperature data from station DOR2).

Daily solar radiation for TLA was derived from two sources. Prior to 1989, data were from the Rainbow Flowage, Wisconsin weather station managed by the Wisconsin Valley Improvement Corporation and located about 20 km from the TLA study lakes; from 1989 to 1993, data were obtained from the North Temperate Lakes LTER weather station at the Woodruff airport ≈ 10 km from the TLA lakes (http://www.limnology.wisc.edu/climate.html). Monthly means were derived. Months missing more than 3 days of data (3 months out of 72) were estimated using regression with data from weather stations from the University of Wisconsin–Extension, Automated Weather Observation Network (http://bob.soils.wisc.edu/wimnext/awon/awon.html) at Antigo (97 km from Woodruff) and Chetek, Wisconsin (157 km from Woodruff).

Daily solar radiation data from DOR were from two DOR meteorological stations (DOR4 from 1982 to 1986 and PT1P from 1987 to 1993). Months missing more than 3 days (16 months out of 72) were estimated using regression with Canadian monthly climate data from Toronto, Ontario (provided by Environment Canada), 175 km from the Dorset meteorological stations.

Available ELA solar radiation data were photosynthetically active radiation (PAR). As PAR is highly correlated with solar radiation and because we were using the data only to calculate correlations with solar radiation measurements from the other sites, the different measurement of radiation for ELA was acceptable. Monthly means were determined. Months missing more than 3 days (7 months out of 72) were estimated using regression with data from Winnipeg, Manitoba (253 km from the ELA meteorological station). There were 2 months where it was not possible to estimate values (5/85 and 10/93). These were set to missing for the analysis.

MLA solar radiation was derived from modeled data based on cloud height and coverage (Meyer & Dale, 1983; Petersen, 1990). Monthly means were calculated.

The lake thermal variables were derived from water temperature profiles from 1982 to 1993. We focused on the summer season (July–August, the period of stable stratification for all 17 stratified lakes). At least one water temperature profile for each month from June through September was required for inclusion of a given lake year to permit interpolation of daily values for monthly average calculations. Otherwise, the thermal variables for that lake year were set to missing in the coherence analysis; each of the 22 lakes had at least 10 years of data. The number of water temperature profiles taken between June and September varied by lake and year from 4 to 55 with the mean number of profiles for a lake in a year being 8.

To create a standard resolution for depth, missing data within a temperature profile were estimated by using linear interpolation to obtain a value for each 1-m depth interval. For the 17 lakes that maintained a stable stratification during July and August, we calculated the epilimnetic temperature, hypolimnetic temperature and thermocline depth. While the thermal structure of lakes has been well described (Birge, 1897; Cole, 1994), we developed standardized definitions for our analyses. The bottom of the epilimnion was calculated as the shallowest depth at which the temperature change between it and the meter depth below was greater or equal to 1 °C. To avoid problems associated with ephemeral warming of surface waters, the epilimnion bottom was constrained to be deeper than 3 m unless the only depth for which the criterion held true was less than or equal to 3 m. Epilimnetic temperature was the mean across depths from the surface to the epilimnion bottom. The thermocline depth was defined as the depth below the epilimnion bottom which had the greatest ratio of difference in temperature to difference in depth. If two or more depths had identical maximum ratios, the deepest was taken as the thermocline depth. Hypolimnetic temperature was the mean across depths from the top to the bottom of the hypolimnion. The top of the hypolimnion was defined as the greatest depth at which the temperature change between it and the depth above was greater than or equal to 1 °C.

Lake thermal variables which depend upon stratification limit the set of lakes included in our detailed analyses. For the expanded 22-lake data set, we calculated an estimate of the near-surface temperature as the average of the temperatures at 1 and 2 m. We did not include the surface reading (at 0 m) because it is often influenced by short-term warming.

For our analyses of lake thermal structure we focused on July through August, the period of stable summer stratification. After computing thermal structure variables for each available sampling date, a mean summer value was determined for each variable by interpolating between sampling dates to obtain a value for each day in July and August and then averaging over the daily values in these two months. For each variable of summer thermal structure (epilimnetic temperature, thermocline depth, hypolimnetic temperature, and near-surface temperature), we then constructed a lake-by-year matrix which was used in coherence calculations.

