Estimation of the width of the nearshore zone in Lake Michigan using eleven years of MODIS satellite imagery

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Abstract:

The nearshore zone, that region of water directly influenced by its proximity to the coast, has received increasing attention in recent years. The extent of the nearshore zone has been defined by some constant descriptive feature: e.g., a specific depth or a particular distance offshore. This type of definition does not allow for the dynamic nature of the relationship between the land and water and how it may be influenced by local, seasonal, or transient effects. Here satellite observations examined evaluate how the width of the nearshore zone in Lake Michigan varies with position along the coastline and with time. Satellite-derived estimates of chlorophyll concentration along seventy-one shore-normal transects spaced approximately 10 km apart around the lake were used to determine the width of the nearshore zone, defined as the point at which the estimated chlorophyll concentration close to the shore approaches the more-uniform offshore concentration. Of a total of 23,807 transects extracted from MODIS observations made between 2003 and 2013, we successfully fit a bi-linear model relating chlorophyll concentration to distance offshore to 15,996. We found that the width of the nearshore zone is variable, both seasonally and spatially. Although the overall median width of 4.5 km (mean width 5.3 km) closely corresponds to the 5 km value used in a number of Great Lakes studies including Lake Michigan, ten percent of the estimates are greater than 8.9 km, likely representing times of enhanced mixing and transport of nearshore waters into the offshore.

Keywords

Coastal Zone, Remote Sensing, Water Quality, Spatial and Temporal Variation

Introduction

The nearshore zone of the North American Great Lakes has received increased attention (Makarewicz and Howell 2012, Mackey and Goforth 2005, Kelly et al. 2015, Yurista et al. 2016) based largely on its importance as the receiving water for tributary-borne chemicals and the emphasis placed on the nearshore in the recently signed Great Lakes Water Quality Agreement (Canada and the United States 2012). Nutrients introduced into the nearshore zone through tributary input, direct discharge and non-point input are associated with the problems of *Cladophora* growth (Higgins et al. 2012,), local eutrophication (Makarewicz and Lewis 2015) and botulism outbreaks (Chun et al. 2013). The nearshore also provides important habitat for many fish species (Lane et al., 1996a 1996b), and its relatively high productivity has become increasingly important in light of the recent oligotrophication of the offshore of a number of the Great Lakes (Barbiero et al., 2012, Estepp and Reavie, 2015). Inherent in the nearshore shunt hypothesis (Hecky et al. 2004) is the physical constraint of water movement in affecting nearshore-off shore movement of nutrients, now heavily influenced by dreissenid mussels. Furthermore, environmental problems in the nearshore are evident to the public who use the zone for recreation, and at water intakes supplying in-basin communities.

The nearshore has been defined in various ways depending on the processes under consideration, though a specific quantitative rationale for any particular definition has often been lacking. Early attempts to identify regions distinct from the uniform offshore area were made in relation to the benthos, which are relatively sedentary and exhibit notable zonation, and were based on physical characteristics, such as the lower limit of wave-action, fluctuation in temperature and the beginning of light diminution, as well as benthic community structure (Shelford 1913, Smith, 1874). Subsequent interest in eutrophication emphasized spatial differences in nutrient concentrations and production with distance from shore [as well as higher variability] (Holland and Beeton, 1972; Ladewski and Stoermer 1973; Gregor and Rast 1979). In this context, Mortimer (1975), while warning that precise unqualified definitions of the nearshore were impractical due to seasonal and short-term changes in hydrographic conditions, suggested nonetheless a zone from 8 to 16 km, while in a later consideration of nearshore currents in the same report, a nearshore strip about 10 km wide was suggested as delimiting the main transfer of energy from wind to total basin motion. The width of this coastal boundary layer (Csanady 1972a, 1972b, 1984; Rao and Schwab 2007) is seasonally variable and influenced by winds inducing upwelling and downwelling (Masse and Murthy 1992). Schelske et al. (1980) suggested a zone of higher nutrient loading, stronger currents and more pronounced wave effects within the 30 m contour, which he pointed out was roughly equal to Mortimer's 10 km limit. In neither case was an attempt made at a quantitative approach to the definition. Alternatively, the nearshore has been defined as the deepest point at which the thermocline intersects the lake bed in late summer and early fall (Edsall and Charlton, 1996), taken in their report as corresponding to the 10-m contour in Lake Superior and the 30-m contour in the other Great Lakes.

Various operational definitions of the nearshore zone have been used in monitoring studies: Lake Ontario (Bertram 1985), 10 km; Lake Michigan, 8 km [called offshore, not open water] (Rockwell et al. 1980); Lake Erie, 7 km (Rathke 1984). Due to differing nearshore bathymetry, a fixed depth contour can result in wide variation in distance from shore. Yurista et al. (2015) used a mixed criterion of either 30-m depth or 5-km distance from shore if 30-m depth had not been reached by that point.

Having a quantitative definition of the nearshore area has become more relevant to the Great Lakes since the signing of the Great Lakes Water Quality Agreement of 2012. Annexes 2 and 4 of the Agreement specify that the governments of the United States and Canada: 1) provide an overall assessment of the state of the nearshore Waters of the Great Lakes, 2) establish priorities for nearshore prevention, restoration and protection measures based on consideration of nearshore and whole-lake factors, 3) maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the Great Lakes and, 4) establish objectives for phosphorus concentrations for the open waters and nearshore areas of each Great Lake. While these goals may be achievable without a consistent definition of the nearshore area of the Great Lakes, quantifying the nearshore, using an observable property (phytoplankton density as estimated by chlorophyll a), links directly to water quality concerns and would remove uncertainty for assessment and the setting of nearshore objectives.

Given the economic and ecological importance of the nearshore, monitoring and assessment covering nearshore region that can be described quantitatively may be desirable. Designing such a program would require a definable sample-frame (Yurista et al., 2015). While this is only one of the difficulties involved in developing a nearshore monitoring program, a statistically based nearshore zone estimate is desirable.

These measurement frame-based definitions of the nearshore are, in concept, similar to the definitions of the Great Lakes nearshore that result from the biological, chemical and/or physical water properties being studied (Rao and Schwab 2007, Mackey and Goforth 2005, Edsall and Charlton 1996). Definitions of the nearshore in these studies rely on bathymetric contours or the strength and directions of coastal processes. In many cases the result is depth or distance from shore delineating the nearshore.,

The approach that we take here to investigate a new surface water-based definition of the nearshore zone uses MODIS satellite imagery to assess transects, drawn perpendicular to the local shoreline, for changes in chlorophyll concentration between the relatively homogeneous offshore portions of the transects, and a break point where chlorophyll values rise toward shore. Although several studies (Bergmann et al. 2004; Lohrenz et al. 2008) have found that the satellite-estimated concentration of chlorophyll in the surface waters of Lake Michigan decreases with distance from shore, these studies have been limited in both their spatial and temporal coverage. Our aim here is to take full advantage of satellite observations to examine the dependence of chlorophyll concentration on distance from the coast on position and time around the lake and throughout the year.

