An assessment of MERIS algal products during an intense bloom in Lake of the Woods

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Lake of the Woods (LoW) is an international (USA/Canada) inland water body under significant water quality pressures from recurring cyanobacteria blooms. Its remote location combined with the hydrologically complex nature of its waters makes adequate in situ monitoring of the lake difficult. This work aimed to test the potential of Envisat’s Medium Resolution Imaging Spectrometer (MERIS) full-resolution imagery for monitoring algal blooms in the lake. A full assessment of MERIS L1 and L2 chlorophyll and chlorophyll-related products was carried out over LoW during an intense surface algal bloom in September 2009. The Case 2 regional model and fluorescence line height/maximum chlorophyll index (MCI) plug-ins for BEAM were assessed for their ability to accurately distinguish the bloom. Results suggest that none of the Case-2-specific algorithms effectively extract chlorophyll concentrations over LoW, whereas the greatest potential is seen within the MCI product. Adjacency effects in near-shore waters are shown to be significant, although the improved contrast between ocean and land processor (ICOL) does not appear to notably improve water constituent retrievals in these waters. Images of L2 MCI are shown to adequately identify the bloom and are used to track the evolution of the bloom across the lake. Evidence is presented for the effects of variable depth distributions of cyanobacteria on the surface signal seen by the sensor; imagery suggests that day-to-day variations in wind-induced mixing have a profound impact on surface algal biomass as detected by remote sensing.

KEYWORDS: MERIS; Lake of the Woods; inland waters; chlorophyll; cyanobacteria

INTRODUCTION

Lake of the Woods (LoW) is an international inland water body spanning the Canadian provinces of Ontario and Manitoba and the US state of Minnesota and is a main tributary to Lake Winnipeg, Manitoba. LoW spans a maximum distance of 105 km from north to south and 90 km from east to west and is hydrologically complex, consisting of an expansive, shallow and well-mixed bay to the south and a large collection of deeper, occasionally stratified, interconnected basins and a series of 14 500 islands to the north. The largest inflow is from the Rainy River in the southern basin, delivering nutrient-loaded water from the predominantly agricultural land surrounding it. The lake attracts extensive recreational usage and cottage development and thus concerns have been raised over increasing...
water quality pressures. There have been anecdotal reports of increasing frequency and intensity of algal blooms in recent years, dominated by cyanobacterial populations (Chen et al., 2009). In June 2008, the US Environmental Protection Agency placed LoW on the Impaired Waters List due to nutrient over-enrichment (DeSellas et al., 2009). Although there has been basic water quality monitoring of the lake by regulatory authorities dating back to the 1950s, extensive lake-wide monitoring opportunities are costly, logistically difficult and thus sporadic, so there are few documented studies of lake dynamics and algal blooms and little is known in detail of seasonal and spatial trends in water chemistry and biological assemblages across the lake (Pla et al., 2005). The Government of Canada has invested $18 million to clean up Canada’s sixth largest freshwater lake, Lake Winnipeg, through the Lake Winnipeg Basin Initiative launched in 2007 under the Government’s Action Plan on Clean Water. As a major tributary to Lake Winnipeg via the Winnipeg River in the north, LoW plays an important role in driving Lake Winnipeg’s water quality and thus is a significant focal point of research and monitoring within this initiative. A LoW remote sensing programme was initiated within Environment Canada in order to document the potential of satellite aquatic colour sensors to adequately monitor algal blooms in the lake.

Algorithms for satellite determinations of chlorophyll, developed historically for Case-1 oceanic waters, have traditionally been based on the spectral changes in water-leaving radiance in the blue and green portion of the visible spectrum brought about by the absorption properties of chlorophyll-a (O’Reilly et al., 2000). Several studies have clearly demonstrated the inadequacy of these algorithms in producing realistic chlorophyll concentrations under optically complex conditions such as those found in turbid coastal and inland waters (Carter et al., 1989; Bukata et al., 1991; Darecki and Stramski, 2004; Dall’Olmo et al., 2005). The failure of these algorithms can be readily attributed to the additional contribution to absorption and scattering at these wavelengths from coloured non-algal particulate and dissolved organic materials. Furthermore, the known inaccuracies in atmospheric correction procedures over turbid waters are also exacerbated at short wavelengths, often producing erroneously low or negative radiances and resulting in large overestimates in chlorophyll concentrations (Moore et al., 1999). As a consequence of these difficulties, much effort has been placed in recent years on developing specific processing tools for Case-2, turbid, coastal and inland waters, particularly with respect to data from Envisat’s Medium Resolution Imaging Spectrometer (MERIS). These have included specific atmospheric correction procedures for turbid waters (Doerffer and Schiller, 2006; Schroeder et al., 2007), correction of near-shore anomalies such as the adjacency effect (Santer and Zagolski, 2009) and novel procedures for extracting water constituents (Gower and King, 2007a; Doerffer and Schiller, 2008a, b; Gower et al., 2008).

