SHORT COMMUNICATION

Time series analysis of algal blooms in Lake of the Woods using the MERIS maximum chlorophyll index

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The MERIS (MEdium Resolution Imaging Spectrometer) maximum chlorophyll index was applied to Lake of the Woods, an inland water body under significant water quality pressure from recurring cyanobacteria blooms, in order to address the commonly raised concern that blooms on the lake have increased recently. Recent trends in bloom characteristics (intensity, timing and aerial extent) were analysed in relation to local climate variables, offering important new insights into the mechanisms driving algal bloom occurrences on the lake.

KEYWORDS: MERIS; Lake of the Woods; algal blooms; cyanobacteria

Lake of the Woods (LoW) is an international inland water body (spanning the Canadian provinces of Ontario and Manitoba and the U.S. state of Minnesota, Fig. 1) under significant water quality pressures due to nutrient over-enrichment (DeSellas et al., 2009). The lake is an important natural, recreational and economic aquatic resource and is a vital source of drinking water for several communities in the region, including the city of Winnipeg. It is a hydrologically and optically complex water system, consisting of an expansive, shallow and well mixed bay to the south and a large collection of deeper, occasionally stratified and interconnected basins to the north. Concerns have been raised in recent years over anecdotal reports of increasing frequency and intensity of algal blooms, dominated by cyanobacterial populations (Chen et al., 2009). In their article “Blooms like it hot”, Paerl and Huismann (Paerl and Huismann, 2008) commented on a link between climate change and the proliferation of harmful cyanobacterial blooms because of warmer waters, stronger stratification and changing patterns of precipitation and their influence on nutrient loadings. There is evidence that LoW experiences earlier spring ice-free dates by up to 2 weeks and air temperatures are on average 2.5°C warmer now than in the 1900s (DeSellas et al., 2009), suggesting more favourable conditions for cyanobacteria blooms than in the past.

With the lake’s remote location and hydrological complexity, MERIS imagery offers an ideal solution for frequent synoptic observations of algal bloom conditions. However, the inadequacy of standard aquatic colour algorithms in producing realistic chlorophyll concentrations under optically complex conditions such as those found in LoW has been clearly demonstrated...
Optical properties of LoW have been shown to be strongly affected by high concentrations of dissolved organic carbon (DOC), localized mineral resuspension and recurring intense algal blooms (Binding et al., 2011). Binding et al. (Binding et al., 2011) carried out a thorough assessment of several chlorophyll and chlorophyll-related products from Envisat’s MERIS sensor for their potential to monitor algal blooms on the lake and found that the Level 2 maximum chlorophyll index (MCI) was the most effective approach for the waters of LoW. The MCI was found to be fairly independent of the effects of high DOC and mineral resuspension as well as the failures in atmospheric correction procedures common with MERIS over eutrophic inland waters (Binding et al., 2011). The MCI quantifies a peak in radiance near 708 nm observed under algal bloom conditions (Fig. 2), measuring the peak as band 9 (centred at 705 nm) relative to a baseline reflectance interpolated between bands 8 (681 nm) and 10 (753 nm). The MCI has been demonstrated in the detection of floating Sargassum (Gower et al., 2006), “super-blooms” of Antarctic diatoms (Gower and King, 2007), and was shown to accurately identify and track the evolution of an intense algal bloom on LoW in 2009 (Binding et al., 2011). Studies utilizing MERIS to detect and monitor algal blooms in inland waters have also been conducted using a range of other approaches from inverse modelling of phycocyanin absorption signals (Simis et al., 2005) to empirical, semi-analytical and neural network algorithms (Matthews et al., 2010; Odermatt et al., 2010). In the present study, the MCI was applied to a time-series of MERIS L2 full-resolution imagery from LoW over the years 2003–2010 in order to assess any recent temporal trends in the intensity and extent of algal blooms on the lake and to gain an insight into bloom timing and evolution.

