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General Aviation Citizen Science Study to Help Tackle Remote Sensing of Harmful Algal Blooms (HABs)

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March 2018

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Summary

We present a new, low-cost approach, based on volunteer pilots conducting high-resolution aerial imaging, to help document the onset, growth, and outbreak of harmful algal blooms (HABs) and related water quality issues in central and western Lake Erie. In this model study, volunteer private pilots acting as citizen scientists frequently flew over 200 mi of Lake Erie coastline, its islands, and freshwater estuaries, taking high-quality aerial photographs and videos. The photographs were taken in the nadir (vertical) position in red, green, and blue (RGB) and near-infrared (NIR) every 5 s with rugged, commercially available built-in Global Positioning System (GPS) cameras. The high-definition (HD) videos in 1080p format were taken continuously in an oblique forward direction.

The unobstructed, georeferenced, high-resolution images, and HD videos can provide an early warning of ensuing HAB events to coastal communities and freshwater resource managers. The scientists and academic researchers can use the data to compliment a collection of in situ water measurements, matching satellite imagery, and help develop advanced airborne instrumentation, and validation of their algorithms. This data may help develop empirical models, which may lead to the next steps in predicting a HAB event as some watershed observed events changed the water quality such as particle size, sedimentation, color, mineralogy, and turbidity delivered to the Lake site.

This paper shows the efficacy and scalability of citizen science (CS) aerial imaging as a complimentary tool for rapid emergency response in HABs monitoring, land and vegetation management, and scientific studies. This study can serve as a model for monitoring/management of freshwater and marine aquatic systems.

1.0 Introduction

Good quality water is essential for human survival and progress. The Great Lakes of North America (Superior, Michigan, Huron, Erie, and Ontario) contain about 21 percent of the world's surface freshwater. Lake Erie, the subject of this report, is one of the largest freshwater lakes in the world. It provides fresh drinking water to about 11 million people. It supports many manufacturing industries along its coastline including a thriving commercial fishing industry. Ranked 9th by area and 15th by volume, it borders the U.S. states of Michigan, Ohio, Pennsylvania, New York, and the province of Ontario in

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Canada. It is divided into three zones: the eastern basin (Erie, Pennsylvania, to Niagara River, New York), the central basin (islands to Erie, Pennsylvania), and the western basin (islands to Michigan). The water quality in the western and central zones is affected mainly by water inflow from the Detroit (about 24 mi long) and Maumee (about 137 mi long) Rivers. These rivers dump millions of tons of suspended and dissolved material every year into Lake Erie’s western basin. The other rivers such as Portage, Sandusky, Huron, Black, Cuyahoga, Grand, and several other smaller tributaries and estuaries along the shoreline also contribute to significant sediment loads. A detailed overview of Lake Erie and its estuaries can be found in Reference 1.

Harmful algal bloom (HAB) outbreaks are a major problem in the Great Lakes, smaller inland lakes, and coastal waters, affecting almost every state in the United States of America (Ref. 2). The adverse impacts of HABs on human health and economy are well-known and described in References 3 to 5. An urgent response to monitor the onset of HABs and their temporal and spatial spread has been a desired but unachieved goal for a long time (Refs. 6 and 7). Unfortunately, Lake Erie epitomizes the HAB problem in this regard (Ref. 8).

1.1 Background and Current Harmful Algal Bloom (HAB) Monitoring Methods

Several complimentary remote-sensing methods are routinely used to monitor HAB outbreaks and water quality assessment. These include space-borne systems (satellites), airborne systems (airplanes, balloons, drones, or unmanned aerial vehicles (UAVs)), and water-borne crafts (boats and ships). Unfortunately, no single remote sensing method, provides sufficient information, especially for water toxicity evaluation, and therefore must be confirmed with in situ water sampling and analysis by professional biotechnicians.

Satellites provide a global view, but are limited in scope by their spatial and temporal resolutions and cloud cover. For example, in the Central and Western Lake Erie region, on average, 80 percent of the time (300 d/year), clouds cover about one-quarter of the sky (Ref. 9). The strengths and weaknesses of satellite imaging for water quality monitoring are discussed in Reference 10. Because of limited resolution, satellite imagery is a partial solution to the emergency-response observation challenge. For example, Landsat resolution is around 30 m and the MODIS around 1 km. The understanding of physical and biological factors affecting bloom dimensions require much finer details on the order of less than a meter. Therefore, few management decisions rely on satellite-derived water quality products as shown in a 2013 survey study by Schaeffer et al. (Ref. 10) supported by NASA. The satellite monitoring of cyanobacterial HAB frequency in recreational waters and drinking water sources was discussed recently by Clark et al. (Ref. 11).

High-flying airplanes are very expensive to operate and clouds can obscure the view. At present, UAV or drone flights are restricted by Federal Aviation Administration (FAA) regulations to line-of-sight operations only at low altitudes (300 to 400 ft AGL), thus covering a very small area. Balloons are not practical as they are unpowered with little steering capability and are dependent upon wind direction. Boats and ships cannot move fast enough to cover a larger region of interest. The best way to ascertain water quality is onsite sampling with expensive and labor-intensive chemical and biological analysis. These efforts are also limited in scope as scientists from government agencies and academic institutions do not have the resources to track water quality through every river and stream in a watershed. The importance of HAB monitoring and response, the state of science and research needs, and airborne and satellite imagery are discussed in detail in References 5 to 7 and References 10 to 13.

2.0 General Aviation (GA) Citizen Science (CS) Methodology and Approach

Our novel approach of utilizing citizen scientist volunteer pilots and small GA airplanes with their rapid response capability bridges a key gap in HAB monitoring capabilities. According to AOPA, in the United States, there are 600,000 private pilots and over 200,000 GA aircraft (https://www.aopa.org/about/general-aviation-statistics/active-general-aviation-aircraft-in-the-u-s). A fraction of this untapped resource can be very valuable to study land and aquatic systems. The citizen scientist volunteer pilots can provide high-resolution imaging data to help scientists develop an early warning system for ensuing algal blooms along America's coastlines, the Great Lakes, and waterways.

Citizen science (CS) can be a valuable tool in tackling scientific problems. CS is scientific research conducted in whole or in part by amateur or non-professional scientists. However, the data collected is openly shared and frequently used by professional scientists in their respective fields of research. For example, NASA has a robust CS program (https://science.nasa.gov/citizenscientists). The U.S. government has recognized the value of CS in recent years, and more agencies are benefiting from the general public's contributions to their missions under the 2017 American Innovation and Competiveness Act (https://www.congress.gov/bill/114th-congress/senate-bill/3084).

The citizen scientist pilots that contributed to this study were volunteers. They were not guided, supported, or paid for by NASA or anyone else nor were they reimbursed for any pilot services, aircraft maintenance, hangar rent, fuel, etc. They collected a large volume of data for distribution to water quality managers and academic researchers.

2.1 Flight Tracks

A typical flight track of over 130 NM one way for the Lake Erie central-western basin and islands is shown in Figure 1(a). Images were collected every 5 s. One flight comprises a total of about 1,500 images on each nadir camera. In 2017, 39 flights were conducted on this route. The other flight track shown in Figure 1(b) included the central basin (Avon Lake, Ohio, to Erie, Pennsylvania). A few flights were conducted on this route when requested by various agencies and academic researchers. All volunteer flights were conducted under visual flight rules (VFR) and some by requesting air traffic control (ATC) flight following in busy airspace such as Cleveland, Detroit, and Toledo. The flight tracks flown have many airports in close vicinity of each other in case an emergency landing is desired. These tracks are easy and safe to navigate as the terrain is pretty flat.

2.2 General Aviation-Citizen Science (GA–CS) Aerial Imaging Cost Comparison

NASA, the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the U.S. Department of Agriculture (USDA), and other agencies frequently use airplanes in land surveys, cartography, agricultural use, and HAB research. The fuel and maintenance costs associated with airborne missions are quite expensive. The academic institutions, researchers, and local water body authorities in general, cannot afford these costs. The bigger the airplane, the higher the cost. As a typical example, a de Havilland Twin Otter airplane employed in HAB monitoring work burns fuel at a rate of 90 gal/h with a cruise speed of 150 kn. Given the fuel cost of $5.39 per gallon (September 19, 2017, at Lorain County Regional Airport (KLPR)) the cost is $485.10 for 1 h to fly a Twin Otter. The maintenance and crew costs are additional. The two GA small airplanes used in this study burn fuel at a rate of 5 to 6 gal/h at a cost of $26.95 to $32.34. The cruise speed of these airplanes is around 110 to 140 kn covering a wide area in a highly cost-effective manner.