Measure of coherence

We used the Pearson product–moment correlation as our measure of coherence. For coherence of air temperature and solar radiation variables (monthly or summer), the correlations were computed between all possible pairs of lake districts (for four districts, there are six pairs) for 12 years of data. For the coherence of thermal structure variables within lake districts, the correlation was computed for a given variable on pairs of lakes within the lake district for 12 years of data. The analysis for between lake-district coherence was based on computing correlations between pairs of lakes, where the first lake came from one lake district and the second from another lake district.

For each lake district and lake-district pair we determined the mean coherence as the arithmetic average of all lake-pair correlations for a given variable. The arithmetic mean might produce a biased estimate. Therefore, we also used Fisher's z-transformation before calculating the mean, averaged the transformed values, and then used the inverse of the z-transformation to compute a mean correlation. The means based on the Fisher's z-transformation differed only slightly (at most by 0.06) from the simple arithmetic average. Here we only report the arithmetic average and the median.

We determined the percentage of strong correlations. We define strong coherence as a correlation greater than 0.50, the significance level for a 5% one-tail test of the correlation coefficient for a sample size of 12. The percentage of strong correlations should be regarded as an index of the strength of coherence rather than an inferential statistic. Data upon which this index is based may not meet the criterion of statistical independence.

Results

Coherence of regional climate

Table 2 The coherence of mean summer (June–August) air temperature between lake districts and the coherence of mean summer (June–August) solar radiation between lake districts

Variable	DOR-ELA	DOR-MLA	DOR-TLA	ELA-MLA	ELA-TLA	MLA-TLA
Air temperature	0.86	0.90	0.78	0.84	0.88	0.88
Solar radiation	0.49	0.45	0.56	0.67	0.45	0.67

Coherence in monthly mean air temperature was high between lake districts during most months, whereas solar radiation was less coherent. All coherence values for monthly mean air temperature between lake districts (Fig. 1a) were high, exceeding 0.50, except for September where MLA was one of the lake districts in the pair and November for DOR-MLA and DOR-ELA. In contrast, only 14 out of 36 coherence values for monthly mean solar radiation between lake districts (Fig. 1b) exceeded 0.50. The coherence for monthly mean solar radiation between the two Wisconsin lake districts was high for May through July and September. In October, the correlations involving DOR as one of the lake-district pair were all negative and the DOR-ELA correlation was strongly negative. This pattern may reflect the influence of autumn lake-effect clouds, as DOR is the only lake district downwind of the Great Lakes.

