Hemispheric-scale planktonic diatom (*Cyclotella*) response to recent warming

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Abstract

- A synthesis of over 200 diatom-based paleolimnological records from nonacidified/ nonenriched lakes show remarkably similar climate-induced taxon-specific shifts since the 19th century across the Northern Hemisphere.
- These diatom shifts occurred in conjunction with changes in freshwater habitat structure and quality, which, in turn, we link to hemispheric warming trends.
- A marked increase in the relative abundances of planktonic *Cyclotella* taxa with concurrent sharp declines in thickly-silicifed *Aulacoseira* taxa and/or benthic *Fragilaria* taxa were observed.
- Unparalleled warming over the last few decades resulted in substantial increases in the length of the ice-free period that, similar to 19th century changes in high-latitude lakes, likely triggered a reorganization of diatom community composition in lakes throughout North America and western Europe.
- Our case studies [Whitefish Bay (Lake of the Woods), Emmett & George lakes (Bruce Peninsula) Ontario] revealed that recent increases in the relative abundances of planktonic *Cyclotella* species and concurrent decreases in heavily silicified *Aulacoseira* and/or benthic *Fragilaria* species were strongly correlated to recent increases in temperature and substantially longer ice-free periods.

Meta-analysis

Timing of *Cyclotella* increases

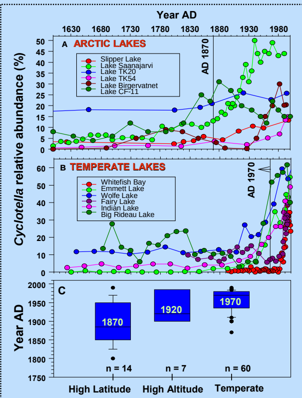


Figure 1. Comparison between the timing of the onset of planktonic diatom increases showing the % relative abundances of *Cyclotella* taxa in a selection of lakes from **A)** high latitude and **B)** temperate regions. The median age of change is illustrated as a straight line. **C)** A comparison in the timing of *Cyclotella* increases among different bioregions (i.e. high latitude, high altitude, temperate) from detailed diatom profiles collected in this meta-analysis. The earlier timing of high latitude sites (median AD 1870) was significantly different ($P<0.05$) than temperate sites (median AD 1970).

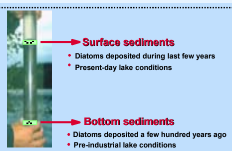
Slipper Lake and Lake TK-20 (Rühland 2001); Lake TK-54 (Paul 2005); Lake Saanajärvi (Sorvari *et al.* 2002); Lake Birgervatnet (Jones and Birks 2004); Lake CF-11 (Wolfe *et al.* 2006); Emmett Lake (Werner *et al.* 2005); Wolfe Lake (Harris *et al.* 2006); Fairy Lake (Quinlan *et al.* 2008); Indian and Big Rideau lakes (Forrest *et al.* 2002).

Skeleton Lake, Canadian High Arctic Photo courtesy I. Lehnherr

Lake of the Woods, Ontario, Canada Photo A. Paterson

Cyclotella stelligera

"Before-After" Paleolimnological Analysis



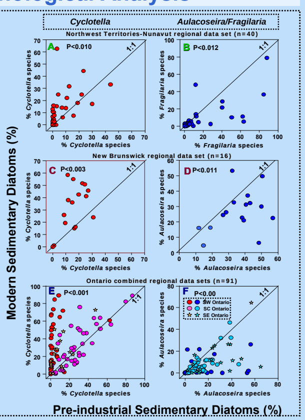


Figure 2. Changes between the % relative abundances of *Cyclotella*, benthic *Fragilaria*, & *Aulacoseira* taxa recorded in modern (top intervals) & pre-industrial (bottom intervals) for regional datasets from **A-B)** NWT & Nunavut in the Canadian subarctic (Rühland et al. 2003), **C-D)** New Brunswick, Canada (Harris et al. 2006), and **E-F)** combined datasets from Ontario including south-western (SW) Ontario, (Werner, 2003), south-central (SC) Ontario, (Hall & Smol 1996), and south-eastern (SE) Ontario, (Reavie et al. 2002). All lakes in figure had a total phosphorus (TP) measurement <20µg/L and/or did not record an increase in diatom-inferred TP. Changes were deemed significant using a Wilcoxan Signed-Rank test.