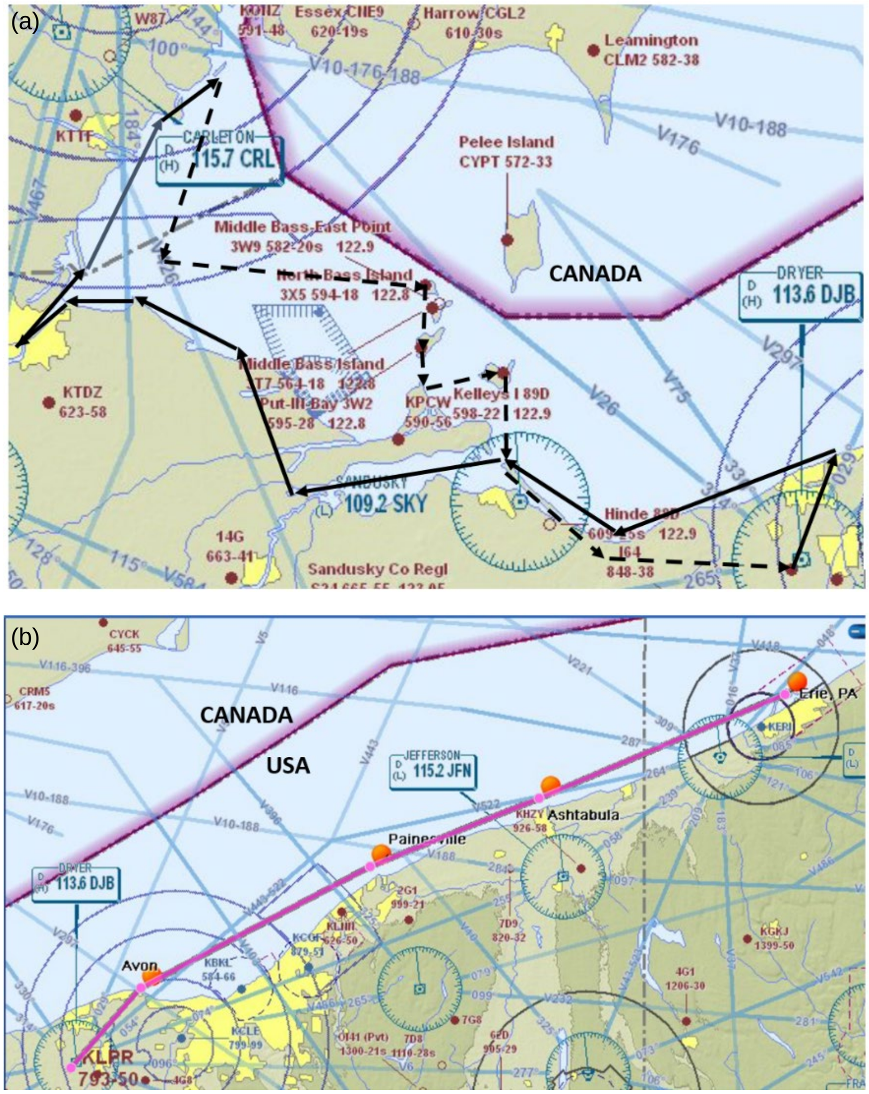


Figure 1.—Flight track overlay on a Jeppesen aeronautical navigation chart using the Aircraft Owners and Pilots Association (AOPA) flight planner. These routes are relatively easy and safe to navigate as there are no mountains. Several easily accessible airports are shown as small red dots. (a) Lake Erie western basin flight track (130 nm). The solid and dashed black lines indicate the flight route. (b) Lake Erie central basin flight track (100 nm). The flight route is indicated by a solid orange line. (AOPA navigation charts used with permission.)

2.3 Camera Selection and Georeferencing

Conventional airborne imaging cameras are normally expensive, bulky, require an operator to operate them in flight, and mechanical mounting installations to the outside or inside of the airplane via a window for nadir imaging. This requires special modifications to the airplane airframe or its structure. Post-processing of images, georeferencing, and providing them to end users can take several months. In the USDA's National Agriculture Imagery Program (NAIP), RGB, and near-infrared (NIR) images are taken once every 2 to 3 years at an altitude of 18,000 to 20,000 ft AGL with a resolution of 1 to 2 m/pixel. Geared for agriculture and land use, these images are available to end users after one year or longer after taking the actual photograph.

In our initial work conducted in the 2014 to 2015 CS campaigns, we used off-the-shelf GoPro Black 3 RGB cameras for aerial imaging. These inexpensive cameras provided excellent images, but they did not have a built-in Global Positioning System (GPS) at that time. Therefore, georeferencing of the post-flight images was quite cumbersome and labor intensive. In the 2016 to 2017 campaigns, we used Garmin VIRB® XE (Part# 010-01363-11) RGB cameras, similar in cost and image quality to GoPro, but with built-in GPS. The images were processed with free-access Garmin software. This made georeferencing very easy. It provided easy viewing on any computer platform (see Figure 2). Each image included positional information (latitude and longitude), date, time, and other information such as aircraft speed, magnetic heading, and altitude. The cameras can be controlled remotely by any smart phone or tablet, such as an iPad, or run directly in automated mode without any operator intervention. The images were stored on a micro Secure Digital (SD) card in the camera for later download. The camera specifications for the VIRB® XE can be accessed at the Garmin website at https://buy.garmin.com/en-US/US/p/165499#specs. The power source for the camera is a tiny battery that is installed inside of the integrated watertight camera, eliminating the need for any external power or wiring from the airplane power system. The integrated camera battery (a rechargeable 980 mAh Li-polymer) at full charge lasts for approximately 2 h of shooting still images every 5 s at an ambient temperature at or above 70 °F. In HD video mode continuous recording, the battery only lasts for 75 min. Each RGB image (12 MP) comprises 4,000 by 3,000 pixels and covers a swath of approximately 1.0 by 0.74 mi at an altitude of 3,000 ft AGL. The images taken every 5 s are stitched together to leave no gap in coverage, as they overlap. An average ground speed of 120 smi per hour or 2 mi/min provides 12 images every 5 s.

One identical RGB camera was modified for NIR imaging. The original IR cut filter was removed and a Roscoe blue filter was placed over the camera lens. During the modification process, the original 4.2-mm lens broke. It was replaced with a 5.4-mm 10 MP lens, which has a slightly narrower field of view (FOV), but is still of excellent quality. The blue normalized differential vegetation index (NDVI) filter specifications are available at https://publiclab.org/notes/cfastie/04-20-2013/superblue

The small size (3.0 in. wide by 1.6 in. high by 1.4 in. deep) RGB and NIR lightweight cameras (about 5 oz each) were mounted on the underside of the aircraft wings (tiedown ring) looking approximately 90° below for nadir shots every 5 s. This camera mounting arrangement provides unobstructed images that are free of propeller blur and glare from cockpit windows and does not require any modifications or changes to the airplane's airframe or its structure. A third camera for videography was mounted on the underside of the other wing looking forward as shown in the Figure 3.

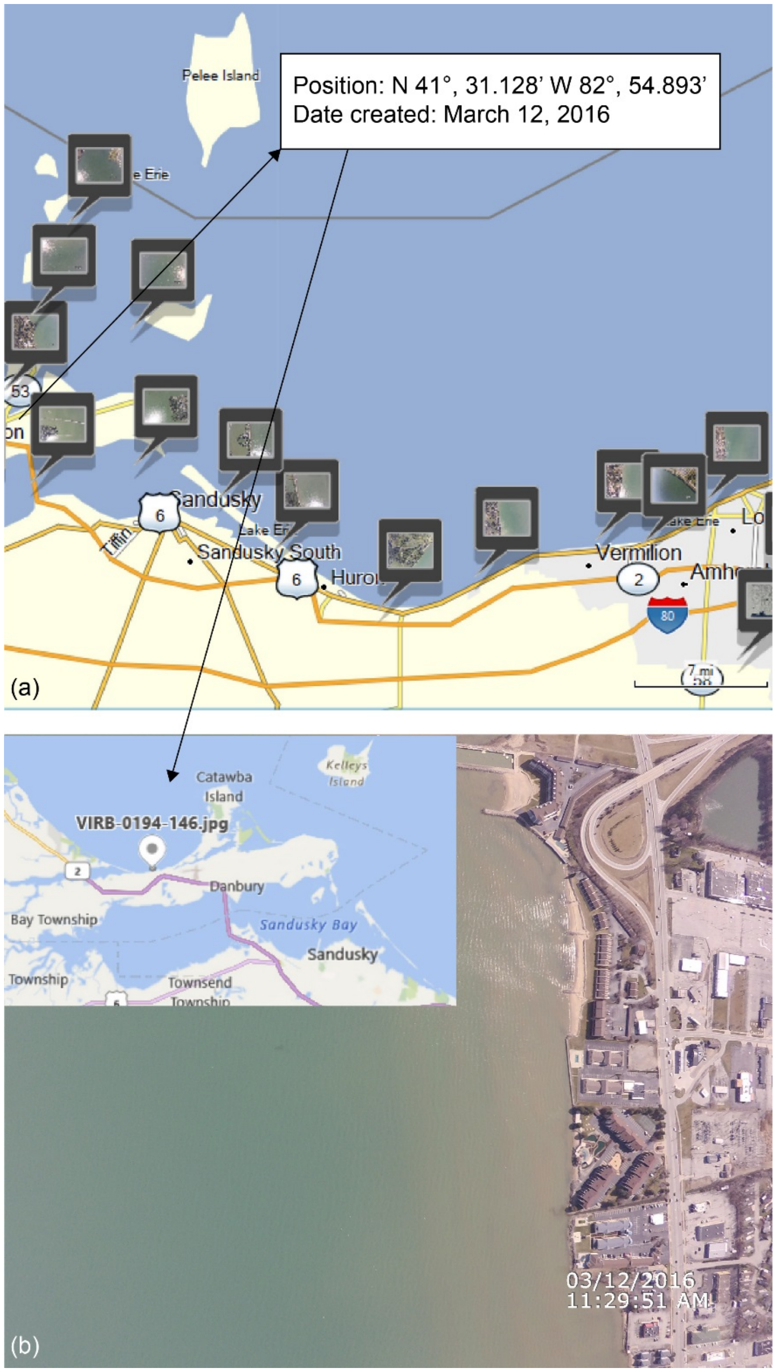


Figure 2.—Accurate georeferencing is key for the harmful algal bloom early warning system. Images are geotagged or geolocated using free Garmin Base Camp and Google Earth apps. The end users can easily access images for their area of interest by clicking on the image frame (a) to view it full screen (b). The insets show positional information.