The freely available processing toolbox for MERIS (BEAM, developed by Brockman Consult under contract to the European Space Agency) incorporates many of these methods into MERIS processing routines, offering the potential for improved interpretation of remote sensing signals over optically complex waters. For open ocean waters, the standard MERIS algal_1 chlorophyll product uses the band ratio algorithm developed by Morel and Antoine (Morel and Antoine, 2007). In Case-2 waters, the standard MERIS L2 water quality products (namely algal_2, yellow_subs and total_susp) are simultaneously retrieved using the neural network algorithm of Doerffer and Schiller (Doerffer and Schiller, 1997) applied to atmospherically corrected L2 spectral water-leaving radiance reflectance. Standard L2 data processing applies a Case-1 atmospheric correction procedure (Antoine and Morel, 2005) unless a pixel is flagged as turbid, in which case the “Bright Pixel” atmospheric correction procedure of Aiken and Moore (Aiken and Moore, 2000) is activated. A BEAM plug-in, the Case-2 Regional (C2R) processor, offers a dedicated Case-2 neural network based atmospheric correction procedure (Doerffer and Schiller, 2008a) and water constituent inversion algorithms (Doerffer and Schiller, 2008b), including two inland water modules for boreal and eutrophic lakes. An issue of particular relevance to remote sensing of small inland water bodies is the adjacency effect, whereby land-reflected radiance is atmospherically scattered into the field-of-view of the sensor, and is thought to result in significant errors in measured near-shore water-leaving reflectance. Santer and Schmechtig (Santer and Schmechtig, 2000) carried out a detailed analysis of the adjacency effect, the results of which were subsequently developed as a BEAM plug-in correction called ICOL (improved contrast between ocean and land; Santer and Zagolski, 2009) which can be implemented alongside the C2R processor to correct for adjacency effects over near-shore waters. A further plug-in is available which extracts two chlorophyll-related products; the fluorescence line height (FLH) and maximum chlorophyll index (MCI). The MCI quantifies a peak in radiance near 708 nm observed under algal bloom conditions and has been demonstrated in the detection of floating Sargassum (Gower et al., 2006) and “super-blooms” of Antarctic diatoms (Gower and King, 2007b). Similarly, the FLH measures a peak in
radiance at around 681 nm associated with solar-induced chlorophyll fluorescence and has been used effectively to measure near-surface phytoplankton biomass (Gower and King, 2007a; Gons et al., 2008).

The objectives of this study were 3-fold: to test the suitability of standard MERIS water quality products for monitoring algal blooms in a hydrographically and optically complex inland water body prone to intense algal blooms; to determine any improvements brought about by adopting dedicated Case-2/near-shore water-processing algorithms; and where appropriate, use MERIS imagery to detect and monitor algal blooms in the lake.

METHOD

Field survey observations

In situ observations of water quality parameters and their associated optical properties were obtained during a field survey on the lake on 15–24 September 2009. Twenty-eight stations were sampled from both the southern basin and the northern bays (Fig. 1), capturing the onset and progress of an intense cyanobacteria bloom (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).

At each station, water samples from the surface mixed layer were obtained and filtered for the determination of phytoplankton pigments (chlorophyll a + phaeopigments, referred to simply as chlorophyll from this point on), suspended particulates (total, inorganic and organic fractions), chromophoric dissolved organic matter (CDOM) and particulate spectral absorption. Concentrations of chlorophyll were determined spectrophotometrically after extraction in acetone according to the methods of the National Laboratory for Environmental Testing (Environment Canada, 1997). Total concentrations of suspended particulate matter (SPM) were measured gravimetrically on pre-weighed 47 mm Whatman GF/F filters after rinsing with distilled water. Organic matter lost on ignition (LOI) was determined after baking the filters for 3 h at 500°C, giving the concentration of mineral SPM and, by subtraction, organic SPM.