Distribution of *Cyclotella* shift in N. Hemisphere

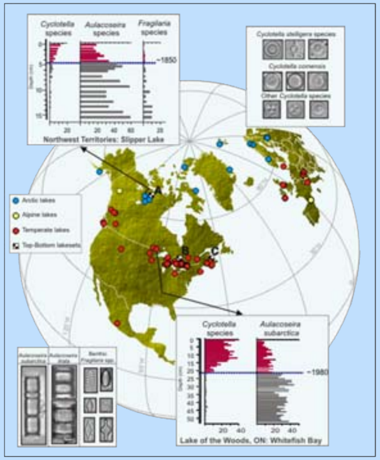


Figure 3. Geographical distribution of diatom-based paleolimnological studies that record an increase in the relative abundances of small, planktonic *Cyclotella* species since the 19th century. Circles represent dated sediment cores where detailed diatom analyses have been undertaken. Simplified stratigraphies from representative regions are provided by the inset figures, which typify both the characteristics & the timing of this trend for Arctic/alpine regions & for temperate lakes in the Northern Hemisphere. Regional-scale coring sites (i.e. "Top-Bottom" or "Before-After" paleolimnological studies) in Canada that record an increase in *Cyclotella* species in the modern sediments are represented by black & white squares, A) NWT & Nunavut, B) Ontario, & C) New Brunswick.

Case Studies

Whitefish Bay: Lake of the Woods, Ontario, Canada

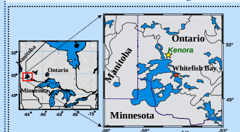


Figure 4. Location of Whitefish Bay (Lake of the Woods, Ontario, Canada) showing the relative location of the Kenora climate station.

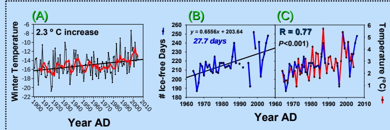


Figure 5. Kenora temperatures have increased substantially, particularly in winter **(A)**. The ice-free period on Whitefish Bay increased by 27.7 days since 1964 **(B)** & is significantly correlated to warming trend at Kenora climate station **(C)**.

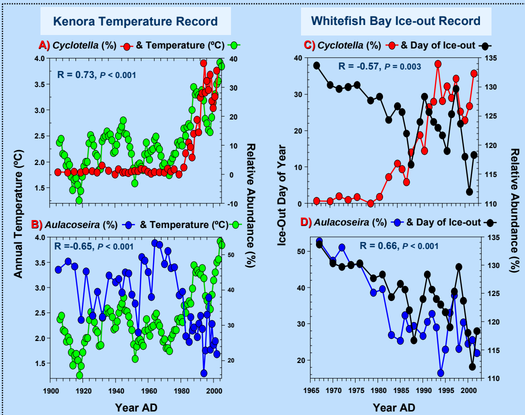


Figure 6. **(A)** Mean annual temperature vs. *Cyclotella* species, **(B)** mean annual temperature vs. *Aulacoseira* species, **(C)** day of ice-out vs. *Cyclotella* species, **(D)** day of ice-out vs. *Aulacoseira* species. No significant relationships were found between atmospherically-derived inorganic nitrogen deposition data available from nearby Experimental Lakes Area (ELA) and diatom trends from Whitefish Bay for both *Cyclotella* and *Aulacoseira* taxa ($P \leq 0.20$) – (data not shown). To enable comparisons to diatom data, a 7-year running mean was applied to the 100-yr temperature record from the Kenora climate station and a 3-year running mean was applied to the 35-yr ice record from Whitefish Bay.

The Kenora temperature data are available from http:/www.ccma.bc.ec.gc.ca/hccd. The Whitefish Bay ice-out data were provided by the Ministry of Natural Resources, Kenora, Ontario, Canada.