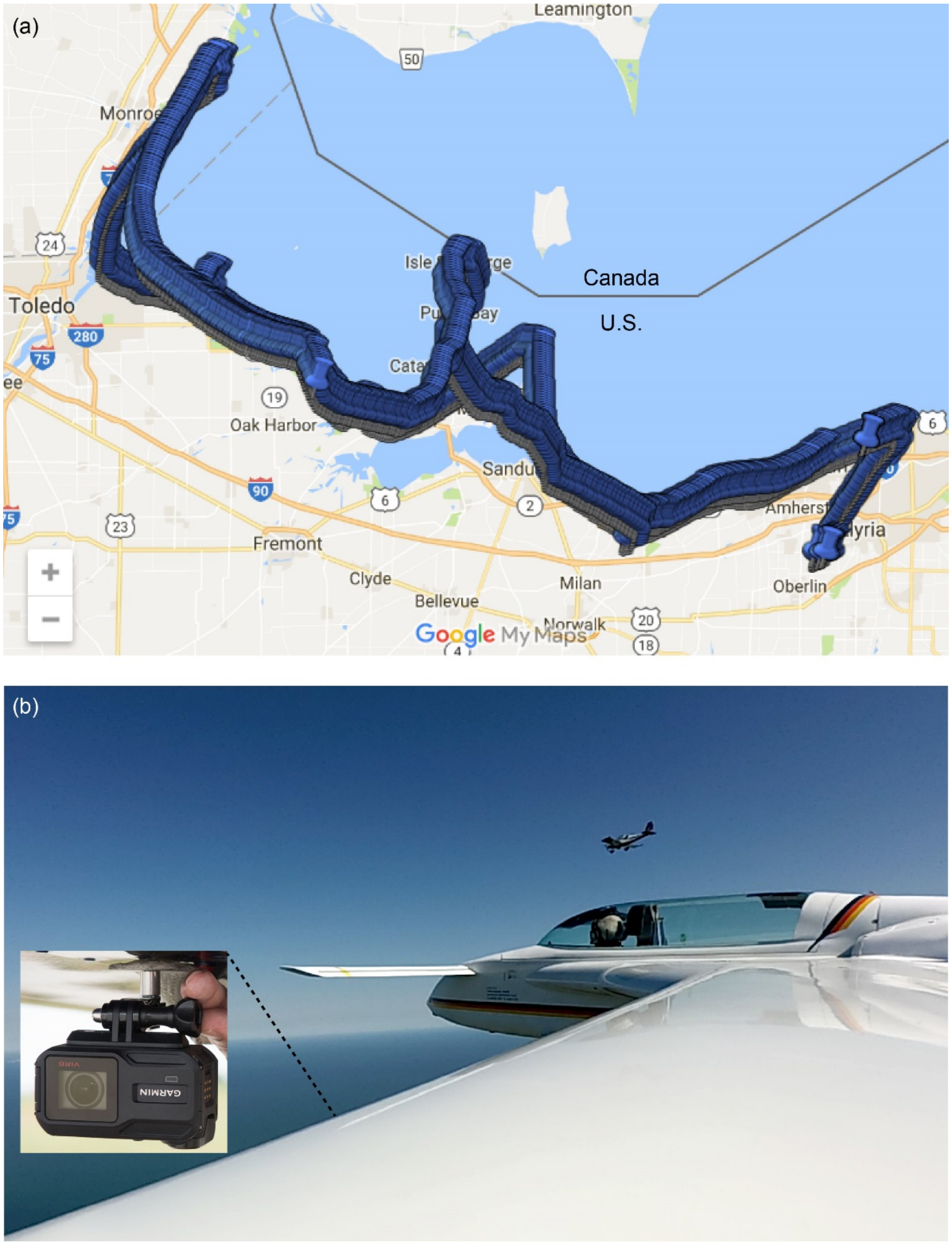


Figure 3.—(a) Each blue pin represents an image collected every 5 s. A total of about 1,500 images per flight are georeferenced and overlaid in the Google map for easy viewing. (b) A total of three cameras were used: one each for RGB and NIR in nadir (vertical) position and one for forward videography (see inset). The cameras were mounted at the tiedown rings aft of the underside of the leading edge of the wings.

3.0 Observations and Results

3.1 Image Quality, Resolution, Calibration, and Ground Truth Validation

A major concern in aerial imaging is to maintain consistent image quality. A moving airplane from very low to high speeds can cause image blurring. The propeller rotation can impart vibrations to the airframe and wings to which the cameras are mounted. Our images were always in sharp focus and found to be free of airplane vibrations in all phases of flight. This is demonstrated in Figure 4.

The images taken from relatively inexpensive cameras (about $400 each) provide a wealth of useful information. The airborne RGB cameras employed in this study documented the color alterations quite vividly. Prior to flight, the cameras were calibrated using well-known and well-characterized targets (runway numbers, threshold markers, and structures). The Rose Garden of Lakeview Park, in Lorain County, Ohio is a unique structure that can be used for camera calibration and resolution calculation. The popular park is located on the southern shore of Lake Erie. It offers a beautiful sandy beach, children's playground, and several other things of interest to visitors. The Rose Garden offers a diverse community of colorful roses arranged in a 48-bed concentric circular structure. Several subtle details can be seen in images taken at an altitude of 3,500 ft AGL and are explained in Figure 5 to Figure 7. The image resolution was found to be around 1.3 ft/pixel. This was further confirmed by imaging a 4-ft by 4-ft mirror array at an altitude of 4,000 ft AGL on the open waters of Lake Erie as shown in Figure 7(b). The mirror array was placed on water by Professor Joe Ortiz to make radiometric measurements to coordinate with aerial imaging at the time of flight.

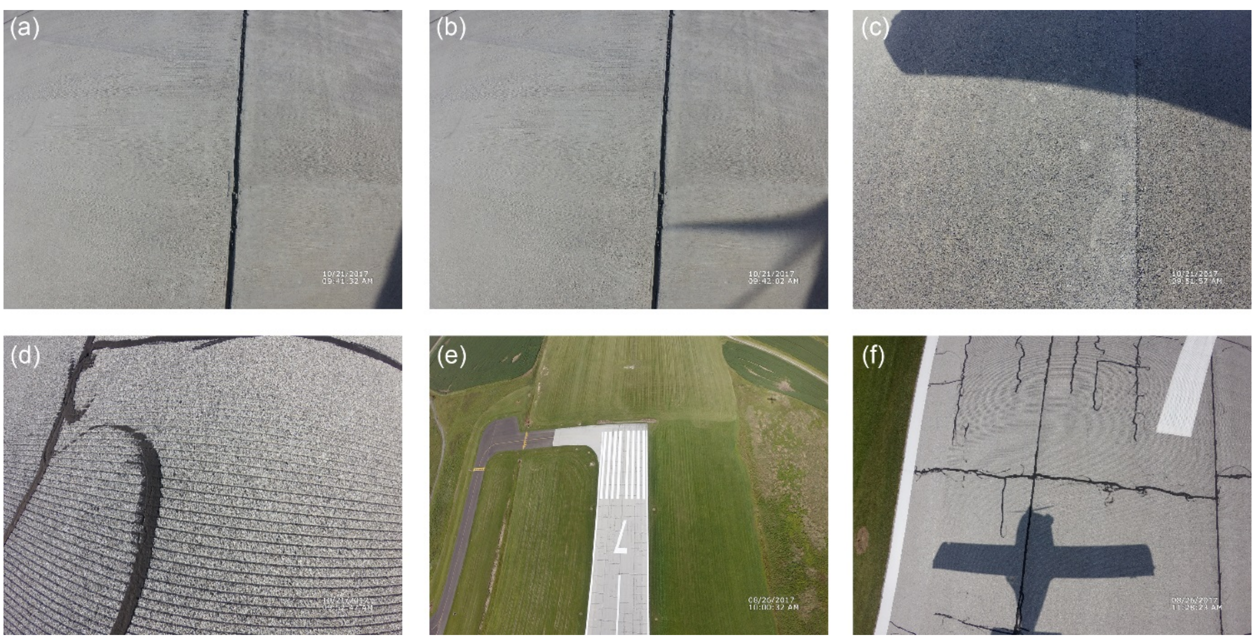
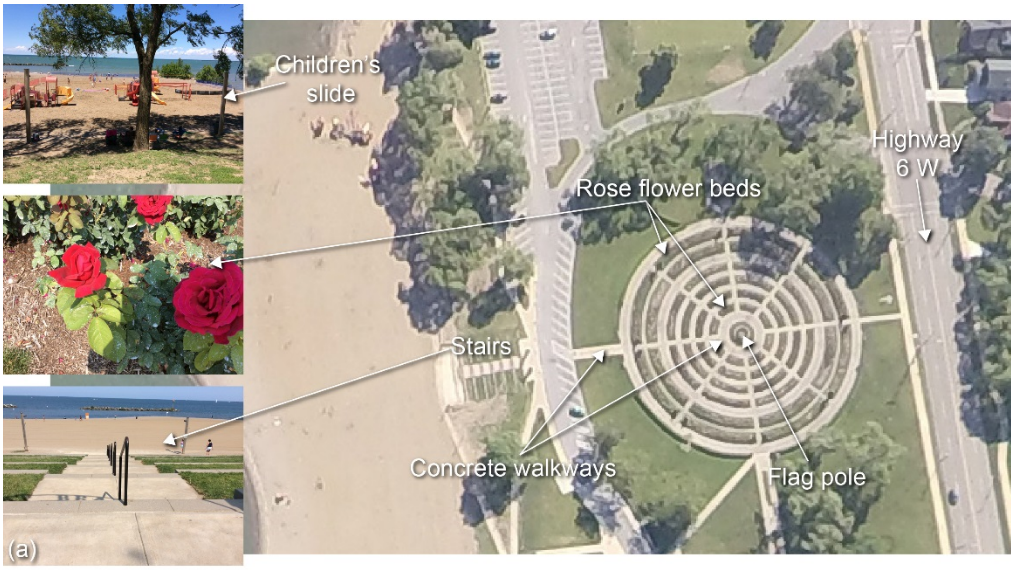


Figure 4.—Vibration and blur-free sharp nadir images. The finer details remain in sharp focus in all phases of flight. (a) Parked airplane with engine off on tarmac. (b) Parked airplane with engine running at the same spot. The shadow at the right bottom is the running propeller. (c) Moving airplane on taxiway at a speed of 7 kn. The shadow on top is the portside wing. (d) Moving airplane on runway (takeoff roll) at a speed of 55 kn. (e) Takeoff and climb at a speed of 70 kn. (f) Landing just before touchdown at a speed of 60 kn.

Figure 5.—Geolocated aerial image taken on June 24, 2017. The brownish patches on the otherwise soft sandy beach are volleyball nets placed for a July 4 volleyball tournament. The insets are photos taken on an iPad for ground validation on the same day. The inset on the right is the display chart at the park indicating how the 48 flower beds are arranged in the Rose Garden.

Figure 6.—In this geolocated aerial image of July 9, 2017, after the July 4 holiday, the volleyball nets are gone, the sedimentation layers north of break walls mostly disappeared, and the water color looks very different. The insets are photos taken on an iPad of the Rose Garden and the water fountain.