Satellite-derived chlorophyll measurements have been used to assess Great Lakes features (Lesht et al. 2002, Kerfoot et al. 2008) and harmful algal bloom development (Stumpf, et al. 2012). The use of chlorophyll measurements to identify the nearshore is not unprecedented. Howell et al. (2012) and Makarewicz et al. (2012) included chlorophyll a in a suite of measurements to empirically determine nearshore:offshore differences. It can be argued that phytoplankton (measured as chlorophyll a) which responds to nutrient loading (Lohrenz et al., 2008) is a relatively robust measure of nearshore:offshore differences and can be used to assess the nearshore, or nearshore:offshore differences in Lake Michigan (Lohrenz et al. 2004, 2008).

Methods

Satellite Observations

The surface chlorophyll-a estimates we used in this study were obtained by applying the Great Lakes Fit (GLF) retrieval algorithm (Lesht et al. 2013, Lesht et al. 2016) to observations made by the MODerate-resolution Imaging Spectroradiometer (MODIS) flown on NASA's Aqua satellite. The raw spatial resolution of MODIS imagery is approximately 1-km at nadir though the actual pixel spacing depends on the geometry of the image and on the location of the pixel within the image. To maintain the fidelity of the original chlorophyll estimates, we did not map or grid the chlorophyll estimates but rather used the raw L2 (geophysical units) values.

We followed the method described by Nezlin et al. (2012) to generate a series of shore-normal, 30-km long transects spaced 10-km apart around the lake from approximately 45.0N latitude south. This northern latitude limit was chosen to avoid the complications posed by the entrances to Green Bay on the west and Grand Traverse Bay on the east. Transects were defined by two points: their starting (shoreline) and their ending (farthest offshore) positions. A total of 71 such transects were generated (Figure 1).

Given the transect definitions, we extracted the satellite data corresponding to each pixel along the transects from every Lake Michigan MODIS image collected between 2003-2013 by using the out=track module of NASA's SeaDAS (v6.4) system (Baith et al. 2001). We defined a complete transect as one for which no more than two pixels were missing; pixels could be missing because of cloud cover, failure of the retrieval algorithm, or because the pixel falls on land. The exact number of pixels comprising an individual transect extraction varies depending on the satellite viewing geometry. For the 23,807 complete transects we extracted, the number of pixels/transect ranged from 8 to 31, with a median of 21. Because the image pixels are discrete, the maximum distance of the most offshore pixel from the starting point of the transect also varies. The range of maximum distances was 25.08 km to 34.24 km. The distribution of maximum distances was nearly symmetric with a mean of 29.93 km and median of 29.94 km. The range of resolution (linear distance represented by an individual pixel) of the transects was 0.99 km to 3.57 km with a mean of 1.49 km.

In addition to distance from shore, we assigned an estimated water depth to each extracted pixel by matching its geographic position to a 1-min resolution bathymetric grid of the Lake (Schwab and Sellers, 1980).

Model fitting

The fundamental hypothesis upon which this study is based is that the chlorophyll concentration will show some dependence on the distance from shore. Chlorophyll concentrations tend to be higher nearshore because nutrient concentrations fueling phytoplankton growth generally are higher closer to shore (Figure 2).

We experimented with two models for describing the change in chlorophyll concentration with distance offshore. The first model was expressed as an exponential decay function

$$c(x) = c_0 + c_1 e^{-\alpha x} + \epsilon \quad (1)$$

in which $c(x)$ is the modeled chlorophyll concentration a distance x from the shoreline, c_0 is the concentration far away from shore ($x >> 0$), $c_0 + c_1$ is the concentration at the coast ($x = 0$), α is a decay constant (units of km^{-1}) and ϵ represents random error.

The second model we considered represents the change in chlorophyll concentration as a bi-linear function of the distance along the transect from shore. Written as

$$c(x) = \alpha + \beta(x-\theta)_- + \beta'(x-\theta)_+ + \epsilon, \text{ in which} \quad (2)$$

$(x-\theta)_-$ represents the minimum of x and θ, $(x-\theta)_+$ represents the maximum of x and θ, β is the slope of the first linear segment, β' is the slope of the second linear segment, θ is the distance at which the two linear segments intersect, and α is the y-intercept of the second segment. Equation (2) may be re-written in terms of the join point (θ) as

$$c(x) = \begin{cases} \alpha + \beta'(x - \theta) + \epsilon, \ x > \theta \\ (\alpha - \beta\theta) + \beta x + \epsilon, \ x \leq \theta \end{cases} \quad (3)$$

We chose to use the bi-linear model in this study because the intersection point between the two line segments can be interpreted unambiguously as the distance from shore where the coastal water is no longer distinguishable from the offshore water. Although the exponential decay model appears to involve one fewer parameter than the bi-linear model, determination of the nearshore/offshore interface location would require introduction of another arbitrary scaling value (e.g. a value of the ratio c(x)/(c0+c1)), analogous to the 1% light level often used to define the photic depth.

We used the R (R core team, 2014) package lm.br (Adams, 2014) to fit the bi-linear model (Eq. 3) to each of the extracted transects. We considered the fit of the model to be acceptable if it satisfied all of the following criteria: (1) the slope of the first linear segment (closest to shore) was negative (concentration decreased away from shore); (2) the significance level (p) of the model was <0.001; (3) the join point (θ) was less than 25 km from shore; (4) the intercept of the first linear segment (representing the coastal concentration boundary condition) is lower than 64.0 mg/m^3 (maximum valid concentration); (5) there were least two pixels inshore of the estimated join point; and (6) the uncertainty associated with the estimated joint point is less than 2.5*average pixel size of the transect. Of the 23,807 extracted transects, 15,996 were accepted and 7,811 rejected. The reasons for rejecting the model fit are summarized in Table 1. Figure 3 shows examples of the bi-linear model fit for both successful and unsuccessful cases.

Results

The distribution of nearshore widths determined by the bi-linear model is truncated on the low end by the requirement that two or more pixels be inshore of the break (Figure 4a). This is a consequence of the nominal one kilometer spatial resolution of the MODIS sensor. Using the distance from shore at which the breakpoint occurred in each of the accepted transects (15,996) as the definition of nearshore width, the mean nearshore width was 5.3 km, while the median was 4.5 km. Overall range of nearshore widths was 1.03 km to 24.42 km. The nearshore widths were at or below 3.4 km for the first quartile of the measurements, while the next two quartiles, or fifty percent of the measurements were between 3.4 km and 6.3 km. The remaining twenty-five percent were wider than 6.3 km. The frequency distribution of depths associated with transect widths (Figure 4b) has a median depth of 24.4 m and a mean depth of 30.9 m. The 25^{th} and 75^{th} percentiles are 18.0 m and 36.4 m respectively. There is an exceptionally long right tail associated with depths of greater than 150 m where the nearshore width extended 20 km or more in areas of steeper bathymetry...When results from all transects are combined by month (Figure 5), there is little difference in overall lake estimates of nearshore width or depth. However, it is apparent that the outliers in the box plot constitute a considerable proportion of all the estimates.