CDOM absorption (\(a_{\text{CDOM}}\)) was measured spectrophotometrically after filtration through 0.2 \(\mu\)m membrane filters. Total particulate absorption (\(a_P\)) was measured using the quantitative filter technique after the concentration of particles on to Whatman GF/F filters [see Binding et al. (Binding et al., 2008) for methods used]. The non-algal particulate absorption (\(a_{\text{NAP}}\)) was determined after bleaching with sodium

![Fig. 1. Station locations in LoW ■, sampling sites; ★, Environment Canada Weather Station.](https://academic.oup.com/plankt/article-abstract/33/5/793/1478931 by guest on 06 January 2019)
hypochlorite and the difference between \(\sigma_{\text{NAP}}\) and \(\sigma_p\) deemed the absorption due to phytoplankton pigments. Absorption measurements were corrected for scattering errors by normalizing spectra to the average absorption measured between 740 and 750 nm assuming no wavelength dependence and using a path length amplification factor of 2 after the theoretical calculations of Roesler (Roesler, 1998). Previous independent measurements of absorption using a Wetlabs AC-9 confirmed the accuracy of the filter pad technique and adopted correction procedures (Binding et al., 2008).

**MERIS image processing**

MERIS full-resolution (300 m spatial resolution at nadir) L1b and L2 imagery was obtained from ESA’s North American rolling archive at http://oa-ks.esa.int/ra/ and processed using BEAM 4.6 (Envisat/Brockman Consult) and associated plug-in extensions. Images were subset to a geographic region bounded by the lat/lon limits: 48.5–50.2°N/93.5–95.5°W. In addition to the L2 spectral water-leaving radiance reflectance and chlorophyll products (algal_1 and algal_2), the L1b_MCI, L2_MCI and L2_FLH products were extracted using the FLH/MCI Processor 1.6.100.

The C2R processor v1.3.2 was applied to the L1b data to extract atmospherically corrected radiance and the algal product C2R Chl_conc, according to the methods of Doerffer and Schiller (Doerffer and Schiller, 2008a, b). Default settings were accepted for all processing parameters except the land–water separation expression, which was changed to “\(\text{toa_reflec}_10 > \text{toa_reflec}_6\) AND \(\text{toa_reflec}_13 > 0.01\)” because the default parameter file and resulting land mask did not accurately delineate the coastline for the region. Chlorophyll estimates from the eutrophic and boreal lakes bio-optical modules were also obtained.

As a secondary processing route, BEAM’s Smile Correction Processor 1.1.2 was applied to the original L1b data in order to correct for variations in the spectral wavelengths of each of MERIS’s five cameras and reduce the effect of camera boundaries (the so-called “smile-effect”). The ICOL Processor v. 1.0.4 was then applied to the smile-corrected L1b radiance file to correct for adjacency effects and then processed with the C2R processor, ensuring that the C2R internal smile correction was turned off. Therefore, two final C2R products were tested: the standard C2R L2 product (with internal smile correction) and the smile-corrected, ICOL-processed C2R product. For clarity, Fig. 2 presents a flow chart describing the various processing stages for each product assessed.

Clear images spanning the sampling period 15–24 September 2009 were obtained and passed through the above processing routines in order to compare the resulting chlorophyll products with in situ observations. Point data from L1b and L2 chlorophyll products

![Fig. 2. Flow chart describing the processing stages to produce each of the L1 and L2 algal and algal-related products using BEAM plug-ins.](https://academic.oup.com/plankt/article-abstract/33/5/793/1478931)
(those producing an estimate of chlorophyll concentrations) and chlorophyll-related products (those producing an index closely related to chlorophyll, such as fluorescence) were extracted for coincident in situ sampling sites from a total of six images. Images for 23 September 2009 are presented in Fig. 3 as examples of each of these products, which will be discussed below in sequence. Table II presents the results of statistical analyses comparing each product with in situ concentrations of chlorophyll through simple linear regressions. The absolute and relative root mean square errors (RMSE) of predicted chlorophyll concentrations were calculated according to Equations (1) and (2), respectively

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n}}$$

$$\text{Rel. RMSE} = \frac{RMSE}{\bar{X}} \cdot 100$$

where $X_i$ and $\bar{X}$ are the in situ and satellite-derived chlorophyll concentrations, $\bar{X}$ the sample mean and $n$ the sample size.

**RESULTS**

**Water quality and optical properties**

Table I presents the basic water quality information and optical properties for this survey and confirms the optical complexity of the waters being studied, describing turbid productive waters (Secchi depths as low as 0.3 m, chlorophyll and CDOM up to 70 mg m$^{-3}$ and 3.53 m$^{-1}$, respectively). Suspended particulates are predominantly organic in nature (mean LOI of 85%) with mineral sediments forming a significant fraction only in the southern basin.