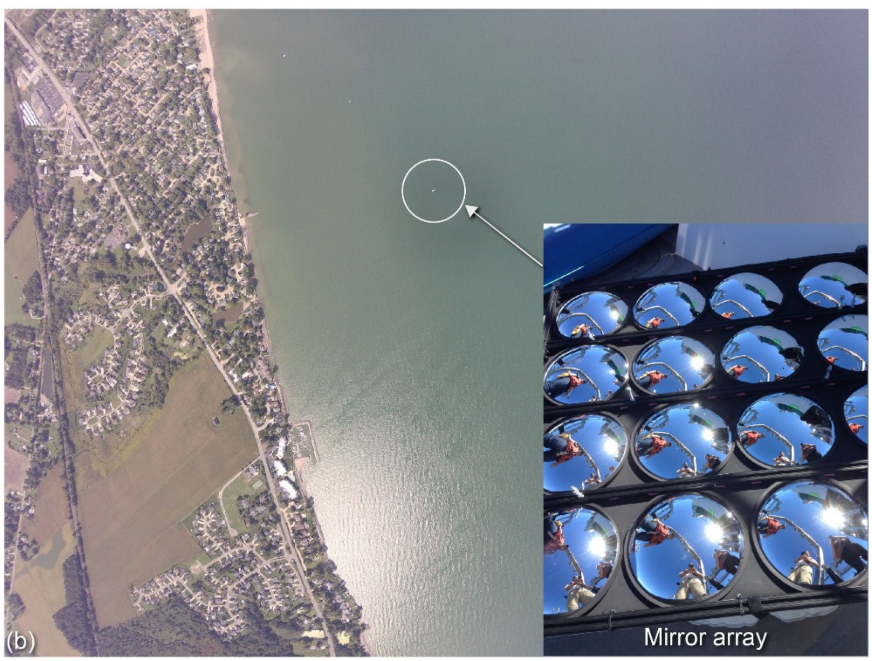


Figure 7.—(a) This zoomed-in aerial image of Figure 6 taken on July 9, 2017, shows structural details, flower beds, stairs to the beach, the sandy beach, and the children's playground. The individual rose plants are around 2 to 3 ft in height arranged in a 48-concentric concrete circular structure. The insets are photos taken on an iPad on the ground on the same day. This structure was used as an imaging target for calculating the camera resolution. (b) Placement of 4-ft by 4-ft mirror array (courtesy of Professor J. Ortiz) on the open waters of Lake Erie.

3.2 Aquatic, Land, and Vegetation Fine Features

The aerial images delineate finer features. The images shown in Figure 8 and Figure 9 highlight these features. The semicircular-shaped Huron Harbor dike at the bottom left of Figure 8 was built by the U.S. Army Corps of Engineers in 1975 as a river pollution dredging disposal facility. The structure is made of steel sheet pile cells and rubble mound. The area now serves as a recreational facility by the Huron Joint Port Authority. The dike details visible in Figure 8 are described by R.J. Bernhagen (Ref. 14). NIR images provide information on chlorophyll content as a marker for healthy vegetation, which shows as pinkish to reddish in color. A comparison of an RGB and NIR image is shown in Figure 9.

Figure 8.—Huron River, Huron Harbor, and Lake Erie. This nadir aerial image taken at an altitude of 3000 ft AGL on September 24, 2017, shows details delineating water, manmade structures, sand, vegetation, sediment layers, boats, and billowing smoke.

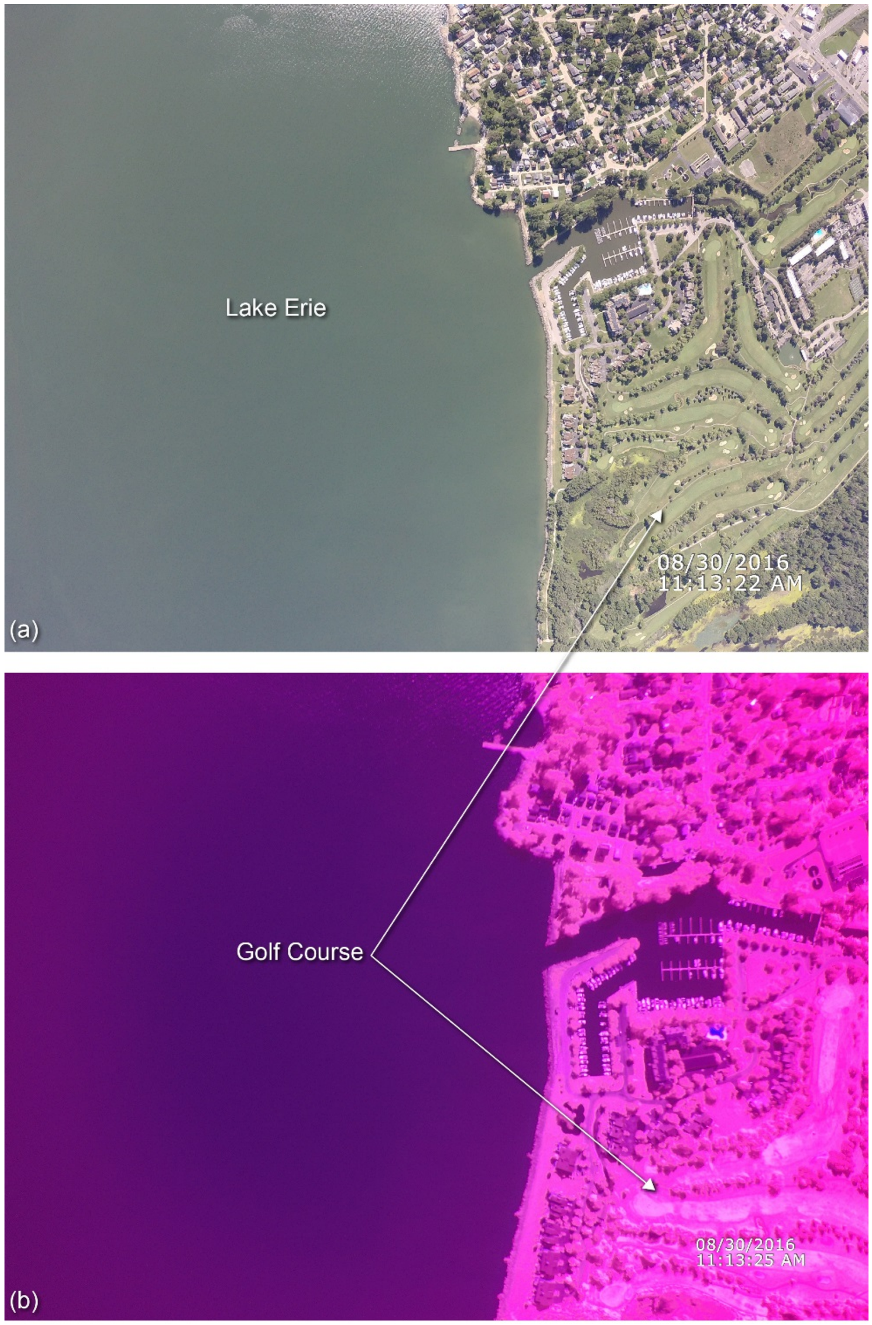


Figure 9.—(a) RGB and (b) NIR images are able to clearly delineate objects such as boats, marinas, roads, land, water, buildings, healthy vegetation, swimming pools, and manicured golf courses. The NIR images can be used to calculate the normalized differential vegetation index (NDVI). The NDVI is commonly used for agricultural assessment of chlorophyll content, indicating the health of vegetation. As described in the text, the NIR camera has a slightly narrow field of view (FOV) so the image appears slightly magnified in comparison to the RGB image.

3.3 Documenting Harmful Algal Blooms (HABs)

HABs in Lake Erie region are made up of blue-green algae, a cyanobacteria that contains chlorophyll. They produce rapidly, are typically found at or near the surface of the water, and are known to produce toxins (https://www.weather.gov/cle/HABabout). The Environmental Protection Agency (EPA) advisories (http://epa.ohio.gov/habalgae.aspx) alert people to avoid water that looks like spilled paint, has surface scums, mats, or films, is discolored or has colored streaks, and has green globs floating below the surface. Our aerial images document these very vividly.

Volunteer citizen scientist pilots can provide a unique perspective of bloom formation and their spread. The high-quality aerial photographs and videos show the early onset of algal blooms, river plumes, sediment dynamics, and flow patterns. We observed and notified NASA, NOAA, academic partners, and other institutions of the bloom that eventually caused the 2014 Toledo shutdown 1 to 2 d before the official notice, alerting scientists and water managers to collect data in the vicinity of the event as it unfolded. Figure 10 shows images in a time sequence that led to a major HAB event, prompting shutting down of drinking water to 500,000 residents of Toledo, Ohio for 3 to 4 d in August 2014. A comparison of August 4 aerial image with NOAA/NASA Experimental Lake Erie Harmful Algal Bloom Bulletin, August 4, 2014, Bulletin 10 is presented in Figure 11(a). We also sent these images to Mr. Colin Brook, Senior Research Scientist and Manager of the Environmental, Transportation, and Decision Support (ETDS) Laboratory at the Michigan Tech Research Institute (MTRI), in Ann Arbor, Michigan. He compared these images with in situ measurements and confirmed a high surface algal mat and chlorophyll concentration of 20 µg/L, as shown in Figure 11(b). This highlights that HAB development is a dynamic system spanning several orders of magnitude both spatially and temporally. Therefore, timing is everything for effective monitoring efforts and GA–CS can play an important role in monitoring HAB development.

Sometimes our images showed white streaks on the water surface. We thought of these as passing boat tracks, but there were no signs of boat activity as observed from the air. We approached the Ohio Department of Natural Resources (ODNR) and requested their help in making ground truth observations over open water. They generously provided their boat for us to make site observations and take measurements. We gave the ODNR boat pilot the GPS coordinates where the aerial images were taken. The white streaks turned out to be foam patches when seen up close. These foam streaks are not seen by satellites nor are mentioned in regular Lake Erie HAB bulletins. We will discuss the presence of intense foam in the following sections.