Emmett & George Lakes: Bruce Peninsula, Ontario, Canada

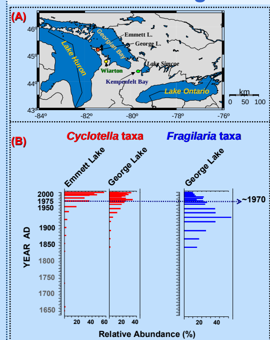
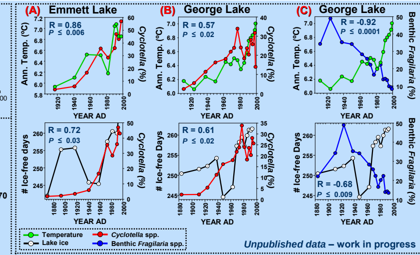


Figure 7. (A) Location of Emmett and George lakes, Wiarton climate station, & Kempenfelt Bay lake ice record, SW Ontario. (B) Simplified diatom profiles from Emmett & George lakes, Bruce Peninsula, Ontario, Canada.

Profiles modified from Werner et al. (2005). Lake & Reserv. Manage. 21: 436-452.



Unpublished data – work in progress

Figure 8. Comparisons between temperature data (Wiarton, Ontario, Canada), # ice-free days (Kempenfelt Bay, Lake Simcoe, Ontario, Canada) and (A) *Cyclotella* percent abundance for Emmett Lake, (B) *Cyclotella* percent abundance for George Lake, and (C) benthic *Fragilaria* percent abundance for George Lake. A 9-year running mean for Emmett Lake and a 15-year running mean for George Lake was applied to the temperature and lake ice data to enable comparisons to the diatom data. Wiarton temperature data are available from Environment Canada & Kempenfelt Bay, Lake Simcoe lake ice records are available from IceWatch Canada.

http://www.cccma.bc.ec.gc.ca/cgi-bin/hccd/main_programs/get_temperature_data

http://www.naturewatch.ca/english/icewatch/

Summary & Conclusions

- Diatom data from over 200 lakes provide a spatially coherent picture that substantial warming over the last few decades have driven taxon-specific changes.
- Strikingly similar diatom shifts are now evident across vast regions of the Northern Hemisphere representing a wide spectrum of lake ecosystems.
- Non-acidified, nutrient-poor, freshwater ecosystems throughout the Northern Hemisphere have crossed important climatically-induced ecological thresholds that were initiated in the 19th century in Arctic and alpine regions, but typically only occurred in the mid-20th century in lakes from mid-latitude regions of North America and western Europe.
- The nature and timing of the taxon-specific diatom changes recorded in our meta-analysis is consistent with climate-related changes in the physical properties in lakes including:
  - a) Length of the open-water season
  - b) Timing, duration and strength of thermal stratification
  - c) Timing and strength of spring freshet
  - d) Timing and duration of spring and autumn overturn
- Changes in these lake-water properties likely provide favourable habitats for small, fast-growing planktonic *Cyclotella* species such as *C. stelligera* complexes and *C. comensis* complexes. These planktonic diatoms may be able to exploit longer ice-free periods and/or deeper, subsurface habitats where nutrient concentrations are somewhat elevated and where light properties become more stabilized as thermal stratification develops (e.g. Fahnenstiel & Glime, 1983).
- The recurring and widespread trend of recent increases in the relative abundances of planktonic *Cyclotella* species and concurrent decreases in heavily silicified *Aulacoseira* and /or benthic *Fragilaria* taxa represented by our three case studies were strongly correlated to recent increases in temperature and substantially longer ice-free periods.
- Synergistic effects between climate warming and other human-induced stressors also occur. However, based on the timing, magnitude, and nature of the diatom shifts from this study, we conclude that warming-induced change in lake-ice cover (and associated limnological changes) was the primary explanatory metric for hemispheric-scale increases in planktonic *Cyclotella* species over the last ca. 200 years.

If the rate and magnitude of temperature increase continues, it is likely that new ecological thresholds will be crossed, many of which may be unexpected.

Further reading

Rühland, K., Paterson, A.M., and Smol J.P. (2008). Hemispheric-scale patterns of climate-related shifts in planktonic diatoms from North American and European lakes. *Glob. Change Biol.* 14, doi: 10.1111

Smol, J.P. *et al.* (2005). Climate-driven regime shifts in the biological communities of arctic lakes. *Proc. Nat. Acad. Sci.* 102: 4397-4402.

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