To examine spatial differences in nearshore width, we divided the lake into sectors on east-west (using the N/S lake axis) and north-south (43.415 degree N latitude) lines (see Figure 1).

Monthly median nearshore widths (Figure 6) indicate systematic differences among the sectors, and some differences among months or seasons. The northeast sector nearshore width ranged from 3.5 km in March and September to 4.8 km in June. Southeast nearshore widths were somewhat higher with a maximum of 6.7 km in May declining for the remainder of the year with lows of 4.3 km in August and September. Overall, the southwest sector had largest nearshore widths ranging from 4.8 km in September to 6.3 km in March. The northwest sector had its smallest nearshore width in April (3.8 km) and rose slowly to a high of 4.6 km in August. It is evident that bathymetry also effects the nearshore width. The southern half of the lake has a gentler depth gradient, and nearshore widths are generally greater those in the north where depth gradients are steeper.

Depth of nearshore boundary

In the northeast sector nearshore depth ranged from 25.5 m in March to 44.2 m in June, the largest range in any sector. The southeast nearshore depth was more constant, ranging from 23.5 m in September to 28.4 m in May. Both southwest and northwest sector nearshore depths were shallower than the eastern half of Lake Michigan, with the southwest ranging from 12.9 m (September and October) to 16 m in March and April, while the northwest nearshore depth ranged from 18.5 m in March and April to 20.2 m in August.

Seasonality

To examine seasonality, we divided transects into those that occurred before or after stratification was established. This was defined operationally by date. Transects from March 1 until May 31 were considered unstratified. Transects from July 1 through September 30 were considered stratified. June was considered a transition month, where stratification becomes established, and was not included in either category. A comparison of these two periods over the entire lake showed a significant difference (Kruskal Wallis, $p < 0.0001$) in nearshore width between the unstratified (4.82 km) and stratified conditions (4.28 km).

All areas of the lake considered in this study had significant differences in nearshore width between stratified and unstratified conditions (Kruskal Wallis, all $p < .006$. As might be expected from the overall greater nearshore width during unstratified conditions, the nearshore width in three of four sectors was larger during stratification. Two sectors were of interest because of the magnitude of nearshore difference between seasons or the seasonal direction of change of nearshore width. The southeast sector displayed greater median nearshore width (5.90 km stratified, 4.41 unstratified) during unstratified months (Kruskal Wallis, $p < 0.0001$), while the northwest sector had greater median nearshore width under stratified conditions (3.91 km stratified, 4.23 stratified) versus stratification (Kruskal Wallis, $p < 0.001$).

There are a number of possible causes for these patterns in nearshore width. The introduction of nutrients from river outflow would become evident as enhanced phytoplankton densities (here measured by chlorophyll), varying with the amount of nutrient and the discharge volume of water into the nearshore. Additionally, water mass movement, in onshore or offshore directions, associated with predominant wind directions and periods of high wind speeds may play a role in changes to nearshore extent.

Tributary input to the nearshore

In order to investigate the first of these possibilities, we compiled the average daily discharge data for the Fox River, near its entry to Green Bay, and the St. Joseph River at the gauging station nearest Lake Michigan for the years 2003 through 2013, matching the range of satellite imagery. The satellite transects chosen for the analyses were 1) the transect immediately south of the mouth of the Sturgeon Bay Ship Canal as it enters Lake Michigan and 2) the transect immediately north of the mouth of the St. Joseph River. With primarily cyclonic currents nearshore (Schwab, et al. 1995, Beletsky and Schwab 2001) these transects are the most likely to be influenced by discharge from the Fox and St. Joseph Rivers. The western, Sturgeon Bay, transect receives an attenuated signal from the Fox River. The Fox River plume follows the east shore of Green Bay (Modlin and Beeton, 1970, Lathrop et al. 1990) and may exit through the Sturgeon Bay ship canal particularly during periods of southwest wind (Miller and Saylor, 1985). However, during other periods, the main points of exit from Green Bay are north of the Door Peninsula.

Perhaps due to the intermittent nature of Fox River water discharge through the canal, we found no significant relationship between nearshore width and Fox River discharge, with lags of up to ten days (Spearman rank correlation: $p > 0.3$ in all cases). There was a small, but significant relationship between nearshore width and St. Joseph River discharge when matching discharge and width from the same day (Spearman rank correlation: $p<.0005$, $r=0.22$), and smaller correlation coefficients when discharge was lagged up to several days.

Seasonal wind patterns effecting the nearshore

Wind data from the Milwaukee, WI, airport were retrieved as monthly averages of direction for the period 2003 to 2012. Data were divided into the periods March through May and July through October. The overall average wind direction, θ, was estimated by using the formula:

$\theta = \mathrm{Atan2}(V_e, V_n)$

$V_e = \Sigma p_i \sin \theta_\iota$ and

$V_n = \Sigma p_i \cos \theta_\iota$

Where V_e and V_n are the E/W and N/S wind vectors and p_i and θ_t are respectively, the proportion of time and angle of wind direction over the season.

The spring, unstratified period, average wind direction was from the ENE at 68^o , while the average summer direction was SSW at 228^o. It is difficult to quantify the relationship between wind direction and nearshore width. However, the differences between stratified and unstratified nearshore widths in the northwest and southwest sectors of the lake must certainly be affected by predominant wind direction. ENE winds would force surface water nearer to the west shore and move it away from the east shore in spring, while SSW winds would reverse the water movement pattern during stratification. In addition to the direction of wind, the duration and average wind speed differed between seasons with measurable wind occurring during 92.2% of the unstratified period with an average wind speed of 4.88 meters per second, while measurable wind occurred during 89.9% of the stratified season with an average wind speed of 4.05 meters per second. The seasonal difference in wind stress, proportional to the square of the velocity, is approximately 45% higher during unstratified conditions. The larger wind forcing during unstratified conditions is evident in the overall larger nearshore width.

Higher offshore winds facilitate mixing of nearshore water with open water and result in wider transient nearshore zones. Setting a criterion of nearshore width greater than or equal to 8.9 km, the upper 10 % of nearshore widths, and separating the transects by lake sectors, we find differences between the sectors in the proportion of transects with nearshore widths at or exceeding this criterion (Table 2). The southeast and southwest sectors predominate in mixing of nearshore into offshore. Transects with large estimated nearshore widths likely represent an important mechanism of mixing, and may be the proportion of transects that represent intrusions of nearshore into offshore water, representing the flux of nearshore nutrients across the average nearshore boundary to the offshore.

Discussion

In recent Lake Ontario nearshore research (Makarewicz, et al. 2012, Howell, et al. 2012), information based on in situ sampling showed the nearshore width to vary, with water of higher total phosphorus and chlorophyll concentrations extending to 4 or 5 km from shore on the south shore of the lake (Makarewicz et al. 2012) and to similar distances on the north shore (Howell et al. 2012). This corresponds roughly with the outer edge of the coastal boundary layer (Rao and Schwab, 2007), a region dominated by along-shore versus cross-shore currents and water movement. This is the area of coastal entrapment (Csanady 1984), where materials introduced to the nearshore tend to remain.