Yannick Baehler, an undergraduate student from Switzerland in Ansari's NASA lab, assembled a compact, lightweight remotely-operated submersible rover from a commercial kit (https://www.openrov.com) for underwater RGB photography and in situ water analysis to compare with aerial images at a cost of less than $1,000. This rover was able to go to a depth of 300 m. It was remotely operated on battery power. We installed optical sensors on this rover to measure water conductivity, temperature, depth, total dissolved solids, RGB, and total light flux. A full report on this work in a PDF file is available (Ref. 15). The water samples collected from this general area were examined under an optical microscope. It showed presence of Planktothrix, a neurotoxin; possibly as a result of outflow from Sandusky Bay. The underwater images taken by the rover's onboard RGB camera showed submerged algal mats. This is shown in Figure 12 and Figure 13.

Similar trends were seen in 2016 aerial images. Figure 14 shows changes in water color and clarity around the crib from early spring to summer, leading to algae and foam formation. According to NOAA's Lake Erie bloom severity data, on a scale of 1 to 10 (10 being most severe), the 2016 bloom was mild at level 3 on the severity scale. This data can be seen at: https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/lakeErieHABArchive/HAB20171107_2017035_LE.pdf

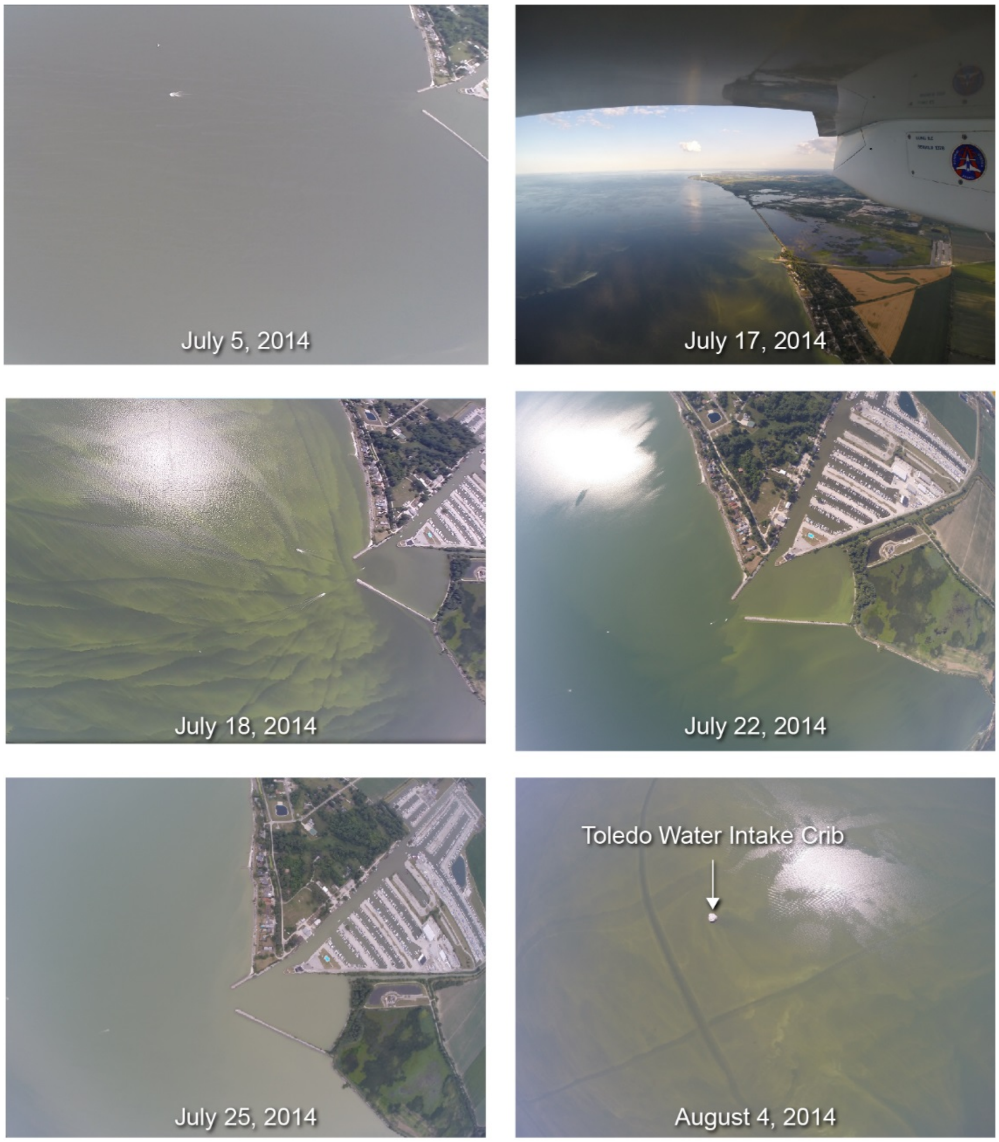


Figure 10.—Early detection of a harmful algal bloom event (HAB). Bottom right aerial photo shows that the Toledo water intake crib is overwhelmed with green-blue algae or microcystis; a toxin. Timing is critical for effective HAB development monitoring systems because HAB development is a dynamic system that spans several orders of magnitude spatially and temporarily.

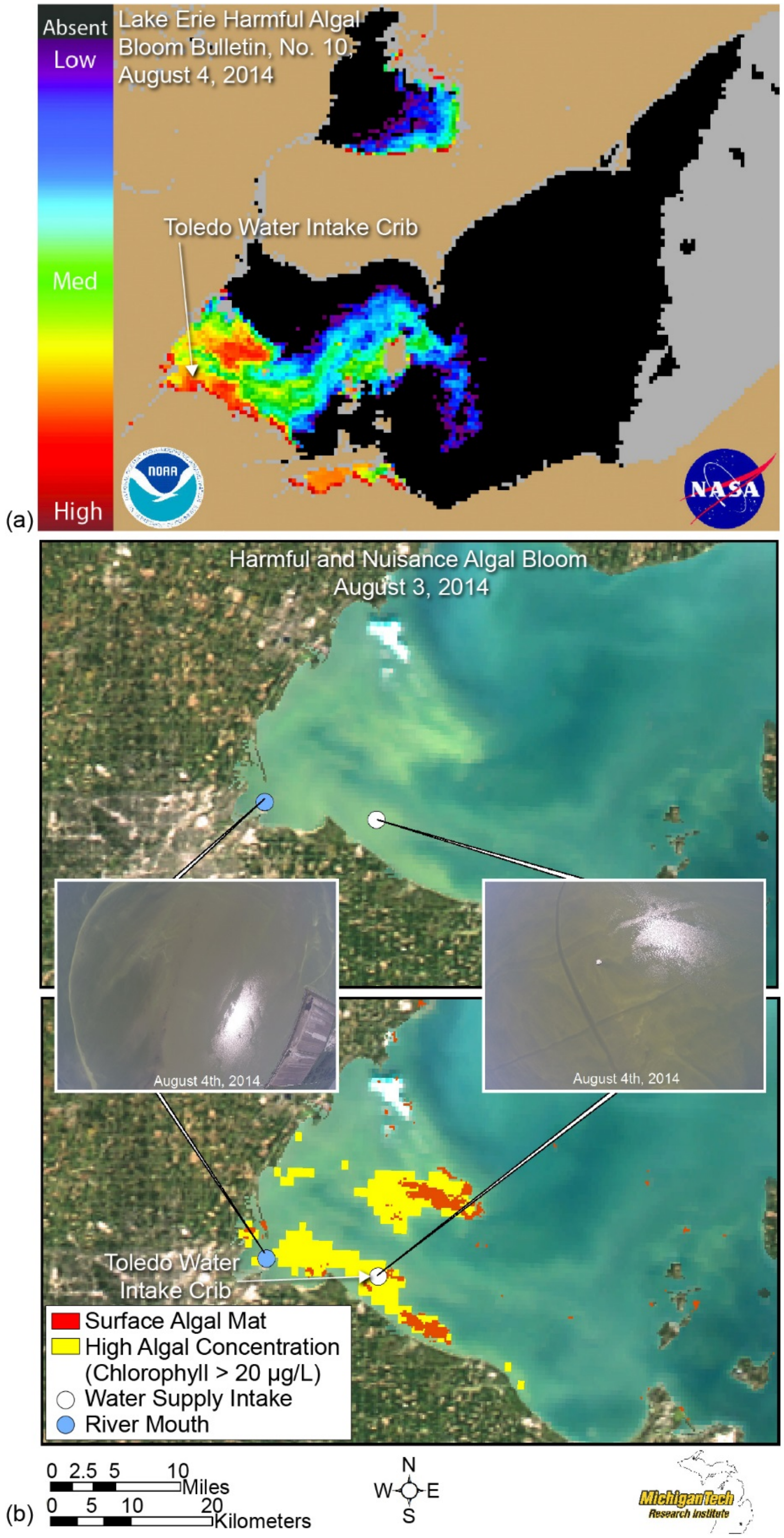


Figure 11.—Comparison of August 4, 2014 Maumee Bay and Toledo water crib images with the Lake Erie HAB bulletin (a) and MTRI in situ measurements (b)

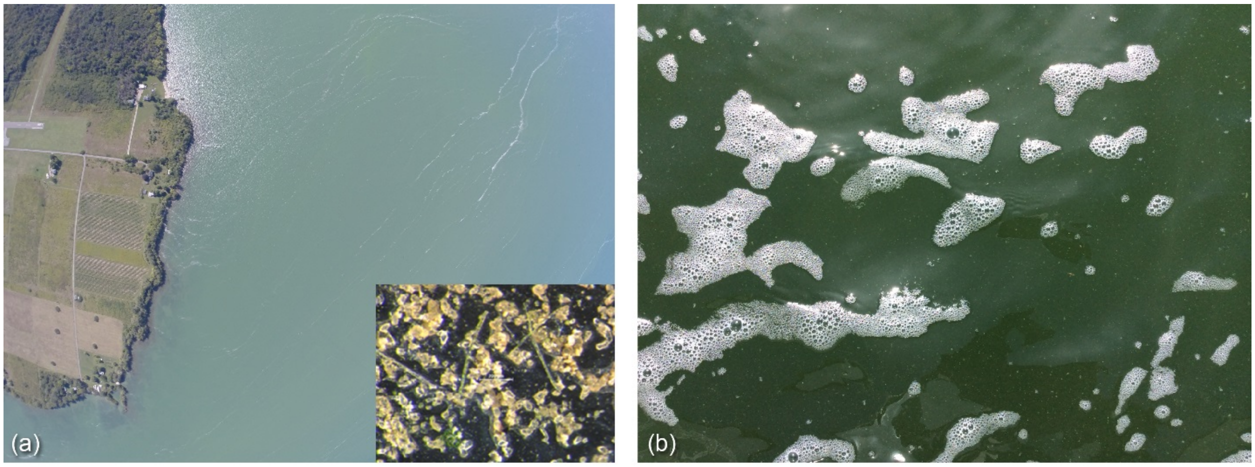


Figure 12.—(a) Aerial image taken at 3,000 ft AGL of North Bass Island. (b) Image taken on an iPad onboard an Ohio Department of Natural Resources boat shows foam at this location. The inset in (a) is an optical microscope image (courtesy of Pete Bonacuse, Analytical Sciences Group, NASA Glenn Research Center) of the water sample, indicating presence of filamentous cyanobacteria *Microcystis aeruginosa* (blue-green) algae.