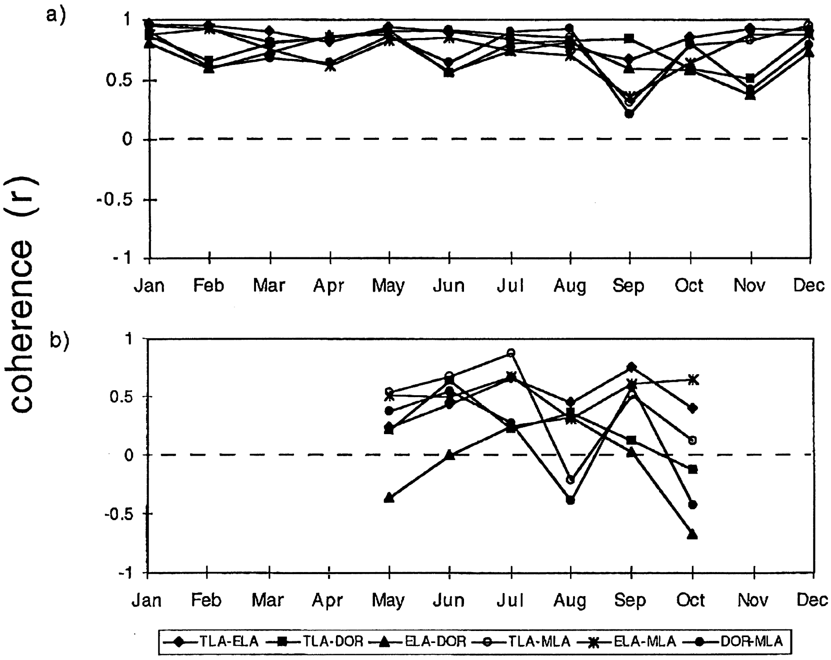

Fig. 1 (a) Coherence of mean monthly air temperature between lake districts by month; (b) coherence of mean monthly solar radiation between lake districts for the months May–October.

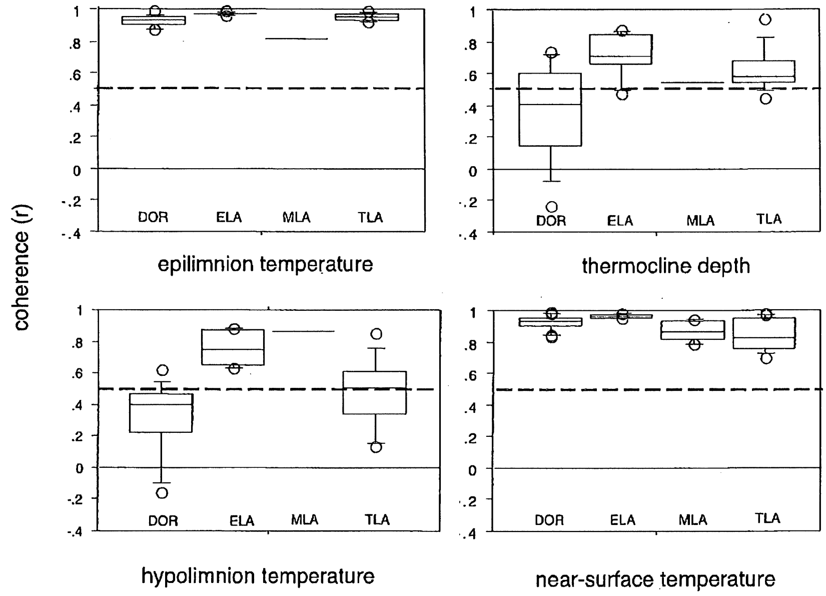

Fig. 2 Box plots of within lake-district coherence for epilimnetic temperature, thermocline depth, and hypolimnetic temperature by lake district (17-lake data set) and the box plot of within lake-district coherence for near-surface temperature (22-lake data set) by lake district. The box plots display the distributions of coherence values for all lake pairs within lake districts. For each box plot, the five horizontal lines display the 10th, 25th, 50th, 75th and 90th percentiles of a variable. Values above the 90th percentile and below the 10th percentile are plotted separately. The dashed lines represent the one-tailed significance test level ($P = 0.05$) for a correlation coefficient with sample size of 12. MLA plots as a single line in cases where there is only one pair of lakes.

In general, coherence in summer means of climatic variables was high. The coherence of mean summer (June–August) air temperature (Table 2) ranged from 0.78 to 0.90. The coherence of mean summer (June–August) solar radiation (Table 2) ranged from 0.45 to 0.67.

Coherence of lake thermal variables within lake district

Epilimnetic temperature was highly coherent within each lake district with values exceeding 0.8 for all lake pairs within each lake district (Fig. 2). The mean coherence for epilimnetic temperature was 0.93 for DOR, 0.97 for ELA, 0.82 for MLA, and 0.95 for TLA (Table 3). Other thermal variables were generally less coherent within a lake district. Coherence of thermocline depth was somewhat high for ELA, MLA, and TLA and the values for hypolimnetic temperature were somewhat high for ELA and MLA. The range of coherence values was greater for these two variables than for epilimnetic temperature (Fig. 2). The lake districts varied considerably in the percentage of strong correlations for thermocline depth and hypolimnetic temperature (Table 4).