Our estimates of nearshore width based on satellite-derived chlorophyll transects vary, on average, between 3.7 and 5.9 km depending on section of shoreline and season. While these values encompass a greater range of nearshore widths than indicated by Makarewicz et al. 2012b and Howell et al. 2012, the data contributing to the estimates are different in collection method and especially, in frequency. The field measurements of the nearshore made on Lake Ontario occurred several times over the year, and were made from boats traveling patterned routes with dimensions of approximately 5 km in the cross-shore direction to tens of kilometers in the along-shore direction. These sampling surveys require considerable time and effort and provide spatially intense data, but are snapshots in time. Despite sampling only twice during the 2008 season, Makarewicz et al. 2012 were able to detect the outer edge of total phosphorus plumes four to, five kilometers from shore. The bathymetry of the coastal region of Lake Ontario is also steeper than much of Lake Michigan, which likely influence the nearshore width differences observed.

Yurista et al. (2016) suggest criteria for nearshore sampling of 30 m depth or 5 km from shore, whichever comes first. These are based on a comparison of EPA offshore water quality measurements and samples from a region based upon their suggested criteria. Variability of parameters in the nearshore region was higher than those offshore, and most parameter means differed significantly between the two regions. The bases for their criteria appear to be, 1) the depth at which the thermocline intersects the lake bottom, 2) the zone in which one can measure tributary influence and 3) hydrodynamic processes. Our data support this a priori determination of the nearshore with median and mean depths and widths of 24.4 and 30.9 m and 4.5 km and 5.3 km respectively

The nearshore zone of the Great Lakes varies over time and space (Yurista et al. 2015). It is an area directly affected by local tributary input (Makarewicz et al. 2012, Howell et al. 2012, Twiss and Marshall 2012) and wind (Csanady 1984). While the generally cyclonic circulation of large lakes (Schwab et al. 1995) may entrain tributary water discharged into the nearshore currents, the velocity and buoyancy of the river plume are partial determinants of the distance offshore that the plume moves, before turning to follow the shoreline due to the Coriolos effect (Masse and Murthy 1992) or entrainment in coastal currents (He et al. 2006)). Once moving along shore, the plume may remain trapped for some distance during periods of weak winds (Csanady 1984). Upwelling-favorable winds force the plume offshore and those favoring downwelling concentrate the plume in a narrower band along shore (Masse and Murthy 1992). Makarewicz et al. (2012) document the latter, narrowing effect of downwelling-favorable winds. Movement of nearshore water away from shore can occur as either part of an upwelling event, or a coastal jet

(Csanady and Scott 1974). The physical coastal boundary layer, which includes our nearshore measurements also varies by season (Csanady 1972a, 1972b), a feature found in our nearshore estimates. Physical constraints and mechanisms of water movement, along shore and perpendicular to shore, have been quantified by measurement and generalized through modeling. Our measurements of nearshore width agree well with the coastal boundary layer width dimension and demonstrate the variability associated with wind driven processes. Quantifying an average nearshore width and demonstrating its variance reinforces physical quantifications of coastal zones and provides a statistical water quality-based delineation of the nearshore.

Satellite-derived chlorophyll measurements have been used to assess Great Lakes features (Lesht et al. 2002, Kerfoot et al. 2008) and harmful algal bloom development (Wynne et al. 2013). The use of chlorophyll measurements to identify the nearshore is not unprecedented. Howell et al. 2012 and Makarewicz et al. 2012 included chlorophyll a in a suite of measurements to empirically determine nearshore:offshore differences. It can be argued that phytoplankton (measured as chlorophyll a) which responds to nutrient loading (Lohrenz 2008) is a relatively robust measure of nearshore:offshore differences and can be used to assess the nearshore, or nearshore:offshore differences in Lake Michigan (Lohrenz et al. 2004, 2008). While the nearshore can be identified by other water properties, particularly specific conductance, and measures of suspended solids (Makarewicz and Lewis 2015), these measures are likely to change over short periods of time through mixing or settling, respectively. Algal growth and chlorophyll synthesis rely on rapid uptake of soluble nutrients. Chlorophyll might be expected to persist at measurable levels after soluble nutrients concentrations have been reduced below measurable levels.

Algorithms for determining surface chlorophyll from satellite imagery perform reasonably well in open water situations (Lesht et al. 2002, 2013, 2016; Shuchman et al. 2013) but may have some inaccuracy in more complex waters (Lohrenz et al. 2008, Harding et al. 2005) where they may overestimate chlorophyll a values when compared with measured in situ concentrations (Mortimer 1988). However, the algorithms have been useful when investigating relative differences in Great Lakes and marine coastal areas (Lohrenz et al. 2008, Acker et al. 2005, Harding et al. 2005). While accuracy of the algorithms for coastal waters can be improved using simultaneous nearshore extracted chlorophyll measurements (Trinh et al. 2017), such measurements were beyond the scope of this paper. While it is true that application of the GLF algorithm to coastal observations is an extrapolation beyond the domain in which the algorithm has been verified (Lesht et al. 2016), we found that only 2.4% of the observations exceeded the concentration value (~ 8 mg m^{-3}) beyond which the GLF uncertainty becomes large. Of course, because the shoreline boundary condition is determined on the basis of extrapolation of the model (Eq. 3) results, the estimated values at x=0 may be higher. We argue, however, that even if the retrieved values of chlorophyll are inaccurate, the fact that they are based on an observed optical property of the water (in this case, the remote sensing reflectance) indicates that something affecting this property (be it chlorophyll concentration, suspended sediment, and/or concentration of colored dissolved organic material) is changing as a function of distance from shore. For our purposes, chlorophyll concentration based on the band ratio is a convenient proxy for whatever it is that distinguishes nearshore from offshore waters.

Conclusions

In agreement with nearshore hydrodynamic features of the Great Lakes (Rao and Schwab 2007), the median nearshore widths for all areas and seasons ranges only from 3.7 km to 5.9 km, within the range of the coastal boundary layer. The overall lakewide median nearshore width is 4.5 km with a distribution that displays a long right-hand tail with some nearshore width estimates at over 20 km. Both observations may have significance in how we view or measure the nearshore, and how materials are moved within the lake.

The Great Lakes Water Quality Agreement, as part of Annexes 2 and 4, specifies that the governments of the United States and Canada: 1) provide an overall assessment of the state of the nearshore Waters of the Great Lakes, 2) establish priorities for nearshore prevention, restoration and protection measures based on consideration of nearshore and whole-lake factors, 3) maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the Great Lakes and, 4) establish substance objectives for phosphorus concentrations for the open waters and nearshore areas of each Great Lake. While these goals may be achievable without a consistent definition of the nearshore area of the Great Lakes, defining the nearshore, particularly based on observable properties, would remove uncertainty for assessment and objective setting.

