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Linking year-to-year *Cladophora* variability in Lake Ontario to the temperature contrast between nearshore and offshore waters during the spring

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ABSTRACT

Images from thermal satellite sensors clearly show the spatial and temporal characteristics of surface temperature distributions during the spring heating period in Lake Ontario. The satellite information combined with summertime beach closure data at Ontario Beach, Rochester, NY, shows that there is a correlation of the percent of summer beach closings caused by accumulation of algae (primarily *Cladophora*) with the cumulative temperature contrast between nearshore and offshore waters during the spring heating period. The physical conditions created by a rapid warming of the nearshore water during the spring warming period appear to generate conditions favorable to *Cladophora* growth in the summer. The results of this study suggest that satellite thermal observations of Lake Ontario in the spring can be used to better understand year-to-year variability of *Cladophora* growth as well as potential reactions to climate change.

Introduction

The rapid warming of nearshore waters in contrast to cold, deep, central lake waters is the primary feature of hydrodynamics during spring in the North American Great Lakes and other large temperate lakes (Malm et al., 1994; Schertzer et al., 1987; Shimaraev et al., 1993; Spain et al., 1976). In Lake Ontario, vertical stratification of the nearshore waters occurs on average about 3 weeks before warming and the onset of vertical stratification in the central waters of the lake. This springtime temperature contrast can affect the circulation pattern of the lake and trap nutrients from tributary runoff and from resuspended sediment in the nearshore water, and thus influence the nearshore biota including benthic algae such as *Cladophora*. The characteristics of spring heating in Lake Ontario and its influence on cross-shore (perpendicular to the shore) exchange were quantified by Rao et al. (2004), who found that cross-shore exchange coefficients were significantly reduced during the spring heating period. This concept is supported by the findings of Moll et al. (1993), who observed high plankton productivity and locally abundant fish populations in the vicinity of the warm-cold boundary. This general pattern of nearshore nutrient enrichment along the south shore of Lake Ontario on 28 May 2008 was also observed and sampled by Makarewicz et al. (2012a).

However, the impacts of the nearshore to offshore gradients on the biota are complicated by recent changes to the nearshore ecology in the North American Great Lakes from the effects of colonization by zebra and quagga mussels (*Dreissena*) in areas that have hard bottom substrates. The invasive mussels are very efficient filters. Their removal of phytoplankton from the water column results in greater light penetration (Holland, 1993; Leach, 1993) and thereby increased area for algae growth as well as redistributing nutrients from the water column to the bottom. Several recent studies have highlighted the importance of this redistribution of nutrients to ecological processes (Hecky et al., 2004; Higgins et al., 2008; Mills et al., 2003; Zhu et al., 2006). One consequence of the nutrient redistribution appears to be the resurgence of the benthic algae *Cladophora* (Barbiero and Tuchman, 2004; Hecky et al., 2004; Higgins et al., 2008; Mills et al., 2003).

Higgins et al. (2008) summarize the various factors that influence *Cladophora* growth, including presence of hard substrate, adequate light and nutrients, and temperature. There is wide variation in the growth response of *Cladophora* to temperature reported in the literature. Minimum temperatures to initiate *Cladophora* growth are reported to range from 6 °C (Bellis, 1967) to 11 °C (Moore, 1978). Reported optimal temperatures for *Cladophora* growth are even higher and also vary widely, from 13 °C to 31 °C. Lester et al. (1988) suggest an experimentally determined optimum of 25 °C, Graham et al. (1982) showed an optimum range of 13 to 18 °C, and Bellis (1967) reported vigorous growth between 15 and 30 °C. Thus nearshore *Cladophora* growth in spring in Lake Ontario is not likely to begin until after the shallow nearshore waters have warmed above 4 °C and, in general, even warmer temperatures are necessary for optimal growth.

Despite the general resurgence of *Cladophora* in Lake Ontario, large variations in the impacts of *Cladophora* die-off during the summer have been observed along the southern shore of Lake Ontario.

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This variation is captured in the records maintained by the Monroe County Health Department beach monitoring program for Ontario Beach in Rochester, NY. For this paper we will use an 11-year set of observations from 2000 through 2010. Specifically, in 2003, 2006, 2008, and 2009 there was very little impact at Ontario Beach from *Cladophora* die-off during the summer (<8% of closings due to algae accumulation). In 2002, 2005, and 2010 there was a moderate amount of beach closings (<20%) due to algae accumulation. In contrast, in the summers of 2000, 2001, 2004, and 2007 the accumulation of *Cladophora* at the beach was a frequent reason for beach closures (≥23%). This variability in annual accumulation of *Cladophora* does not appear to be caused by changing nutrient levels in the lake-wide water column. Further, lake-wide average clarity is currently stable (Binding et al., 2007), hard bottom substrate is very stable, and mussel lifespan is more than a year. However, each year during the spring heating period, elevated, but spatially variable concentrations of phosphorus and nitrogen in the nearshore of Lake Ontario occur (Howell et al., 2012; Makarewicz et al., 2012a,b). One potential driver of the observed variability is year-to-year change in climate forcing of water temperature during the spring heating period and thus variability in the physical control of nutrient distributions as previously described. The *Cladophora* data collected at Ontario Beach and thermal satellite data used to create the Great Lakes Surface Environment Analysis surface temperature data product offer the opportunity to test the influence of physical forcing by examining the relationship between spring heating and summertime *Cladophora* growth as measured by algae accumulation along the shore in southern Lake Ontario. The goal of this work is to establish if there exists a signal in the springtime thermal imagery that relates to *Cladophora* accumulation in the summertime. The identification of a signal in the thermal imagery that can be linked to *Cladophora* accumulation will advance the development of multivariate models for predicting *Cladophora* growth.