MERIS full-resolution (300 m spatial resolution at nadir) L2 imagery was ordered through the ESA/VEGA Technologies ordering system Eoli-sa, and processed using the freely available processing toolbox for MERIS (BEAM 4.6, developed by Brockman Consult under contract to the European Space Agency). All cloud-free images during ice-free months (June–October) for the years 2003–2010 were selected, subset to a geographic region bounded by the latitude/longitude limits 48.5–50.2°N/93.5–95.5°W, and processed to L2 MCI using the FLH/MCI Processor 1.6.100 plug-in extension. The number of cloud-free images of the lake varied from year to year but was able to adequately capture the onset and
progression of the bloom each year. MCI was converted to an estimated chlorophyll concentration using equation (1) after Binding et al. (Binding et al., 2011). Field surveys on the lake in recent years have captured the onset and progression of intense cyanobacteria blooms (predominantly *Aphanizomenon flos-aquae* in the southern more turbid waters, and *Anabaena* spp. in the northern, typically clearer and often stratified waters, S. Watson, Environment Canada, personal communication). While the MCI product does not actively discriminate cyanobacteria from other algal communities, we are confident, based on these field observations in addition to long-term anecdotal evidence, that the MCI signal here (and therefore the derived chlorophyll concentration) can be predominantly attributed to these recurring cyanobacteria blooms.

$$\text{Chl} = 1457\text{MCI} + 2.895$$ (1)

Lake-wide median chlorophyll concentrations were determined for each image after creating a region of interest polygon which excluded pixels meeting the conditions of the land and cloud flags. In addition, derived chlorophyll concentrations were used to determine the aerial extent of the bloom on the lake. This was carried out according to the trophic status definitions of Vollenweider and Kerekes (Vollenweider and Kerekes, 1982) whereby chlorophyll concentrations > 25 mg m\(^{-3}\) were deemed to be hypertrophic conditions, in the range 8–25 mg m\(^{-3}\) eutrophic and those < 8 mg m\(^{-3}\) combined meso- and oligotrophic conditions. Total numbers of pixels falling within each of these categories were determined as a fraction of the total water pixels.

Figure 3 presents the seasonal bloom cycles for the period 2003–2010, along with average monthly precipitation and air temperature from an Environment Canada weather station at Kenora, on the north shore of the lake. Figure 3a and b confirms a consistent annual algal bloom cycle with MCI-derived chlorophyll concentrations peaking at the end of August to beginning of September each year. Average monthly bloom aerial extent consistently shows 50–80% of the lake reaching eutrophic or hypertrophic conditions each year. The year 2006 had noticeably higher than average peak chlorophyll concentrations and resulted in eutrophic conditions across as much as 80% of the lake’s surface. Meteorological data suggest that 2006 was the warmest (peak summer temperature of 21.9 °C, following the mildest winter temperatures) and driest of the years studied. The second largest peak in chlorophyll (in 2003) coincided with the second highest peak temperatures (21.2 °C) and although there was significant rainfall in the month of September, the preceding months rainfall were below average. The least intense bloom periods with the peak median chlorophyll concentrations of 10–15 mg m\(^{-3}\) and average aerial extent of hypertrophic waters of 1–19% of the lake were observed in 2008 and 2009 during the two coolest years, with mean summer temperatures reaching 19.5 °C and 17.6 °C, respectively.

While there have been concerns that blooms have been increasing in frequency and extent in recent years, results here do not corroborate such a fear, with no significant increasing trend in either intensity (chlorophyll concentrations, Fig. 3a) or extent (aerial coverage, Fig. 3b) over the observation period. In fact, there is some suggestion (although not statistically significant) of a decreasing trend in both bloom intensity and the aerial extent of hypertrophic conditions on the lake. There are, however, other bloom features of interest; the imagery was analysed to determine the day on which peak bloom chlorophyll concentration (Peak Chl
Fig. 3. Time-series of (a) lake-wide median MCI-derived chlorophyll concentrations, (b) average bloom aerial extent according to trophic status (see text for definitions) as a fraction of open water, (c) monthly total precipitation (mm) at Kenora and (d) monthly mean air temperature (°C) at Kenora.
Day) was observed each year. A significant trend of increasing Peak Chl Day was found during the observation period 2003–2010, showing that the bloom is occurring on average nearly 4 days later each year [equation (2)].