Figure 3 presents a plot of partitioned dissolved and particulate absorption across the spectrum, whereby algal, CDOM and mineral absorption are represented as a percentage of total absorption (including pure water). Absorption components represent the average of all samples measured in this study. This confirms the dominance of CDOM absorption across much of the visible spectrum, being responsible for as much as 50% of absorption even at 580 nm. Only at wavelengths longer than 600 nm does algal absorption begin to dominate the non-water absorption signal, suggesting the need to either account for the optical properties of CDOM in methods to extract chlorophyll from visible wavelengths or consider longer wavelengths in the red and near-infrared where the contribution from CDOM may be negligible. Absorption at wavelengths beyond 700–750 nm is commonly accepted as having minimal contribution from dissolved and particulate absorption and is dominated by the strong absorption by pure water.

**Standard L1b products**

Cloud-free true colour images compiled from L1b radiance during the bloom period clearly captured the onset and progress of an intense algal bloom in the surface waters of LoW. The bloom was found to

![Figure 3. Spectral absorption of the main optically active constituents as a proportion of total absorption.](https://academic.oup.com/plankt/article-abstract/33/5/793/1478931/fig-a335-fig3)
Chlorophyll products and 10. The L1b MCI image (Fig. 4B) appeared to a baseline radiance level interpolated between bands 8 and 10. The L1b MCI image (Fig. 4B) appeared to accurately delineate the surface bloom structure as suggested both by the true colour image and field observations at the time of image acquisition. A strong correlation was found between L1b MCI and in situ chlorophyll \( R^2 = 0.74 \) with a relative RMSE in predicted chlorophyll of 39%.

Standard L2 products

The full spectral L2 reflectances are shown in Fig. 5A for those pixels with coincident in situ observations. All stations (and indeed all pixels within LoW) were seen to exhibit negative reflectance in the bands centred at 412, 443 and 490 nm, with some remaining negative across almost the entire spectrum. Despite this, spectra were indicative of high algal biomass, exhibiting strong chlorophyll absorption and fluorescence features. The standard MERIS algal_1 product (not shown), based on a simple blue to green ratio algorithm, was ineffective, with lake-wide values set to 0.009644 mg m\(^{-3}\).

<table>
<thead>
<tr>
<th>Chlorophyll-related products</th>
<th>Relationship with Chl(_a)</th>
<th>N</th>
<th>( R^2 )</th>
<th>RMSE (mg m(^{-3}))</th>
<th>Rel. RMSE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1b MCI</td>
<td>Chl(_a) = -2491FLH + 3.878</td>
<td>17</td>
<td>0.571</td>
<td>7.32</td>
<td>50.28</td>
</tr>
<tr>
<td>L2 MCI w. ICOL</td>
<td>Chl(_a) = 1457MCI(_s) + 2.896</td>
<td>17</td>
<td>0.720</td>
<td>5.91</td>
<td>40.59</td>
</tr>
<tr>
<td>L2 FLH</td>
<td>Chl(_a) = -2491FLH + 3.878</td>
<td>17</td>
<td>0.571</td>
<td>7.32</td>
<td>50.28</td>
</tr>
</tbody>
</table>

Table II: Statistics summary for a point-wise comparison between MERIS chlorophyll (Chl\(_a\)) or chlorophyll-related products and coincident in situ chlorophyll concentrations (Chl\(_a\)).
diminishing and becoming negative) in mesotrophic and eutrophic waters. It is known that in cyanobacteria, most of the chlorophyll-a molecules belong to the non-fluorescing PSI (Mimuro and Fujita, 1977), therefore the reduced fluorescence yield from this bloom may also contribute to the absence of a discernible FLH signal. This observation should be of note not only for the application of MERIS FLH but also the equivalent fluorescence product derived for the MODIS-Aqua sensor.

**C2R processor**

The water-leaving reflectance resulting from the C2R atmospheric correction appeared to be significantly improved from the standard L2 reflectance (Fig. 5B), in that the reflectances were positive and exhibited typical spectral signatures for turbid waters, although the chlorophyll-related spectral features were not as prominent as for the standard L2 spectra. The C2R atmospheric correction procedure does not include the simulation of inelastic scattering processes, and therefore chlorophyll fluorescence features are not represented. The chlorophyll product resulting from the C2R water quality processing (Fig. 4F) was not in qualitative agreement with the known bloom distribution; low chlorophyll concentrations in the northern lakes and bays were well represented but in the southern basin there was an inverse relationship with the known bloom structure. Unexpectedly, the distribution in the southern basin was opposite to that of the standard algal_2 product, which was derived using the same method after differing atmospheric correction routines. Furthermore, the concentration range was rather limited for the known conditions in the lake (the MERIS image suggests concentration ranges for the majority of lake waters of 10–15 mg m$^{-3}$, compared with the measured concentration ranges of 2–

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Fig. 4. MERIS L1 and L2 chlorophyll and chlorophyll-related products for LoW on 23 September 2009.
70 mg m\(^{-3}\), with some regions known to be far in excess of this). Derived C2R Chl_conc were in poor agreement with in situ chlorophyll concentrations, with an \(R^2\) of just 0.159 and a relative RMSE of 80%. The method overestimated moderate chlorophyll concentrations (up to \(\sim 20\) mg m\(^{-3}\)) and underestimated concentrations greater than 20 mg m\(^{-3}\).

