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An analysis of satellite-derived chlorophyll and algal bloom indices on Lake Winnipeg

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ABSTRACT

Lake Winnipeg has experienced dramatic increases in nutrient loading and phytoplankton biomass over the last few decades, accompanied by a marked shift in community composition towards the dominance of cyanobacteria. Comprehensive lake-wide observations of algal blooms are critical to assessing the lake's health status, its response to nutrient management practices, and an improved understanding of the processes driving blooms. We present an analysis of the spatial and temporal variability of algal blooms on Lake Winnipeg using satellite-derived chlorophyll and indices for algal bloom intensity, spatial extent, severity, and duration over the period of ESA's MERIS mission (2002–2011). Imagery documented extensive blooms covering as much as 93% of the lake surface. Bloom conditions were analysed in the context of in-lake and watershed processes to gain further insight on the drivers of bloom events. Day to day bloom variability was driven primarily by intermittent wind mixing events, with quiescent periods leading to the formation of dense surface blooms. Seasonal bloom distribution was consistent with light limitation in the south basin and lake circulation transporting bloom material towards the north-east shore. Inter-annual variability in average bloom severity was related to both total phosphorus (TP) loadings and summer lake surface temperatures. Results provide a valuable historical time series of bloom conditions to which ongoing observations from Sentinel-3's OLCI sensor can be added for longer term monitoring and change detection.

Introduction

Many regions of Canada have seen increases in the frequency and magnitude of harmful algal blooms (HABs), posing serious threats to the integrity of fresh and marine aquatic ecosystems and significant public health risks (Pick, 2016; Winter et al., 2011; Stumpf et al., 2012; Watson et al., 2008; Kling, 1998). Lake Winnipeg (Manitoba) for example has experienced a major shift in trophic status in recent decades resulting in widespread severe algal blooms and earning it the dubious titles of "Canada's Sickest Lake" (MacDonald, 2009) and "Threatened Lake of the Year" (Global Nature Fund, 2013). The major concern is with cyanobacteria-dominated HABs, which not only impair the quality and integrity of surface waters but also have the potential to produce potent toxins affecting humans and other organisms. Lake Winnipeg supports multiple ecosystem services, e.g. commercial fisheries, leisure and recreational activities, the generation of hydroelectric power, and is an important drinking water resource; therefore, the proliferation of HABs can lead to significant socio-economic costs. The impact of these blooms is dependent on their timing, location, severity and species composition, and their effective management requires an understanding of the complex interaction of physical, chemical and biological factors which drive them (Anderson et al., 2002; Bertani et al., 2017).

In addition to the fundamental role of nutrient enrichment in promoting algal blooms, biogeochemical processes altering nutrient stoichiometry and bioavailability can modify in-lake nutrient retention and cycling and have a significant impact on bloom conditions (Isles et al., 2015; Matisoff et al., 2017). Meteorological forcing contributes to hydrodynamic processes which affect turbidity, circulation and residence times, and the magnitude and timing of river discharges (Mitrovic et al., 2003; Verspagen et al., 2006). Long and short term variance in lake temperature can have multiple effects on HAB formation, location, and composition, for example by influencing ice cover, thermal stability, moderating algal growth rates and species dominance (Butterwick et al., 2005; Kosten et al., 2012; Paerl and Huisman, 2008). Extreme weather events can promote sporadic bloom occurrences (Michalak et al., 2013; Paerl and Huisman, 2008) while wind mixing and circulation patterns modify their vertical distribution and advective transport (Moreno-Ostos et al., 2009; Kanoshina et al., 2003). The introduction of invasive species and associated ecosystem alterations (Vanderploeg et al., 2001) may also contribute to short and long term variations in bloom location, severity, and composition. Resolving the role of these processes remains a significant challenge to

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understanding day-to-day, seasonal, and inter-annual variability in bloom conditions (Bertani et al., 2017; Isles et al., 2015).

While algal blooms on Lake Winnipeg (LW) have been a natural, historical occurrence, accelerated nutrient loading over the last two decades has led to an increase in the frequency, severity and extent of blooms (McCullough et al., 2012; Bunting et al., 2016; Kling et al., 2011). The watershed, spanning an area of approximately 1 million km^2, has experienced considerable change since the middle of the last century brought about by intensified agricultural practices and livestock production, urban development, and changing hydrology (Bunting et al., 2016; Schindler et al., 2012). Nutrient loading to the watershed has increased dramatically (Schindler et al., 2012) and changes in runoff and river discharge patterns have led to more frequent and intense spring floods (McCullough et al., 2012; Schindler et al., 2012; Bunting et al., 2016). McCullough et al. (2012) reported a doubling of phosphorus concentrations in LW between 1990 and 2000, accompanied by considerable increases in algal abundance (Lévesque and Page, 2011; Schindler et al., 2012). A state change from mixed algal assemblages to a dominance of cyanobacteria, particularly nitrogen fixing species, has also been reported, along with concerns over possible increases in toxigenic species of cyanobacteria (Kling, 1998; Kling et al., 2011; Lévesque and Page, 2011).

The threatened state of LW and potential for further decline in ecosystem integrity led the Province of Manitoba and the Government of Canada to announce the Lake Winnipeg Basin Initiative (LWBI) in 2007, a program aimed at supporting local stewardship action, monitoring, and research activities, to address the impacts of nutrient enrichment and to inform watershed-based nutrient-reduction strategies. Targets have been set by the Province of Manitoba to reduce phosphorus levels by 50% in an effort to restore lake conditions to a pre-1990 state and reduce the frequency and severity of algal blooms (ECCC, 2013). Comprehensive lake-wide observations of the extent and severity of algal blooms on the lake are critical to assessing the lake's response to implemented nutrient management practices, as well as further understanding in-lake and watershed processes driving spatial and temporal variability in algal bloom conditions.