For the expanded 22-lake set, the near-surface temperature was highly coherent within a lake district with mean coherence being 0.92 for DOR, 0.96 for ELA, 0.87 for MLA, and 0.86 for TLA (Table 3). These means are similar to the means for epilimnion temperature, although the range of coherence values for near-surface temperature is greater than the range for epilimnetic temperature (Fig. 2). The percentage of strong coherence was 100% within each lake district (Table 4).

Coherence of lake thermal variables between lake districts

Epilimnetic temperature was highly coherent between lake districts with coherence for lake pairs between lake districts ranging from 0.60 to 0.94 (Fig. 3). In general, the coherence of thermocline depth was weaker; hypolimnetic temperature was not coherent for most lake pairs between lake districts (Table 3). With the exception of the ELA-TLA comparison, the percentage of strong coherence (Table 4) for hypolimnetic temperature was less than for other variables and ranged from 0 to 10%.

For the expanded 22-lake set, the near-surface temperature was highly coherent between lake districts

Table 3 The mean coherence of lake thermal parameters within and between lake districts. The median coherence is given in parentheses. Sections a–c are based on the 17-lake data set. Section d is based on the expanded 22-lake data set

	DOR	ELA	MLA	TLA
(a) Epilimnion temperature				
DOR	0.93 (0.94)			
ELA	0.73 (0.74)	0.97 (0.97)		
MLA	0.80 (0.81)	0.81 (0.83)	0.82 (0.82)	
TLA	0.81 (0.81)	0.81 (0.81)	0.81 (0.81)	0.95 (0.96)
(b) Thermocline depth				
DOR	0.37 (0.40)			
ELA	0.32 (0.30)	0.71 (0.71)		
MLA	0.50 (0.48)	0.30 (0.29)	0.55 (0.55)	
TLA	0.51 (0.49)	0.40 (0.40)	0.63 (0.60)	0.62 (0.58)
(c) Hypolimnion temperature				
DOR	0.31 (0.39)			
ELA	0.06 (0.10)	0.76 (0.75)		
MLA	0.05 (0.08)	– 0.02 (0.00)	0.87 (0.87)	
TLA	0.05 (– 0.02)	0.46 (0.55)	0.07 (0.12)	0.48 (0.51)
(d) Near-surface temperature				
DOR	0.92 (0.93)			
ELA	0.71 (0.71)	0.96 (0.96)		
MLA	0.75 (0.74)	0.84 (0.86)	0.87 (0.87)	
TLA	0.75 (0.78)	0.78 (0.77)	0.83 (0.85)	0.86 (0.82)

Table 4 The percentage of strong coherence for lake thermal parameters within and between lake districts. Sections a–c are based on the 17-lake data set. Section d is based on the expanded 22-lake data set

	DOR	ELA	MLA	TLA
(a) Epilimnion temperature				
DOR	100			
ELA	100	100		
MLA	100	100	100	
TLA	100	100	100	100
(b) Thermocline depth				
DOR	40			
ELA	21	83		
MLA	50	13	100	
TLA	50	30	90	90
(c) Hypolimnion temperature				
DOR	13			
ELA	8	100		
MLA	0	0	100	
TLA	10	55	0	60
(d) Near-surface temperature				
DOR	100			
ELA	100	100		
MLA	100	100	100	
TLA	98	100	100	100

with mean values for lake-district pairs ranging from 0.71 to 0.84 (Table 3). These results were similar to the coherence values of epilimnetic temperature based on the 17-lake data set. The overall range of coherence values ranged from 0.34 to 0.94 (Fig. 3). At least 98% of the between lake-district coherence values were strong (Table 4) for each lake-district pair.

Discussion

Regional climate coherence

Interannual variation in summer mean air temperature is a coherent climatic signal across a broad extent in the Upper Great Lakes Region. The coherence between lake districts ranged from 0.78 to 0.90; hence, ≈ 60–80% of the variation in mean summer air temperature at a site can be explained by temperature variations at the other lake districts.