The majority (59%) of nearshore widths from the entire dataset are five kilometers or less, and 75% are 6.3 km or less. We suggest a 5 km nearshore width definition for the Lake Michigan nearshore as both water quality and physical measurements support values close to this. When nearshore widths exceed 5 km, it is likely that winds and tributary inputs are moving surface waters offshore into deeper, open lake areas. The number of transects with estimated nearshore widths greater than our suggested 5 km indicates the utility of the methodology for understanding mixing of nearshore and offshore waters. Ten percent of nearshore widths were greater than 8.9 km, indicating movement of water with higher chlorophyll and associated nutrient levels lakeward from shore. That is, water initially entrained by physical processes in the nearshore is mixed into offshore, open water, with some frequency. Frequency of these mixing events varies annually and seasonally. The median depth associated with the 5 km nearshore is, at 22.3 m, only slightly deeper than the 20 m depth contour used in some nearshore work (e.g. Yurista et al. 2015). As sampling logistics and plans seem to rely more on distance offshore than depth (Makarewicz et al. 2012, Howell et al. 2012), the water quality based nearshore width distance has practical appeal.

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Table 1. Distribution of rejection criteria for unacceptable bi-linear model fits to the Lake Michigan transect chlorophyll data.

Criterion	Slope	P value	θ distance	*C(0)*	Points	θ uncert
Number	1833	2934	18	20	1179	1827

Table 2. Number of nearshore width estimates greater than 8.9 km, by lake sector and month, with the total number of 'good' transects during the month and sector.

	March	April	May	June	July	August	Sept.	Nov.
NE > 8.9 km	1	5	24	27	34	29	10	12
NE Total	291	436	389	496	741	817	731	417
NW > 8.9 km	3	1	10	36	32	73	45	15
NW Total	286	527	490	446	479	543	532	235
SE > 8.9 km	96	83	99	48	39	49	50	70
SE Total	479	554	399	459	685	786	762	600
SW > 8.9 km	112	102	102	71	77	121	97	50
SW Total	438	515	422	333	424	503	516	264

Figure Captions:

Figure 1. Lake Michigan shore-normal transects with lake sector divisions. Bathymetric contours are at 25 meter intervals

Figure 2. Estimated chlorophyll concentrations versus distance along transect for 10 transects off the eastern shore of Lake Michigan in 2013. Transects are identified by shore point latitude, dots are retrieved values color-coded by month, and curves represent the locally weighted smoothed (LOESS) relationship for all the data.

Figure 3. Example fits of the bi-linear model (Eq. 3) to data collected between March 19 and March 26, 2009 from the transect located at 41.7233 N along the eastern shore of Lake Michigan. Panel (a) illustrates a case of model failure because the uncertainty of x* was too large (> 2.5 times the average pixel size), panel (b) illustrates a successful fit of the model, panel (c) illustrates a case of model failure because the significance level of the model fit exceeded 0.001, and panel (d) illustrates a case of model failure because there were too few points (pixels) inshore of the join point

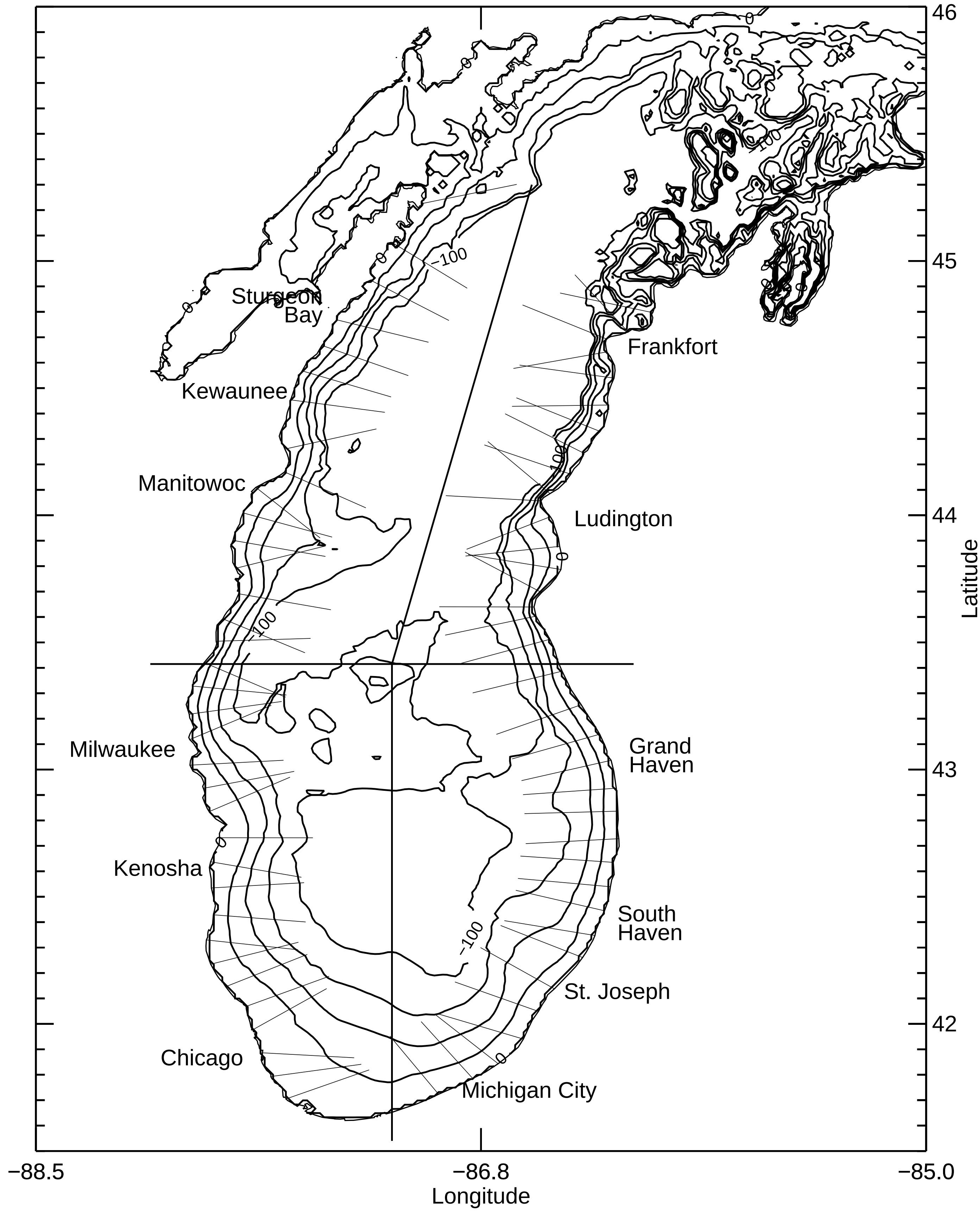
Figure 4. Nearshore width (A) and depth (B) frequency distributions, all years and transects. Box and whisker plots show the 5^{th} and 95^{th} percentiles (whisker limits), 25^{th} and 75^{th} percentiles (box limits), mean (*), and median (vertical line) of each distribution.

Figure 5. Boxplots showing distribution of nearshore width (top) and depth (bottom) estimates by month. Box limits are 25^{th} and 75^{th} percentiles, whisker ends are 5^{th} and 95^{th} percentiles, and

dots show individual values of the largest 5% estimates. Box widths are proportional to the number of estimates in each month.