Earth observation satellites offer frequent, synoptic views of inland waters that enable quantitative assessments of algal biomass and have been used to provide valuable insights into bloom conditions in turbid eutrophic lakes similar to LW (e.g. Lake of the Woods: Binding et al., 2011a; Lake Erie: Stumpf et al., 2012). Chlorophyll retrieval algorithms for turbid eutrophic waters often make use of wavebands in the red and near-infra-red, which capture the red-edge reflectance feature associated with dense surface algal blooms (Gower et al., 2008; Gilerson et al., 2010). The Maximum Chlorophyll Index (MCI) and similar red/near-infra-red algorithm approaches have been well validated in turbid eutrophic waters and are considered to be fairly independent of the effects of high DOC and mineral scattering as well as the uncertainties in reflectance brought about by the challenges of atmospheric correction over turbid eutrophic inland waters (Gower et al., 2008; Gilerson et al., 2010; Binding et al., 2013). Binding and Zeng (2017) derived a suite of quantitative indices for algal bloom intensity, spatial extent, severity, and duration, based on MCI-derived chlorophyll. These bloom indices have been applied to the OLCI sensor (Ocean and Land Colour Instrument) on the European Space Agency's (ESA) Sentinel-3 satellite, launched in February 2016, and are now used routinely by Environment and Climate Change Canada (ECCC) for fully automated bloom monitoring of several turbid eutrophic lakes in Canada (including Lake Winnipeg). In order to assess temporal changes in LW blooms and provide baseline bloom conditions for future change detection, those bloom indices have been applied to historical imagery from ESA's MERIS (Medium Resolution Imaging Spectrometer) sensor for the period 2002–2011. Here we present an assessment of the MERIS-derived chlorophyll and algal bloom indices in order to describe seasonal and inter-annual variations in bloom conditions on LW. Bloom indices are in turn analysed against key environmental and meteorological variables to assess the role of these factors in bloom development on the lake.

Methods

Description of study area

LW (Fig. 1) is the 10th largest freshwater lake in the world, covering a surface area of 23,750 km^2. It consists of a shallow, well-mixed, and turbid South Basin (SB), and a deeper, clearer North Basin (NB), separated by a narrow and hydrologically complex channel (the Narrows). The average depth of the lake is 9 m in the SB and 13.3 m the NB, with the deepest waters (up to 60 m) found within the Narrows. The lake has a relatively short residence time of 3 to 5 years (Lévesque and Page, 2011). Flow is generally northward from the SB through the Narrows, to the outflow of the lake at the Nelson River, which drains north-east into Hudson Bay. The majority of the riverine input is delivered via the Red River (16% of the inflow, draining an agriculturally dominated watershed) and Winnipeg River (49% of the inflow, draining a predominantly boreal watershed) into the SB and the Saskatchewan River (25% of the inflow, originating in the foothills of the Canadian Rockies) into the NB. Despite lower discharge, the Red River is typically the main source of nutrients to LW, contributing 68% of the annual total phosphorus (TP) load (Lévesque and Page, 2011). LW is characterised by low water clarity brought about by high concentrations of dissolved organic matter and localised mineral resuspension. The lowest water clarity is observed in the shallow south basin due to the discharges from the Red River (sediment laden and nutrient rich) and Winnipeg River (CDOM rich) and wind-driven sediment resuspension. Highest water clarity is typically observed in the deeper NB.

Satellite image processing & analysis

MERIS full resolution (300 m spatial resolution at nadir) level-1 imagery was obtained through the ESA/VEGA Technologies ordering system Eoli-sa, and processed using the freely available MERIS processing toolbox (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 2002–2011 were selected. The time-series is limited to 2002–2011 due to the failure of the MERIS sensor in the spring of 2012, after which no comparable spectral satellite data was available for the extraction of the MCI until the launch of OLCI. Images were subset to a geographic region bounded by the latitude/longitude limits 50.0–54.0°N/95.5–99.5°W, and processed to the level-1 MCI using the FLH/MCI Processor 1.6.100 plug-in extension. The MERIS MCI quantifies a peak in radiance near 700 nm observed under algal bloom conditions, measured as the height of radiance in band 9 (centred at 708 nm) relative to a baseline interpolated between bands 8 (681 nm) and 10 (753 nm). The relationship between in situ surface chlorophyll-a concentrations (Chl) and coincident (exact day match ups) MERIS L1-MCI is consistent with those observed in the similarly turbid waters of Lake of the Woods and Lake Erie (Fig. 2). Eq. (1), from a linear least-square-fit to the LW dataset was subsequently applied to daily cloud free MERIS imagery of LW to convert the L1-MCI to surface Chl.

$$\begin{aligned} &\mathrm{LW\ Chl} = 5.8433\mathrm{MCI}_{L1} + 9.45 \\ &R^2 = 0.807,\ n = 27,\ p<0.01 \end{aligned} \tag{1}$$

In addition to chlorophyll retrievals, a selection of quantitative algal bloom indices were derived (Table 1). The algal bloom flag was raised on a pixel by pixel basis when Chl was in excess of 10 $\mu g\ l^{-1}$. All subsequent indices were measured only on those pixels flagged as a bloom. Mean bloom Chl gives a measure of the overall intensity of the bloom,