While coherence in summer mean air temperature was consistently high, there was considerable variation in the monthly coherence. Most of the monthly values were high; during some months, however, one lake district appeared to be disconnected from the regional climatic pattern seen at the other three lake districts. For example, MLA in September had

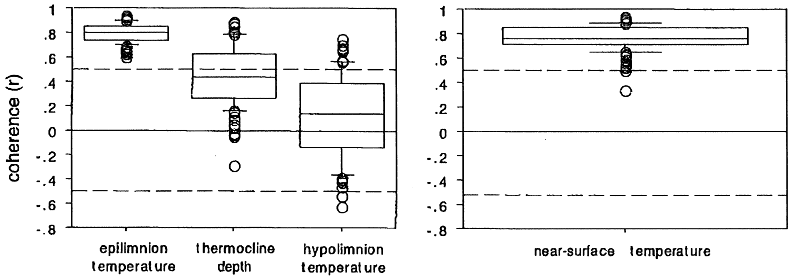

Fig. 3 As in Fig. 2, but for coherence between lake districts.

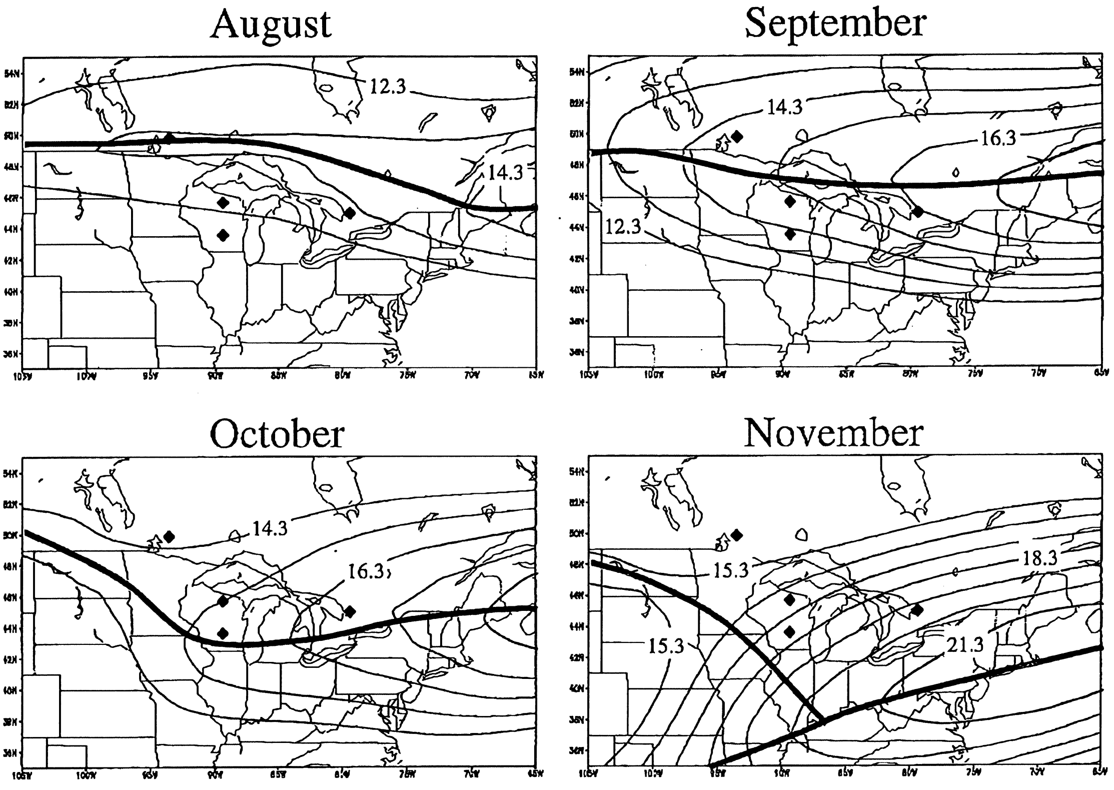

Fig. 4 Long-term monthly mean 500-mbar wind speeds over east-central North America for August–November 1968–96. Data obtained from the NCEP/NCAR reanalyses (Kalnay *et al.*, 1996). Contours start at 12.3 m s^{-1} (August and September), 14.3 m s^{-1} (October), and 15.3 m s^{-1} (November) and increase by 1 m s^{-1}. Thick lines denote approximate locations of the jet stream, as determined by the axis of maximum wind speed. Diamonds indicate locations of the four lake districts.