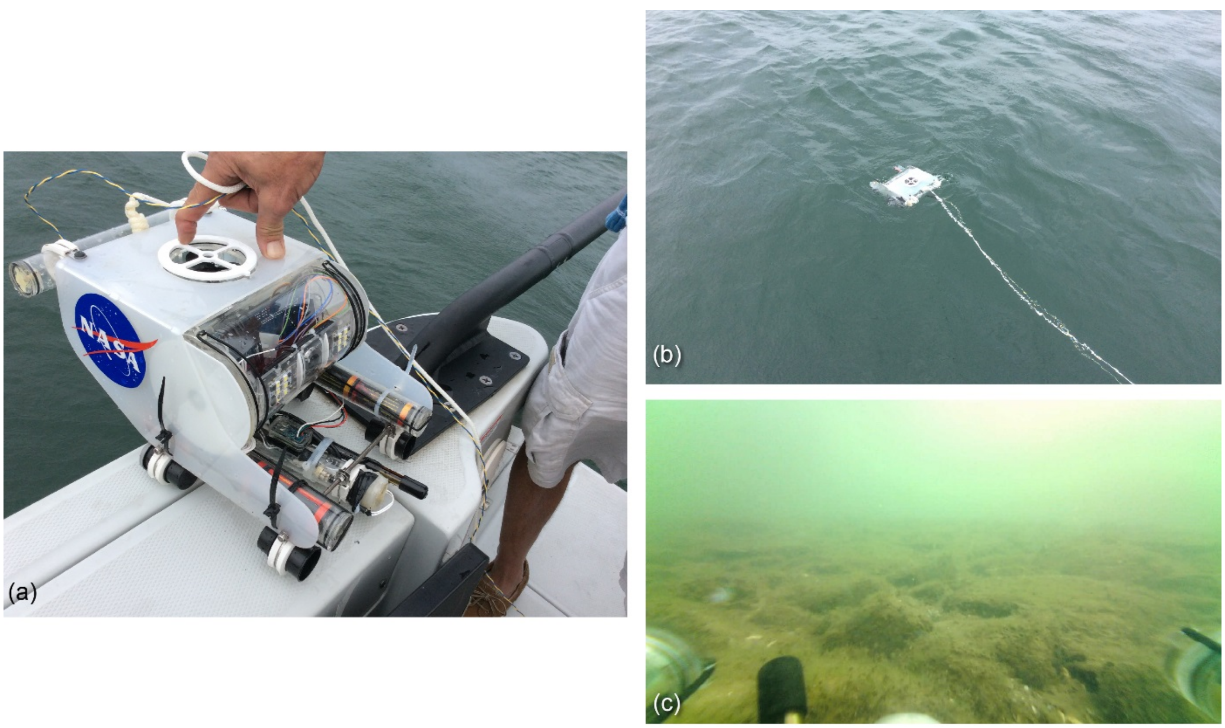


Figure 13.—(a) Submersible rover for in situ measurements. (c) Rover descending to record data. Underwater photograph of submerged algal mat (c) at a depth of 6 ft about 1 mi near the shore of the City of Lorain's water filtration plant in Ohio.

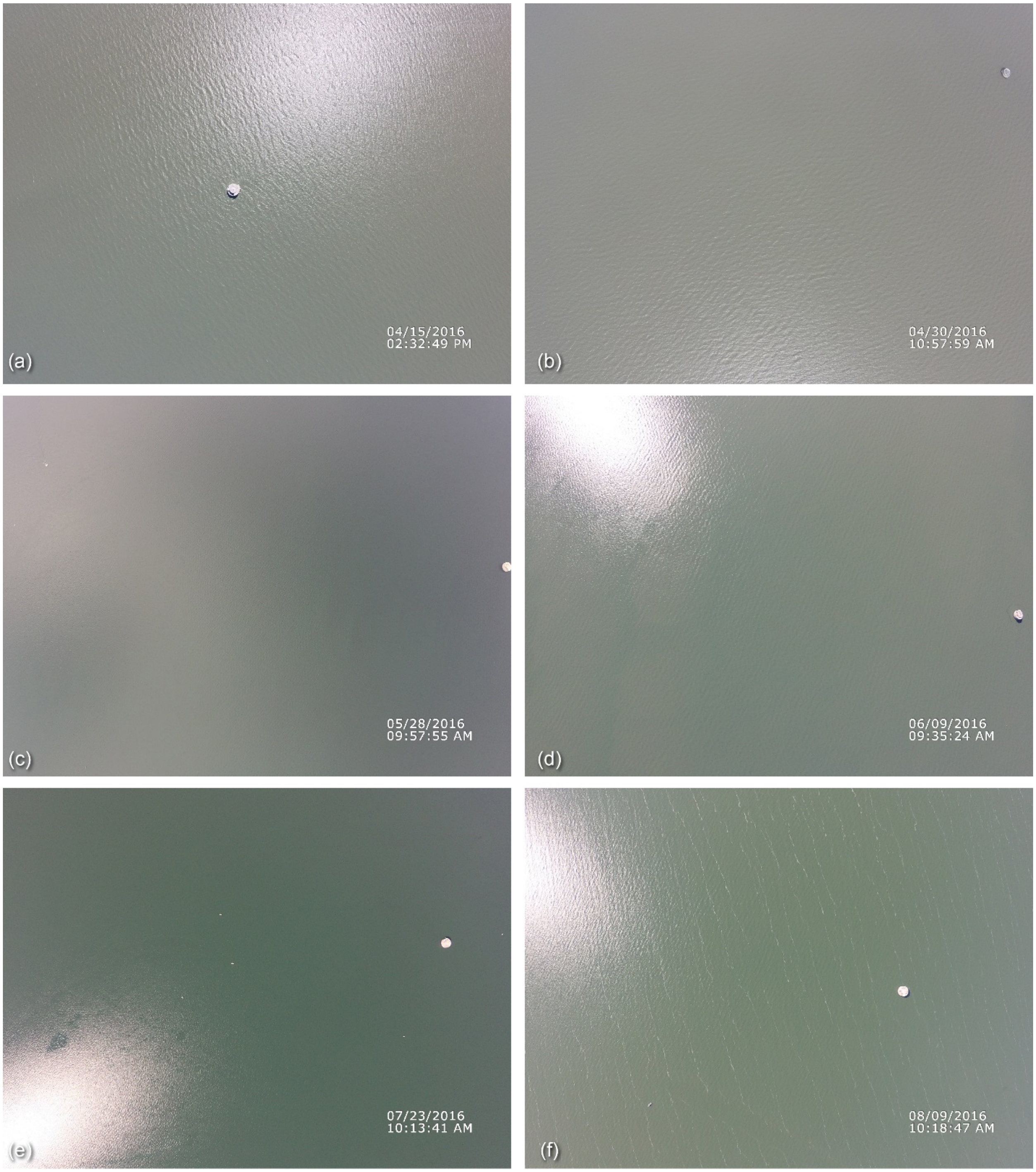


Figure 14.—Changes in water color and clarity around the Toledo water intake crib from early spring (a) to (b) to late spring (c) to (d) to summer (e) to (f). Note the foam appearing in (f). The 2016 HAB season was mild (around level 3) on NOAA's severity scale.

From June 17 to October 21, 2017, 39 GA-CS flights were flown and post-flight images and reports were provided within hours to scientists and researchers of several federal, state, and local governmental agencies, universities, and water quality managers working on western Lake Erie HAB and water quality issues. For effective monitoring, we started early in the HAB season to keep an eye on plume dynamics and nutrient uploading of Lake Erie through its many rivers and tributaries, which may lead to toxic blooms depending upon rainfall and higher ambient temperatures.

Located on the scenic shore of Lake Erie, Crane Creek State Park (between Port Clinton and Toledo) is a freshwater marsh home to more than 300 species of birds, which include herons, waterfowl, warblers, gulls, and the bald eagle. The two nadir images (Figure 15) taken about three weeks apart show the development of a HAB event. These small patches, not visible by satellites or high-flying airplanes, can be a warning sign that can lead to major HAB outbreaks.

The images showing spatial and temporal distribution of river plumes, leading to an early onset of HAB formation, can also be helpful to Lake Erie hydrology modelers interested in river flooding and soil erosions studies.

3.4 Vertical Migration of Blue-Green Algae

HABs can manifest as visual discolorations in water bodies and, at times, as surface scums that appear as paint-like slicks or clotted mats. In Lake Erie, we observed the color of surface scums mostly as light to dark and fluorescent to brownish green. We paid special attention to the Toledo area in general and to the water intake crib in particular because of our 2014 experience discussed earlier in Figure 10. The Lake Erie HAB bulletins, an official NOAA product, provide excellent information on cyanobacterial levels. In 2017, its distribution did not start until the first week of July. The RGB aerial image of Toledo water intake crib taken on June 21, 2017, is shown in Figure 16. This image seems to indicate significant amount of greenish or chlorophyll-rich water around the crib; perhaps an early sign for HAB development. We also note there is no foam present at this time. The algae decomposition or decay is probably very slow at this early point in time.