\[
\text{Peak Chl Day} = -7418.57 + 3.8214 \text{ year}^2 \\
R^2 = 0.51, \quad P < 0.05, \quad n = 8
\]

The apparent link between bloom characteristics and climatological forcing was investigated further. Table I shows the correlation matrix for each of the measured parameters. The analysis confirms a negative correlation between timing and extent of blooms, suggesting that more intense bloom years occur earlier in the year, whereas the weaker blooms occur later in the season. While there was no significant correlation with individual monthly temperatures, there was a strong positive correlation with the August cumulative temperature (defined here as the sum of monthly mean temperatures between January and August), suggesting that there is no single threshold temperature that prompts bloom occurrences but that it is prolonged warming that sets the stage for a strong bloom year. In addition to the dependence on temperature, bloom intensity was also negatively correlated with spring precipitation (defined here as the sum of total precipitation for April through July each year). A multiple regression showed that August cumulative temperature \((T, ^\circ C)\) and AMJJ Precipitation \((R, \text{mm})\) explained 77% of the variability in yearly peak bloom intensity [equation (3)], confirming the earlier suggestion of intense blooms occurring during dry, warm years.

\[
\text{Peak Chl} = 20.67 - 4.19R + 0.46T \\
R^2 = 0.77, \quad P < 0.05, \quad n = 8
\]

Timing of the bloom showed no significant relationship with temperature, instead being dependent on precipitation (and by inference, nutrient loadings) with a strong correlation between Peak Chl Day and total spring precipitation. Results have shown a time-series of intense algal bloom occurrences on LoW over the last decade, with average monthly bloom extent resulting in eutrophic conditions across as much as 80% of the lake’s surface. Peak bloom years were found to be coincident with warm, dry summers. This is in agreement with Kling (Kling, 1998) who reported on phytoplankton communities in Lake Winnipeg, describing year-to-year variability being largely related to climate and nutrient controls, with large blooms of cyanobacteria occurring during warm, dry years. The factors thought to explain the success of cyanobacteria in lakes are complex and include increased phosphorous concentrations, low light-energy requirements, buoyancy regulation aiding nutrient uptake at depth as well as elevated temperatures (Dokulil and Teubner, 2000). Cyanobacteria have been found to favour higher temperatures compared with other species such as diatoms and green algae, giving them a competitive advantage under conditions of warming waters (Johnk et al., 2008). Observed changes in the timing of the bloom observed in LoW, however, are somewhat counterintuitive, with expectation that with warming waters, the bloom would occur earlier in the season. Seasonal timing of phytoplankton blooms has been reported as occurring up to 4–5 weeks earlier in the North Sea in the last 50 years in response to regional climate warming (Edwards and Richardson, 2004) and other studies have documented earlier algal blooms in the Arctic (Kahru et al., 2011). Results here suggest that while bloom intensity and extent appear to be strongly associated with lake temperatures, temporal shifts in the timing of the bloom each year appear to be driven more by variations in precipitation events and subsequent nutrient loadings to the lake.

While detailed in situ observations are essential in determining causal links between bloom dynamics and climatic forcing, this study provides, for the first time, a lake-wide quantitative assessment of recent bloom activity on LoW and offers important new insights into the factors driving bloom occurrence, timing and

<table>
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<th>Year</th>
<th>Day of peak chlorophyll</th>
<th>Peak chlorophyll concentration</th>
<th>Peak hypereutrophic aerial extent</th>
<th>April–July cumulative rainfall</th>
<th>January–August cumulative temperature</th>
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<td>0.819*</td>
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intensity on the lake. Such synoptic analyses of seasonal bloom occurrences using remote sensing are key to advancing our understanding of the mechanisms that control these potentially harmful algal blooms and in developing sound predictive models for climate change impacts on algal blooms. Continued monitoring of the lake to allow a longer term analysis may shed more light on evolving trends.

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REFERENCES