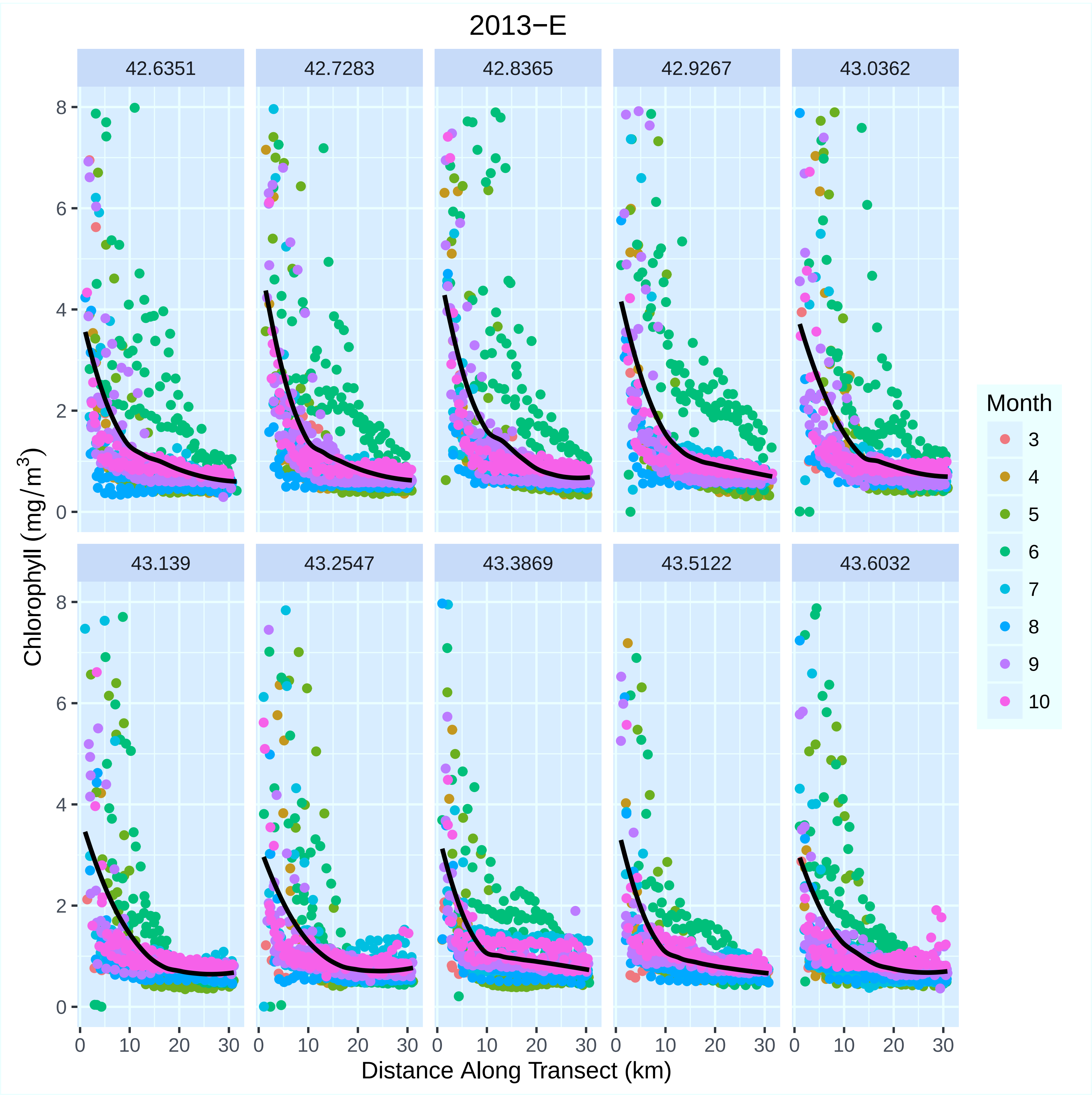
Figure 6. Monthly median nearshore width (a) and depth (b) by lake sector. Error bars represent 25^{th} and 75^{th} percentiles.

Figure 1



46
45
44
43
42
Latitude
−88.5
−86.8
−85.0
Longitude
Sturgeon
Bay
Kewaunee
Manitowoc
Milwaukee
Kenosha
Chicago
Michigan City
St. Joseph
South
Haven
Grand
Haven
Ludington
Frankfort
−100
0

Figure 2



2013−E
42.6351
42.7283
42.8365
42.9267
43.0362
43.139
43.2547
43.3869
43.5122
43.6032
Chlorophyll (mg/m3)
Distance Along Transect (km)
Month
3
4
5
6
7
8
9
10