We observed vertical migration of blue-green algae to the water surface within 24 h from August 8 to 9. This is shown in Figure 17 and Figure 18. The aerial image taken on August 8, 2017, at 10:21 a.m. (Figure 17(a)) shows a considerable amount of submerged algae and/or chlorophyll-rich water. The corresponding satellite data (Figure 17(b)) taken on August 8, 2017, at 11:26 a.m. shows mild cyanobacteria activity in this general location. The satellite data was posted 2 d later on August 10, 2017.

The aerial images (Figure 18) taken 24 h later documented an intense HAB outbreak (10:38 a.m., August 9, 2017) in RGB (a) and NIR (b). The satellite data is not available for this date and time because the satellite does not make a pass every day. The next pass was 4 d later on August 13, 2017, which was reported on August 14, thus missing the August 9 event. Fortunately, Professor Thomas Bridgeman and his team from the University of Toledo were on a boat (Figure 18) collecting samples at the time aerial image was taken. He confirmed the upward mobility of blue-green algae to have caused this outbreak.

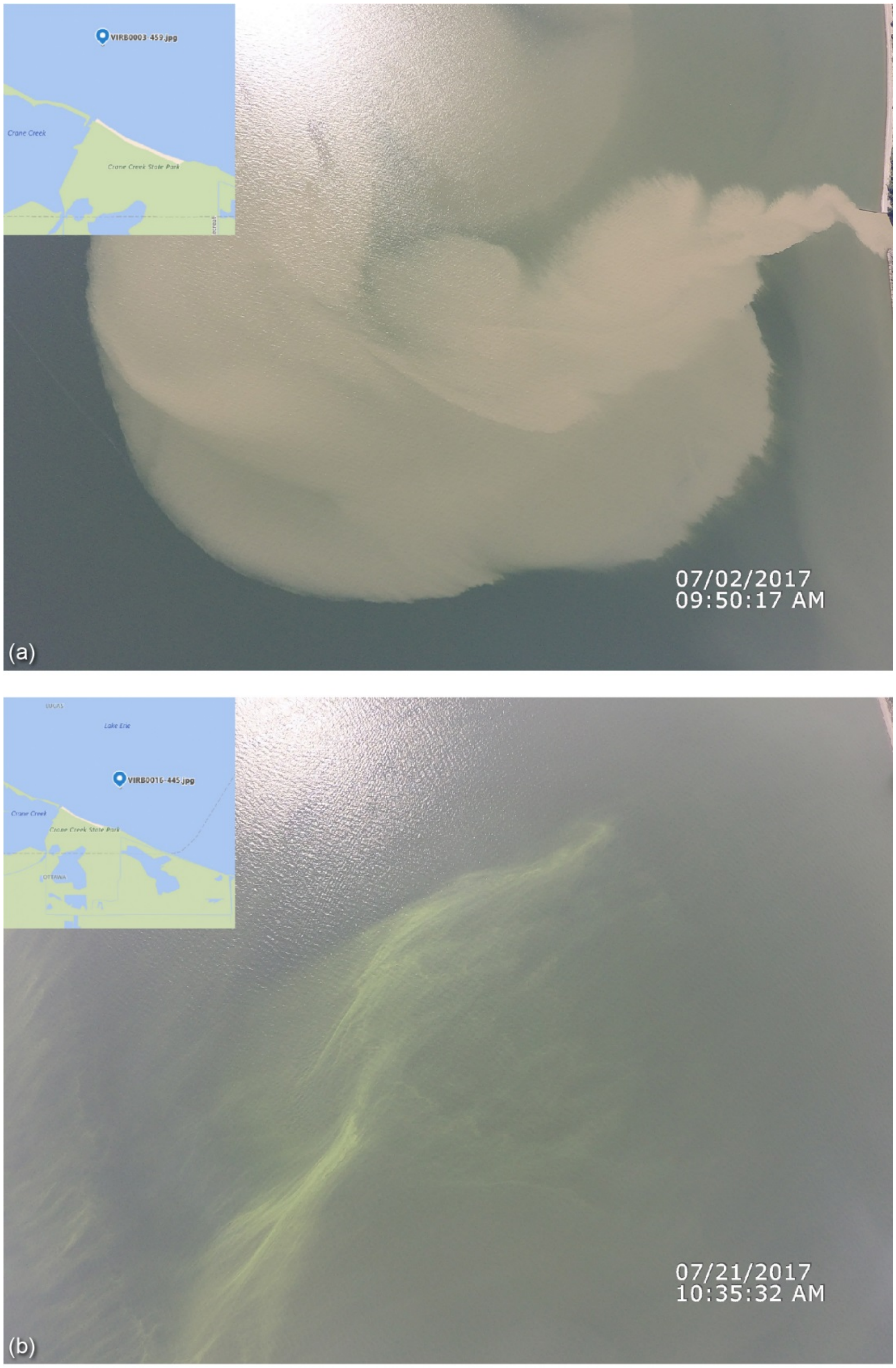


Figure 15.—Plume Dynamics and Algae Bloom at Crane Creek State Park: Early "Embryonic Stage" (a) of a potential algae bloom after a rain event on July 2, 2017. It looks like an "Umbilical Cord" feeding nutrients into Lake Erie's western basin which led to green fluorescent algae bloom formation on July 21, 2017 (b). The filamentous fibrous structure is clearly visible.

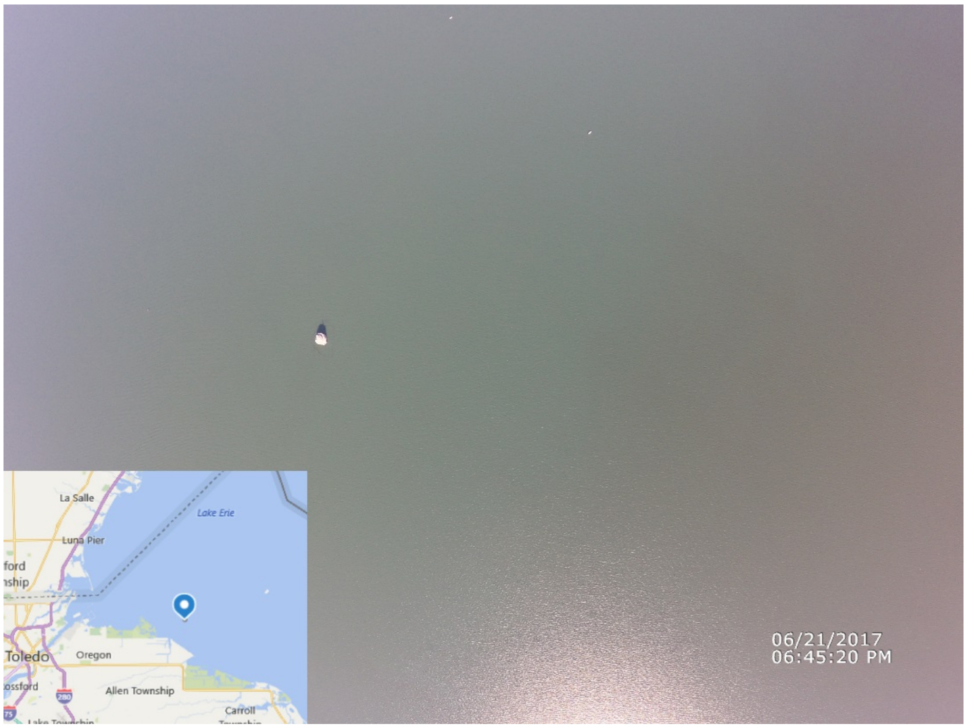


Figure 16.—On June 21, 2017, the surface water around the Toledo water crib shows greenish color indicative of chlorophyll-rich water. There is no indication of foam as seen in later images from August-November.