The boreal and eutrophic modules utilize the same C2R neural network atmospheric correction algorithm but use different data sets of inherent optical properties to train the bio-optical models. These optical properties were measured in lakes in Finland and Spain classified as either boreal lakes, within which the absorption by CDOM was high, or eutrophic lakes, within which the optical properties were dominated by phytoplankton (Doerffer and Schiller, 2008b). Results of the eutrophic lake processor (Fig. 4G) also showed chlorophyll distributions directly opposite to the distribution observed in the true colour image in the southern basin. The boreal lakes processor (Fig. 4H), while producing more realistic concentration ranges, again failed to accurately reproduce the known surface bloom distribution with results in poor agreement with in situ concentrations.

### Adjacency effects and the ICOL processor

Over near-shore pixels, stray light reaching the sensor originating from land reflectance leads to erroneous elevations in L1b TOA radiance in red and near infra-red (NIR) wavebands. This so-called “adjacency effect” contributes to the over-correction of atmospheric effects over the visible bands (through the overestimation of the aerosol optical thickness), increasing the uncertainty in L2 atmospherically corrected spectral water-leaving reflectance and resulting water quality parameters. The ICOL tool was developed by Santer and Zagolski (Santer and Zagolski, 2009) to correct for these adjacency effects and is available as a BEAM plug-in for MERIS processing. The importance of adjacency effects in MERIS imagery of LoW and the efficacy of the BEAM ICOL processor were assessed using L1b images of top of atmosphere spectral radiance before and after ICOL processing. A region-of-interest mask was created to include waters within 5–10 pixels from the shore for L1 and L2 images from 23 September 2009. Analysis of near-shore versus offshore pixels confirmed strongly elevated top-of-atmosphere radiance (by up to 60%) in the near-shore zone at wavelengths greater than 700 nm relative to offshore pixels. At wavelengths less than 700 nm, the difference was reversed, but was small (less than \(-5\)%). The increase in radiance in the NIR near the shore is suggestive of an adjacency effect, although may also be brought about, at least in part, by uncertainty in the land–water separation masks, inclusion of mixed land/water pixels or simply increased near-shore turbidity.

By comparing the L1b spectral radiance before and after ICOL processing for those waters masked as near-shore and off-shore, the estimated adjacency effect was found to account for as much as 15% of the L1b radiance at wavelengths greater than 700 nm in the near-shore, whereas within off-shore waters the effect contributed less than 5%. Analysis of the band 13 radiance at 865 nm confirmed the same structure as was evident at shorter wavelengths, associated with surface distributions of algal material, and suggests that the assumption of zero water reflectance at 865 nm (as is made in the estimation of the aerosol optical thickness) may not be valid in these waters and may lead to an overestimate of the adjacency effects correction. Application of the ICOL correction within the C2R processor led to a significant increase in L2 radiance reflectance for wavelengths less than 700 nm, increasing to as much as 20% at 412 and 443 nm.

Despite an apparently significant contribution from the adjacency effect towards measured water-leaving radiance, it was evident, however, that correction using the ICOL processor did not significantly improve the retrieval accuracy of chlorophyll products using the C2R processor. Results in Table II confirmed a small decrease in the correlation between L1b MCI calculated after ICOL correction and in situ chlorophyll...
concentrations, compared with uncorrected L1b MCI. In contrast, the ICOL-corrected L2 C2R chlorophyll product showed a small improvement in the correlation with in situ chlorophyll, albeit not of great significance.

**Monitoring LoW algal blooms**

According to the results of this study, the L1 and L2 MCI produced comparable correlations with in situ chlorophyll concentrations (Table II). However, although the L1b MCI clearly shows value for qualitative identification of bloom activity, and a strong correlation was shown to exist between chlorophyll and L1B MCI over several images, there is some concern here over its use in quantitative assessments of temporal algal bloom dynamics due to the inevitable variability in TOA radiance brought about by differing atmospheric conditions. For this reason, the atmospherically corrected L2 MCI product was chosen as a tool for monitoring the onset and progress of the bloom over LoW. The ICOL processor was not used on this occasion. All clear images for the month of September were processed to assess the progress of the bloom in the lead up to and during the field survey on the lake (Fig. 6). The bloom appears to have initiated in the southern main basin of the lake with most of the northern channels remaining fairly clear. Towards the end of the month, the bloom extended further into the northern and eastern channels.