Methods

Remote sensing data analysis

The satellite data products used to study the nearshore and lake-wide heating behavior were acquired from the Great Lakes Surface Environment Analysis (GLSEA). The GLSEA is a daily digital map of the Great Lakes surface water temperature produced at the National Oceanic and Atmospheric Administration (NOAA) CoastWatch Great Lakes Node. The GLSEA image product of water surface temperature imagery is obtained from NOAA Polar Operational Environmental Satellites (POES). The POES satellites carry the Airborne Very High Resolution Radiometer (AVHRR) imaging sensor. Each satellite passes over a given area twice a day. The AVHRR has five radiometric bands including three thermal infrared channels: Channel 3 (3.55–3.93 μm), Channel 4 (10.3–11.3 μm), and Channel 5 (11.5–12.5 μm) that have been used to implement various multi-channel sea surface temperature algorithms (Leshkevich et al., 1993, 1997; Schwab et al., 1999). The GLSEA image data size is 512 by 512 pixels from 1994 to mid 2003, and 1024 by 1024 pixels from mid 2003 to present. Lake surface temperatures are updated daily with information from the cloud-free portions of the previous day's satellite imagery. If no imagery is available due to cloud cover, a smoothing algorithm is applied to the previous day's map. We obtained the yearly temperature data as an ASCII file along with the Great Lakes water mask that is used to correctly register the data and recreate the lake image.

For each year of the study, images from year day 90 to year day 180 were analyzed to determine the time history of surface temperatures for a nearshore region in the Rochester Embayment and for surface temperatures of an offshore region north of the Rochester Embayment. Fig. 1 is a representative example of a daily surface water temperature image of Lake Ontario created from the GLSEA ASCII data. The locations of the nearshore and offshore regions used for determining surface temperatures are indicated in Fig. 1. By inspection of Fig. 1 it is clear that for other locations around the lake the definition of nearshore and offshore regions with respect to distance from shore will vary.

The time histories of springtime heating of the coastal waters for each year from 2000 to 2010 were determined by examination of three measures of temperature derived from the images. First, the average surface temperature within the nearshore region was calculated for the western Rochester Embayment from the Genesee River piers west for about 10 km (Fig. 1). The average temperatures rather than the individual pixel temperatures were used here to provide a general sense of nearshore warming less influenced by local stream inputs and local circulation patterns. For each year, the first day when the average water surface temperature in this region exceeded 4 °C was identified. Since 4 °C is the temperature of the maximum density of water, this date indicates the onset of vertical stratification in nearshore waters. Second, the time histories of the springtime heating of the deep waters for each year from 2000 to 2010 were determined by examining the 5-day moving average minimum surface temperatures within the offshore region north of the Rochester Embayment (Fig. 1). For each year, the day that the smoothed minimum temperature in the offshore region consistently exceeded 4 °C was identified. These dates indicate the completion of vertical stratification in these deep waters. The difference between the dates of nearshore stratification and offshore stratification is the number of days defined here to be the duration of the primary heating season. Finally, for a measure of temperature contrast between the nearshore region and the offshore region, the temperature differences between the values calculated for the two regions for each year day were found and summed over a systematically varied range of year days. Within this matrix of date ranges for the temperature contrast calculation, the earliest start date was year day 105 and increasing to the latest start date of year day 125, in 5-day intervals. The choice of year day 105 as the earliest start date was dictated by the presence of shoreline ice in 2008 and 2009 in the GLSEA time series images until just prior to day 105. The end date for the range varied from 10 days after the start date up to year day 175, at 5-day intervals.

Field data

Ontario Beach on Lake Ontario is a public beach monitored by the Monroe County Health Department and is located in the Rochester Embayment just west of the Genesee River piers, Rochester, New York USA (Fig. 2). Ontario Beach is typically completely closed for one-quarter to one-third of the beach season (late June to the end of August) due to any of five criteria determined by the Monroe County Health Department: accumulated algae, poor water clarity, high local rainfall, prior day bacterial counts, or high Genesee River flow. For this study, only the accumulated algae data are examined. The data records of the Monroe County Health Department do occasionally specify the genus of algae, e.g., *Cladophora* or *Spirogyra*, but most often the generic term “algae” is recorded. However, for the years with the highest accumulation volumes (2000, 2001, and 2007) the observed algae is most often specified to be *Cladophora*.

Accumulated algae is cited by the Monroe County Health Department as a closure criterion because of increased bacterial counts that are associated with the decay of the algae as well as the reduction in water clarity due to the organic debris in the water. The beach is closed when estimated algae or other organic debris volume exceeds 42.5 cubic meters. The 42.5-cubic meter measurement applies to any section of the beach and is used as a way to characterize the density of algae concentrated along the beach. For measurement purposes, the Monroe County Health Department splits Ontario Beach, which is overall approximately 400 m long, into four sections. The eastern most section adjacent to the piers is always closed. The other three sections of the beach are sampled according to the