Figure 3

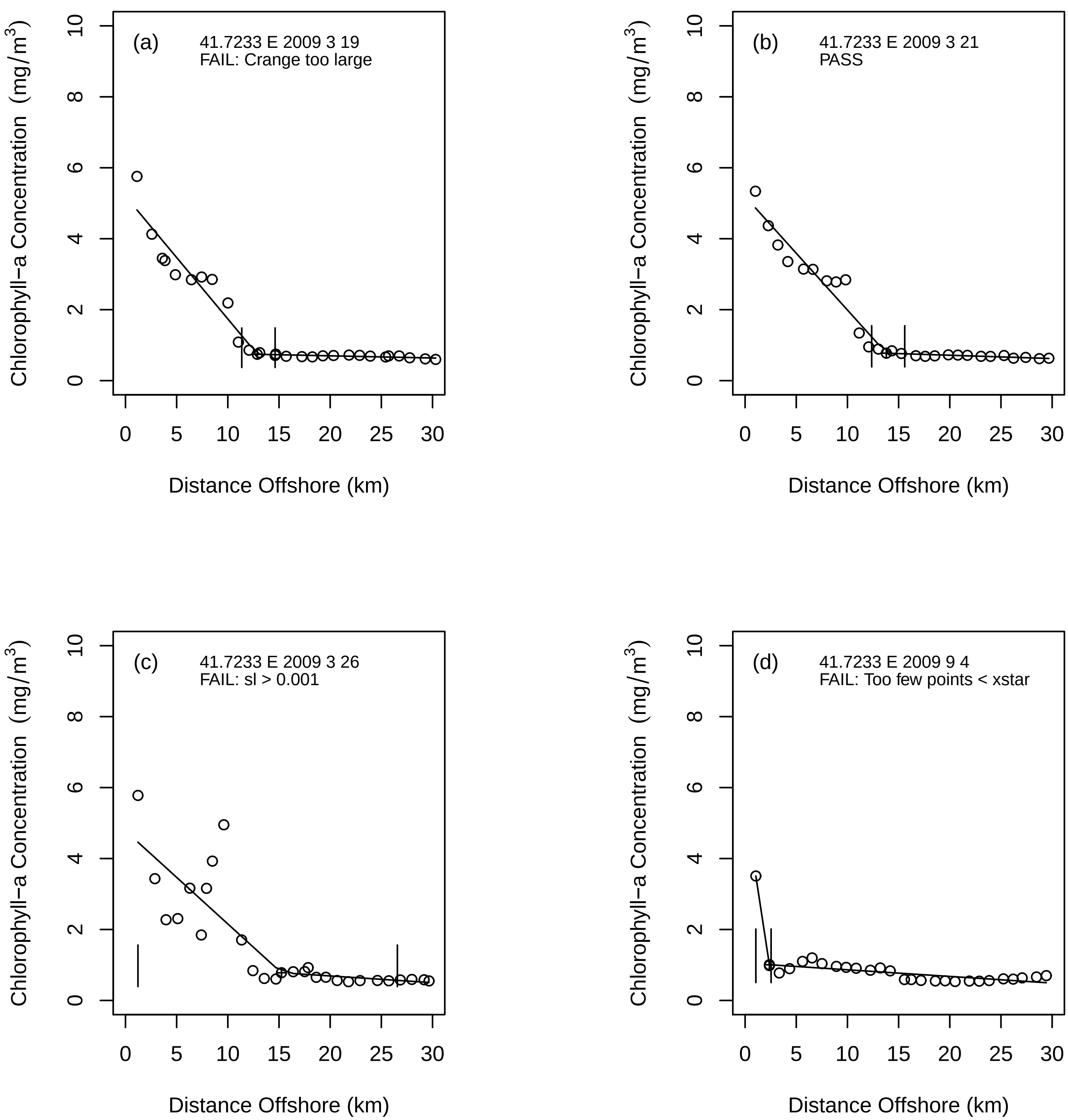

(a)
41.7233 E 2009 3 19
FAIL: Crange too large
(b)
41.7233 E 2009 3 21
PASS
(c)
41.7233 E 2009 3 26
FAIL: sl > 0.001
(d)
41.7233 E 2009 9 4
FAIL: Too few points < xstar
Chlorophyll−a Concentration (mg/m3)
Distance Offshore (km)
0
2
4
6
8
10
0
5
10
15
20
25
30