Long-term monitoring of the lake has been conducted by the Ontario Ministry for Natural Resources Fisheries Assessment Unit, under which the lake is routinely divided into seven sectors that have been defined as limnologically and geologically distinct (DeSellas et al., 2009). Regional differences in MCI within these sectors (the boundaries of which are shown in Fig. 7) were analysed in order to study in more detail the progression of the bloom in the lake. Region-of-interest polygons were created for each of zones 1–7, and statistics for each region were extracted from every available clear image. The median MCI for each zone during the bloom is presented in Fig. 7 and highlights the


**Fig. 6.** Time series of MERIS L2 MCI in LoW, September 2009.
variations in bloom conditions between the seven demarcated zones. Zone 3 to the east of LoW exhibited the least productivity, with MCI being below a detectable peak throughout the year. Zones 4–7 showed signs of earliest bloom activity, with higher background MCI in the lead up to the main bloom initiating in late August/early September around day 243. Zones 4 and 5 appeared to bloom most intensely first, with zone 7 reaching a similar magnitude towards the middle of September (~day 257) and zone 6 a few days later towards the end of September (~day 265). Zone 2 exhibited significantly lower MCI during August but also showed evidence of a bloom initiating on day 243, with zone 1 blooming almost 2 weeks later. Zones 1 and 2 showed both shorter and less intense bloom activity than the central and southern zones. Beyond day 257, the bloom in all zones was highly variable, fluctuating in intensity from day to day. Altogether, the zone separation suggested a progression in bloom activity from an early, intense and prolonged bloom in the southern, western and central zones and a later, less intense and shorter bloom in the northern portions of the lake, with eastern sections exhibiting no notable bloom activity for the entire period. These observations are consistent with the nutrient loadings to the lake, known to be predominantly from the Rainy River, which leads to high phosphorous and nitrogen concentrations throughout the southern part of the lake, with moderate concentrations in the north-central zones and low concentrations at sites away from the main south-north flow of water (DeSellas et al., 2009). The area contained within zone 3 is fairly isolated from the main direction of water flow and is therefore less likely to be influenced by nutrient loadings from the southern part of the lake.

The imagery in Figs 6 and 7 confirmed a highly dynamic bloom, with much variability over short time scales and with the bloom seemingly disappearing from the lake suddenly between one day and the next. This observation prompted an assessment of meteorological forcing on the lake and its effects on bloom dynamics. Hourly wind data were available from an Environment Canada weather station (Fig. 1), the analysis of which suggested a close agreement between lake-wide MCI and wind speeds (Fig. 8); peaks in MCI coincided with periods of reduced wind speeds (centred around days 247, 256, 261 and 268) and minima in MCI coincided with periods of elevated wind speeds (centred around days 242, 252, 259, 264 and 270). This was indicative of the repeated surfacing and mixing of algal material during calm and turbulent periods, respectively. It is suggested that during wind events, algal cells were dispersed through the water column, thus decreasing the
surface biomass seen by the satellite sensor, whereas during calm conditions, the positively buoyant cells rose to the surface en masse creating an intense bloom which was clearly seen from space. That there were no discernible peaks in MCI during wind events prior to the bloom (Fig. 8; days 220–240) suggests that the method is fairly independent of the effects of mineral resuspension, which is also supported by the absence of any enhanced MCI signal in shallow near-shore areas where strong resuspension might be expected.

The buoyancy effects of cyanobacteria are well documented (see Moreno-Ostos et al., 2009); cells possess the ability to form gas-filled cavities that reduce cell density making them float to the surface. This vertical migration through the water column enables access to optimal levels of light and nutrients. The influence of wind-induced mixing on the surface accumulation of positively buoyant cyanobacteria can be described using the function $\Psi$ (see Oliver and Ganf, 2000):

$$\Psi = 1 - \frac{5W_s}{u_*}$$

where $W_s$ is the floating velocity of the cyanobacteria and $u_*$ is the wind-induced surface shear velocity, which can be calculated according to:

$$u_* = \left( \frac{\rho_a K_u U^2}{\rho_w} \right)^{0.5}$$

where $\rho_a$ and $\rho_w$ are the density of air (1.2 kg m$^{-3}$) and water (1000 kg m$^{-3}$) respectively, $K_u$ is the surface drag coefficient ($1.3 \times 10^{-3}$) and $U$ is the wind speed (m s$^{-1}$) 10 m above the water surface. A floating velocity for $A$. flos-aquae of 22 m day$^{-1}$ ($25 \times 10^{-3}$ m s$^{-1}$) was used after observations by Walsby et al. (Walsby et al., 1995).