much lower coherence with the other three lake districts than they shared with each other. DOR exhibited a similar pattern in November. We suggest that these disconnections between districts are related to interannual variations in the position of the jet stream (which denotes the approximate boundary between warm and cold air masses). This explanation is based on an examination of the monthly mean wind speed at the 500 mbar pressure level (roughly 5.4–5.8 km elevation), using data from the NCEP/NCAR reanalyses (Kalnay *et al.* 1996). Long-term monthly mean values for 1968–96 indicate that the mean axis of the North American jet stream is positioned north of the Great Lakes in August and over Lake Superior in September (Fig. 4). The jet stream shifts southward over MLA and DOR in October and south of the Great Lakes by November. Thus, on average, the jet stream moves southward over the lake districts during the months of August through November. This close proximity of the jet stream to the lake districts suggests that interannual variations in the position of the jet stream during these months has the potential to 'divide' the lake districts through exposure to different air masses, thereby lowering the coherence in surface air temperature. Indeed, we observe such jet stream behavior during some of the particular years with air temperature anomalies out-of-phase between lake districts.

The size of a region studied and the degree of homogeneity in climatic forcing variables will affect the level of coherence. Wynne *et al.* (1996), for example, reported a wide range of coherence values in ice break-up dates for 62 lakes on the Laurentian Shield. They found that lake pairs in close proximity or oriented along an east–west swath had strong coherence in ice phenology. Some lake pairs had a negative coherence which may reflect out-of-phase variation owing to control by different air masses.

Mean summer solar radiation exhibited less coherence across the region than did air temperature, and coherence between lake districts varied considerably. These results suggest that solar radiation is a more local-scale climatic driver than air temperature. This difference is understandable, because air temperature is primarily a function of large-scale air masses, while solar radiation variations are driven largely by changes in cloud cover. Clouds, in turn, are a function not only of air masses, but also humidity and lifting mechanisms such as cold fronts or localized convection. This necessary combination of conditions leads to variations in cloud cover over much shorter distances than air temperature. An alternative explanation for lower coherence for solar radiation may be a data quality issue because we used solar radiation data from multiple weather stations for some of the lake districts.

Response of lake thermal variables

Epilimnetic temperature and the near-surface temperature are highly coherent both within and between lake districts. Thus, extrapolation from results on a limited set of lakes should be possible considering the temporal variability of temperatures within the mixed layer of similar lakes across the Upper Great Lakes Region.

For thermal variables describing conditions deeper in the lake, the connection with other lakes diminishes. Coherence of thermocline depth between lake districts is weaker than coherence of epilimnetic temperature. With the possible exception of ELA-TLA, hypolimnetic temperatures are not coherent between lake districts. The temperature of the hypolimnion is sensitive to weather events, e.g., wind events, during the period when the lake is beginning to stratify. After stratification, the hypolimnion is buffered from variation in air temperature and solar radiation and thus does not integrate the summer climate. For the most part, coherence for hypolimnetic temperature within a lake district was stronger than between lake districts. Lake morphometry varies within the lake districts but the lakes are more likely subject to the same local weather. Local scale climate seems important to interannual variation in hypolimnetic temperature.

Inter-annual variation in local climate appears to introduce a substantial amount of coherence in lake thermal structure within lake districts. For example, for ELA and MLA, all the thermal variables are highly coherent within each lake district; within TLA, epilimnetic temperature, thermocline depth, and the near-surface temperature are highly coherent. The lake districts vary, however, in the degree of coherence. For epilimnetic temperature and thermocline depth, ELA has the highest mean coherence of all four lake districts, and between 83 and 100% of the coherence values are strong. In contrast, DOR has the lowest mean coherence for thermocline depth and hypolimnetic temperature, and the range of values for lake pairs extends lower. Why would lake districts display different levels of coherence in thermal variables? Several explanations may apply. First, the lake districts vary in the heterogeneity of the lakes included in this study. Thus, lake districts with a greater diversity of lake morphometry and water clarity may display lower coherence. Indeed, ELA with highest coherence has the lowest coefficients of variation in surface area and mean depth. However, the rankings of lake districts by coefficient of variation of surface area and mean depth did not correspond to the ranking by coherence.