Figure 4

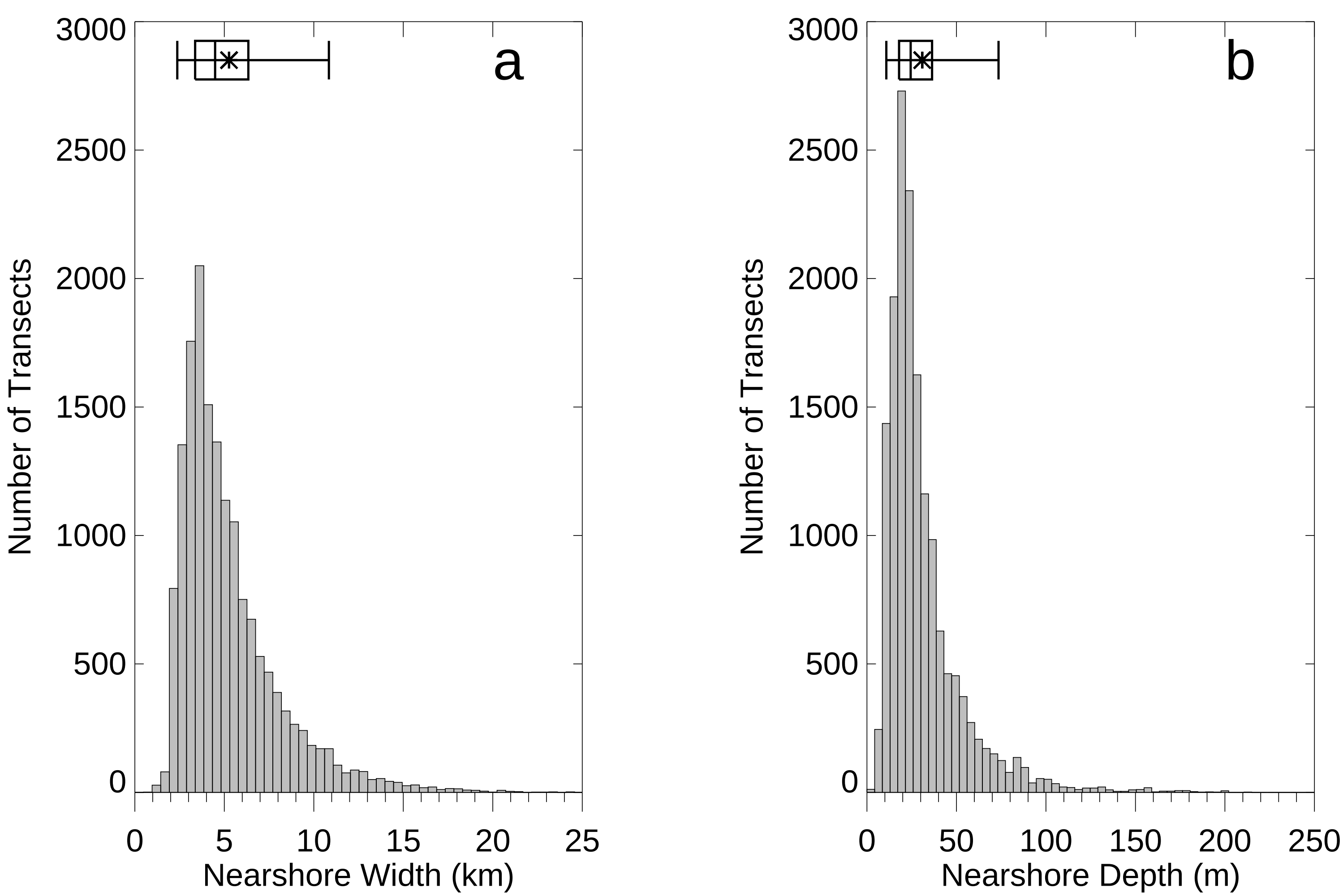
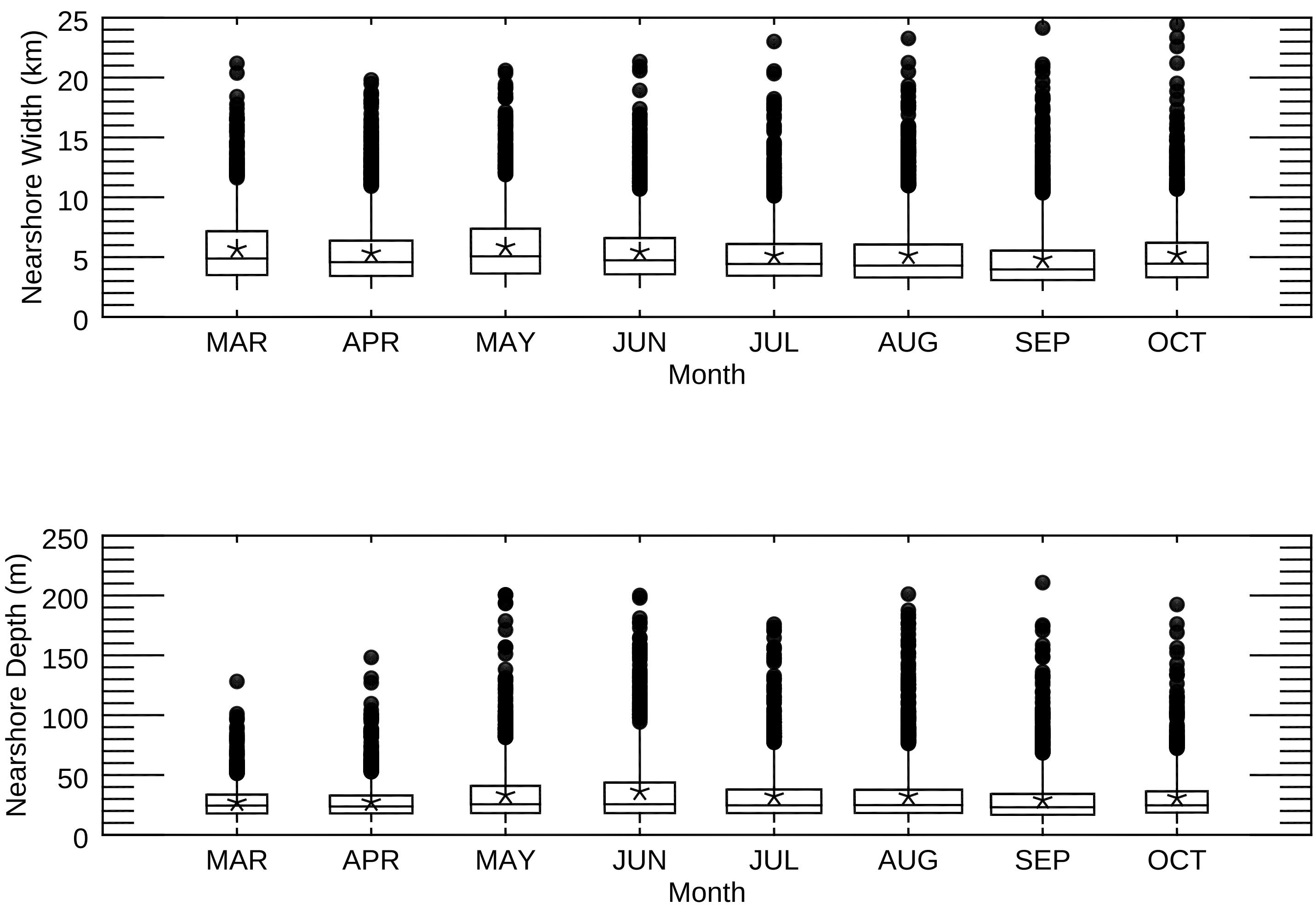
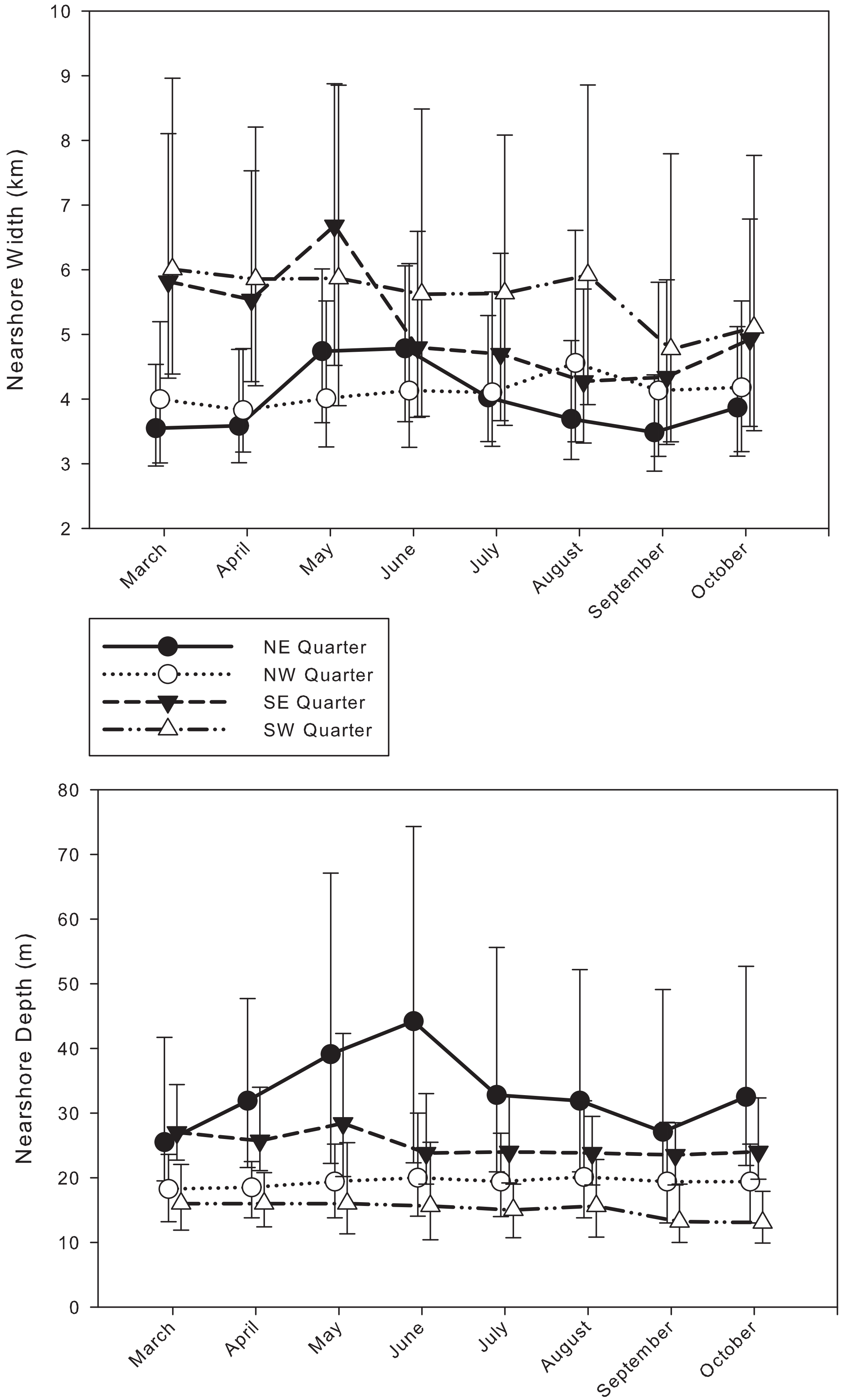

a
b
Number of Transects
0
500
1000
1500
2000
2500
3000
0
5
10
15
20
25
Nearshore Width (km)
0
50
100
150
200
250
Nearshore Depth (m)

Figure 5



Nearshore Width (km)
25
20
15
10
5
0
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
Month
Nearshore Depth (m)
250
200
150
100
50
0
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
Month

Figure 6



Nearshore Width (km)
10
9
8
7
6
5
4
3
2
March
April
May
June
July
August
September
October
NE Quarter
NW Quarter
SE Quarter
SW Quarter
Nearshore Depth (m)
80
70
60
50
40
30
20
10
0
March
April
May
June
July
August
September
October