For $\Psi > 1$, turbulent mixing is minimal such that the buoyancy effects of the cyanobacteria cells allow surface biomass accumulation to occur; whereas for $\Psi < 1$ the buoyancy effects are overwhelmed by turbulent mixing such that the cells are vertically mixed through the water column. The threshold wind speed above which a surface bloom of $Aphaniizonmenon$ might be dispersed is 3 m s$^{-1}$ and is shown in Fig 8 to accurately distinguish the conditions of surface algal accumulation from more dispersed algal populations as inferred from the MCI signal.

**DISCUSSION**

This paper presents an assessment of the MERIS L1 and L2 chlorophyll and chlorophyll-related products for LoW, a productive, optically complex inland water body bordering both Canada and the USA. Statistical and qualitative analysis of the MERIS chlorophyll products confirmed that none perform adequately in monitoring bloom conditions on LoW. All pixels in the lake were flagged as turbid, therefore activating the “Bright Pixel Atmospheric Correction” procedure of Aiken and Moore (Aiken and Moore, 2000), which assumes that a significant portion of the radiance at 708, 778 and 865 nm is attributable to suspended particulate scattering. Here, the significant non-zero water-leaving reflectance in the NIR was driven almost exclusively by algal particulates, not mineral, which along with the chlorophyll-related reflectance peak at 708 nm may have caused the failure of this atmospheric correction procedure under these conditions.

Despite producing more realistic reflectance spectra, the C2R processor, ICOL processor and resulting chlorophyll products did not appear to provide superiority over the standard L2 products. This is in agreement with other studies that suggest that the benefits of the ICOL processor are still somewhat uncertain. The ESA-funded project “Development of MERIS lake water algorithms” produced a validation report on the use of the C2R and ICOL processors in a number of European and African lakes and reported contradictory findings that ICOL improved the agreement between MERIS and in situ spectral reflectances, but did not improve the estimates of water quality constituents (Koponen et al., 2008). Odermatt (Odermatt et al., 2009) assessed the C2R and ICOL processors over oligo- and meso-trophic perialpine lakes and reported that MERIS products perform better without the ICOL processor. Kratzer et al. (2008) carried out an assessment of an additional MERIS Case-2 water properties processor developed by Schroeder et al. (2007) in coastal waters of the Baltic Sea, but it seems only fairly limited assessment and validation of any of these processors has been carried out over turbid productive waters.

Results presented here identified a limited range of retrieved chlorophyll concentrations, with C2R underestimating high chlorophyll and overestimating low chlorophyll concentrations. This is in agreement with the results of Odermatt et al. (Odermatt et al., 2009) who observed overestimated chlorophyll concentrations in the range 9–20 mg m$^{-3}$ in European alpine glacial lakes and Ruiz-Verdu et al. (Ruiz-Verdu et al., 2008) who showed overestimated chlorophyll concentrations for Lakes in Finland for concentrations in the range 3–15 mg m$^{-3}$. Low concentrations (below 3 mg m$^{-3}$) were suggested by both authors to be underestimated by the C2R processor. Overestimated chlorophyll concentrations by the C2R processor could be attributed at
least in part to the apparent inability of the C2R processor to accurately determine the contribution to the remote sensing signal from yellow substance, which was shown here to be a major contributor to the optical properties of LoW.

Within the C2R processor, there is a quality control feature (chi-square) which determines, on a pixel by pixel basis, whether the reflectance spectrum is within the range of the simulated set of reflectances used to train the neural network (Doerffer and Schiller, 2007). Chi-square was greater than 4 (the threshold above which results are deemed out of the scope of the algorithm) for a large number of the pixels over the lake during the survey dates, ranging from 47 to 72% of the total pixels over water. Of those pixels coincident with in situ observations used to test the models, this was less, at 29%. These figures suggest that a large proportion of LoW waters are not appropriate to the current C2R processor. However, agreement between C2R chlorophyll estimates and in situ observations was not significantly improved by removing stations with $\chi^2 > 4$ from the analysis (Chl$_i$ = 0.788Chl$_M$ + 6.672, $R^2 = 0.212$, RMSE = 12.02, Rel, RMSE = 86.42, n = 12). The negative correlation between in situ chlorophyll and MERIS-derived chlorophyll concentrations under the C2R eutrophic processor (shown in Table II) was driven predominantly by three stations which fall out of the scope of the algorithm. As with the results of the standard C2R processor, however, removal of these stations resulted in no improvement in the correlation (Chl$_i$ = $-0.0159Chl_M + 16.409$, $R^2 = <0.01$, RMSE = 12.46, Rel, RMSE = 89.58, n = 13). The C2R chlorophyll products are produced using an inversion technique based on neural networks to simultaneously retrieve all water constituents. Perhaps by increasing the ranges of inherent optical properties used in the training of the neural networks to include a greater variety of optically complex waters, the C2R lakes processors might be improved to provide more broadly applicable water quality products.