A second explanation of why lake districts may have different levels of coherence is that the lake districts vary in the size of their study area. As the size increases, there will be greater variability in local climate conditions across the study area possibly resulting, in part, from greater variability in elevation. DOR had a larger study area by almost a factor of three and it had the lowest coherence. Third, the data sets for the lake districts vary in the sampling intensity of thermal profiles during the summer stratification period. Less frequent sampling can filter out real variability in the thermal variable estimates and lower estimates of coherence. DOR had the lowest sampling frequency of all four lake districts with an average number of thermal profiles per lake in a year over the June through August period of 6.9 as compared to 8.5 for TLA, 9.0 for ELA and 10.3 for MLA.

For a given thermal structure variable and lake-district pair, lake pairs can vary over a wide range of coherence. What lake characteristics account for high coherence? Within TLA, similarity in water clarity and average epilimnetic depth were related to higher levels of coherence in water temperature variables (Baines *et al.*, 2000). Transparency has been shown to be a major determinant of mixed layer depth for small lakes (< 500 ha) on the Canadian Shield (Fee *et al.*, 1996). Variation in dissolved organic carbon (DOC) is an important source of variation in transparency. The DOR lakes range in DOC from 1.8 to 5.0 mg C L^{-1} and exhibited the greatest range in thermocline depth coherence values. Note, however, there were more DOR lakes included in the analysis and this fact may contribute to a greater range. The clearwater TLA lakes range from 1.9 to 4.0 mg C L^{-1} and had a narrower range of thermocline depth coherence values. The two dystrophic lakes at TLA have DOC levels of 8.7 and 16.3 mg C L^{-1}. When these two lakes are included in the analysis (coherence of near-surface temperature), TLA had the greatest range of coherence values. These findings suggest that differences in light penetration among lakes influenced the level of coherence. Coherence has also been shown to be related to similarity in morphometry with area to mean depth ratios serving as an index of exposure to climate (Magnuson *et al.*, 1990).

Between 60 and 80% of the interannual variation in mean summer air temperature at a site represented a region-wide pattern. How much of this region-wide signal is driving coherence across the region in lake thermal variables? The high level of coherence in epilimnetic and near-surface temperature among lake pairs across lake districts suggests that a significant portion of a region-wide climatic signal is transmitted to the upper waters of lakes. However, lake temperature is controlled by multiple climatic factors including solar radiation, air temperature, wind speed, and humidity. In addition, within lake factors modulate the climatic drivers. Thus, we expect coherence to be less for lake thermal variables than for individual climate drivers.

What factors lead to a high level of interannual coherence of a variable at a regional level? The interannual dynamics of lake properties is the resulting mix from internal and external factors (Magnuson & Kratz, in press). Thus, high regional coherence is favored by (1) a large spatial scale of the climate drivers, (2) temporal integration of the response variable with longer periods of integration yielding greater coherence, (3) little lake specific modulation or filtering of the climate signal, and of course (4) low measurement error.

In summary, the availability of climate and lake thermal data from lake districts across the Upper Great Lakes Region provided an opportunity to test the spatial extent of coherence in climatic variables and lake thermal variables. High coherence in air temperature and water temperature in the upper waters of lakes occurred across the region. The high level of coherence in epilimnetic temperature is consistent with region-wide coherence in climatic drivers. In contrast, region-wide coherence in thermocline depth was only moderate and for hypolimnion temperatures it was nonexistent for most lake pairs. Thus, region-wide climate dynamics drive region-wide dynamics in epilimnetic temperatures while thermocline depth and hypolimnetic temperatures appear to be determined to a greater extent by local climate modulated by lake specific properties.

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