The MERIS chlorophyll-related products (L1 and L2 MCI, FLH), on the other hand, produced acceptable correlations with in situ chlorophyll concentrations, demonstrating potential for their use in monitoring intense algal blooms on the lake. This suggests that despite obvious and extreme deficiencies in the standard atmospheric correction procedures over these waters there may still be value in the derived L2 data, particularly when non-ratio products are derived and short wavelength visible bands are avoided. Regardless of frequent negative radiances across the spectrum, it appears that the L2 MCI product, because it measures the relative difference between bands rather than a band ratio, or absolute radiance, still produces valuable, and indeed fairly accurate, estimates of algal distributions over inland waters. A regional fit to the MCI may therefore be the most appropriate tool for monitoring chlorophyll concentrations under bloom conditions in LoW, although more extensive validation is proposed. The strong correlations between in situ chlorophyll and MERIS MCI products were in some respects surprising considering the highly dynamic nature of this bloom and the fine-scale variability in surface accumulations observed in the field. Clearly subpixel variability of this magnitude would contribute significantly towards the unexplained variance in these correlations. Furthermore, the relationship between chlorophyll concentrations and MCI would depend on the algal populations present and the associated variations in their pigment composition and optical properties, so further consideration of the effects of variable inherent optical properties (IOPs) may provide an enhanced product, and this is the subject of ongoing research. Although the effects of variable IOPs would clearly have a critical effect on the retrieval accuracy of methods adopting full-spectrum analyses, the wavelength dependency of the MCI product means that it is first almost entirely independent of CDOM, except perhaps in the most extreme conditions, and also appears to be fairly robust under the effects of mineral sediments. A further potential source of error might be in any contribution to the remote sensing signal from bottom reflection. This certainly might be a contributing factor in the failure of those algorithms adopting wavelengths with greater penetration depths; however, for the conditions observed in this study, it is estimated that 90% of the satellite-measured MCI signal originated from just the top 15–50 cm of the water column, thus largely eliminating concerns regarding bottom reflectance.

For this study, the L2 MCI product was extracted for a time series of images during an intense cyanobacteria bloom in September 2009 during which coincident in situ samples were obtained. The imagery showed a highly dynamic bloom evolution as observed by the satellite sensor and suggested evidence of repeated mixing and re-surfacing of algal cells in response to wind-induced mixing on fairly short time scales. The effect of such variable depth distributions on satellite determinations of blooms has attracted some interest in recent years. Kutser et al. (Kutser et al., 2008) modelled the variability in remote sensing reflectance for a variety of simulated vertical distributions of cyanobacteria and confirmed that the vertical structure of the distribution of cyanobacteria biomass in the water column would have serious impacts on the remote sensing reflectance spectra. From these spectra (their Fig. 3b, for
20 mg m\(^{-3}\) of chlorophyll), we estimate that the MCI would increase 3–4-fold (from roughly 0.001 to 0.003–0.004) between situations of vertically mixed chlorophyll to those where chlorophyll is concentrated in the surface layer (their “Top 1m” or “Slope” profiles). The maximum variation in LoW lake-wide average MCI over a fairly short time period was seen here (Fig. 8) to be from 0.004 to 0.0014, a factor of 3.5, thus corroborating the modelling results of Kuster et al. (Kutser et al., 2008).

Several investigators have stressed the importance of conducting in situ bloom monitoring on short time scales in order to adequately characterize such dynamic processes (Moreno-Ostos et al., 2009) but this would be logistically and financially demanding. This work clearly demonstrates the benefit of frequent, synoptic, observations of inland water algal blooms from satellite remote sensing. Results suggest, however, the need to in some way both consider the vertical distribution of algae in algorithm development and fully resolve the depth distribution of in situ sampling for validation exercises. Perhaps in combination with a 3D hydrodynamical model describing vertical water column structure, imagery such as this may produce significant improvements in comprehensive cyanobacteria monitoring activities on LoW.

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