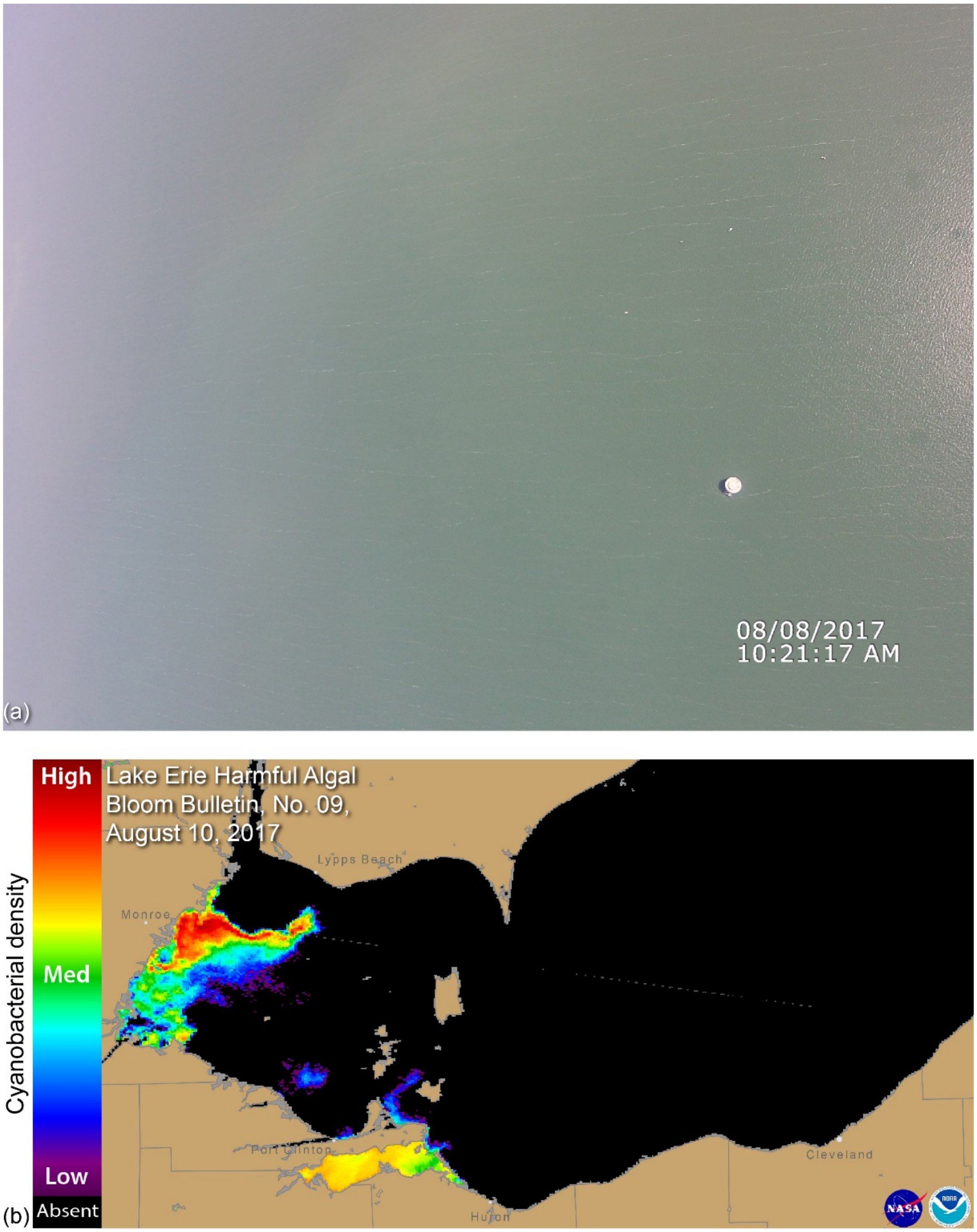


Figure 17.—(a) Toledo water intake crib at 10:21 a.m. on August 8, 2017, showing submerged algae or chlorophyll-rich water. (b) Mild cyanobacterial index on the same date and close to the same time (11:26 a.m.). The satellite data bulletin (b) was posted on August 10, 2017, and can be seen at: (https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/lakeErieHABArchive/HAB20170810_2017009_LE.pdf).

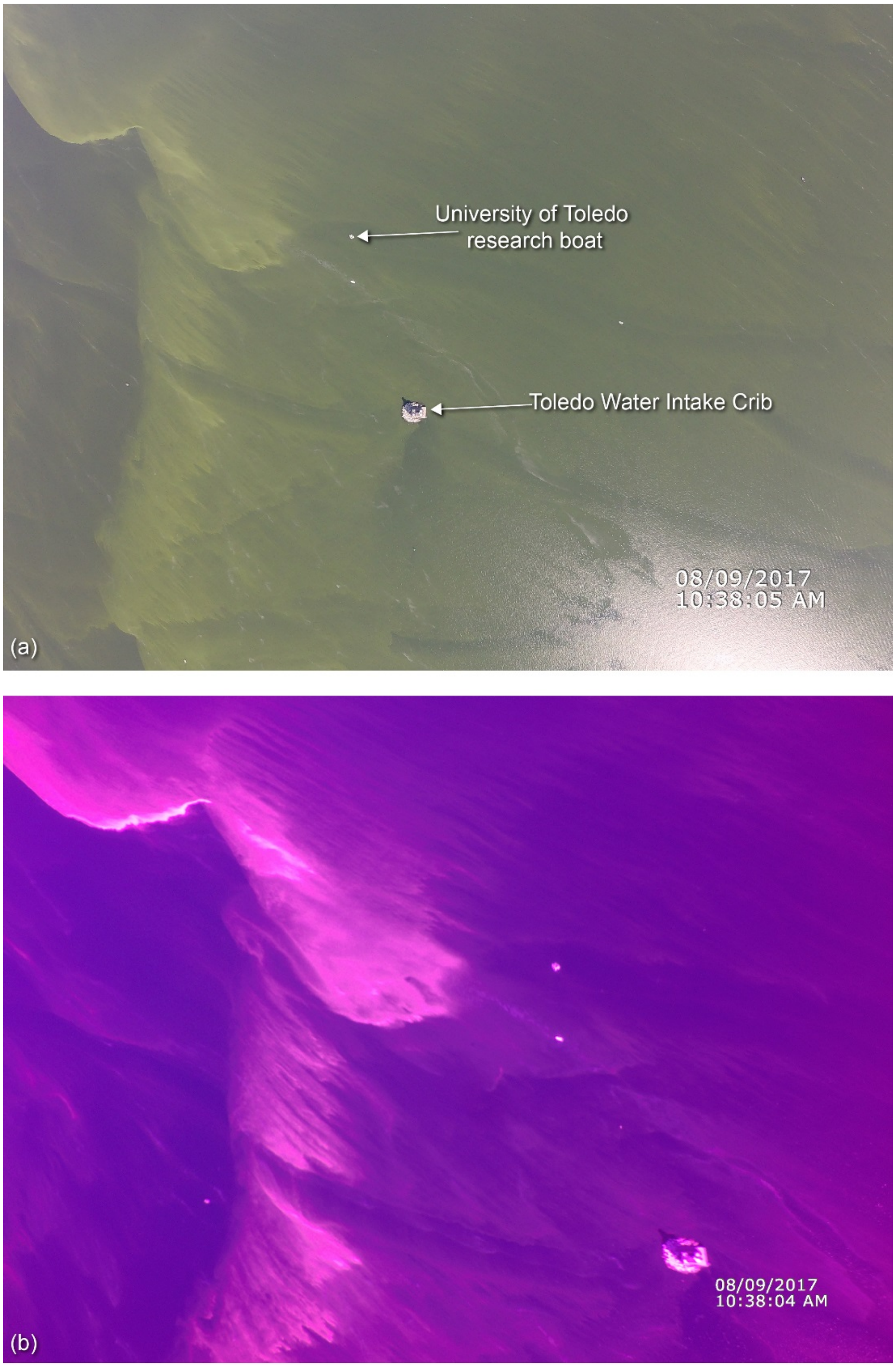
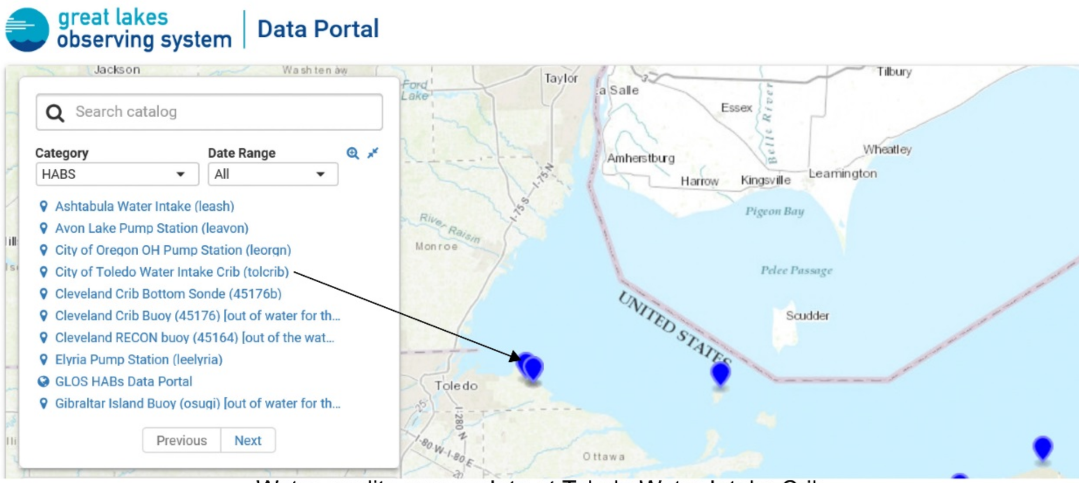


Figure 18.—Harmful algal bloom outbreak within 24 h (10:38 a.m., August 9, 2017) in RGB (a) and NIR (b) of the area shown in Figure 17. The NIR image corroborates the presence of higher chlorophyll levels seen in the RGB image of the algal mat and/or scum. The top tiny white dot in the photograph is the research boat from the University of Toledo where Professor Thomas Bridgeman and his team confirmed the upward mobility of blue-green algae to have caused this outbreak. The satellite data is not available for this date/time.



Water-quality sensor data at Toledo Water Intake Crib

Figure 19.—Screen shot of Great Lakes Observing System website data portal. This website provides real-time water quality parameters during the active HAB season at a few locations. The corresponding aerial images are shown in Figure 17 to Figure 20.

TABLE I.—WATER QUALITY PARAMETERS FOR THE DATES WHEN FLIGHTS WERE FLOWN OVER THE TOLEDO WATER INTAKE CRIB AND THE MAUMEE BAY

GLOS[a] water quality parameters	August 8, 2017	August 9, 2017	August 26, 2017	August 27, 2017
Turbidity, NTU	5.53	7.62	14.64	13.88
B–G algae, rfu	0.32	1.12	2.82	2.57
Chlorophyll, rfu	1.29	2.17	0.88	0.98
Specific conductivity, µS/cm	230.15	242.59	233.22	235.15
Temperature, °C	23.36	23.21	22.70	22.57
pH	8.54	8.54	9.07	9.01

[a]Great Lakes Observing System.

We made an attempt to correlate our aerial observations with in situ measurements of water quality parameters available at the Great Lakes Observing System (GLOS) Data Portal (https://portal.glos.us/). This is shown in Figure 19 and Table I.

The tabulated parameters indicate turbidity, blue-green (B-G) algae, chlorophyll, and conductivity values increase from August 8 to 9, 2017, as seen in images of Figure 17 and Figure 18. A significant increase in turbidity and B-G values is seen in images shown for August 27, 2017, in Figure 20. However, there is a remarkable decrease of chlorophyll values and an enormous presence of foam. The foam is formed by the surfactants from decomposing algae. The bubbles are formed when these organic compounds are mixed with air. When the bubbles aggregate, they create large foam mats on the water surface (https://www.michigan.gov/documents/deq/deq-oea-nop-foam_378415_7.pdf). The excess foam is sometimes the result of too much phosphorus in the water (http://www.rappflow.org/resources/faq.html). Perhaps this is reflected in higher turbidity values.

The GLOS water quality data is collected continuously using Yellow Springs Instrument's (YSI's) data sonde multiprobe instruments placed at three different locations at different depths. These are Tollsps, Tolcrib, and Buoy sondes 45165. The Tollsps is at the lake bottom and Tolcrib is approximately 1 to 2 m below the water surface inside the crib. The Buoy sondes 45165 just west of the Toledo water intake crib is about 1 m deep and it is closest to the crib as shown in the aerial images. The water quality parameter values for blue-green algae and chlorophyll shown as relative fluorescence units (rfu) are

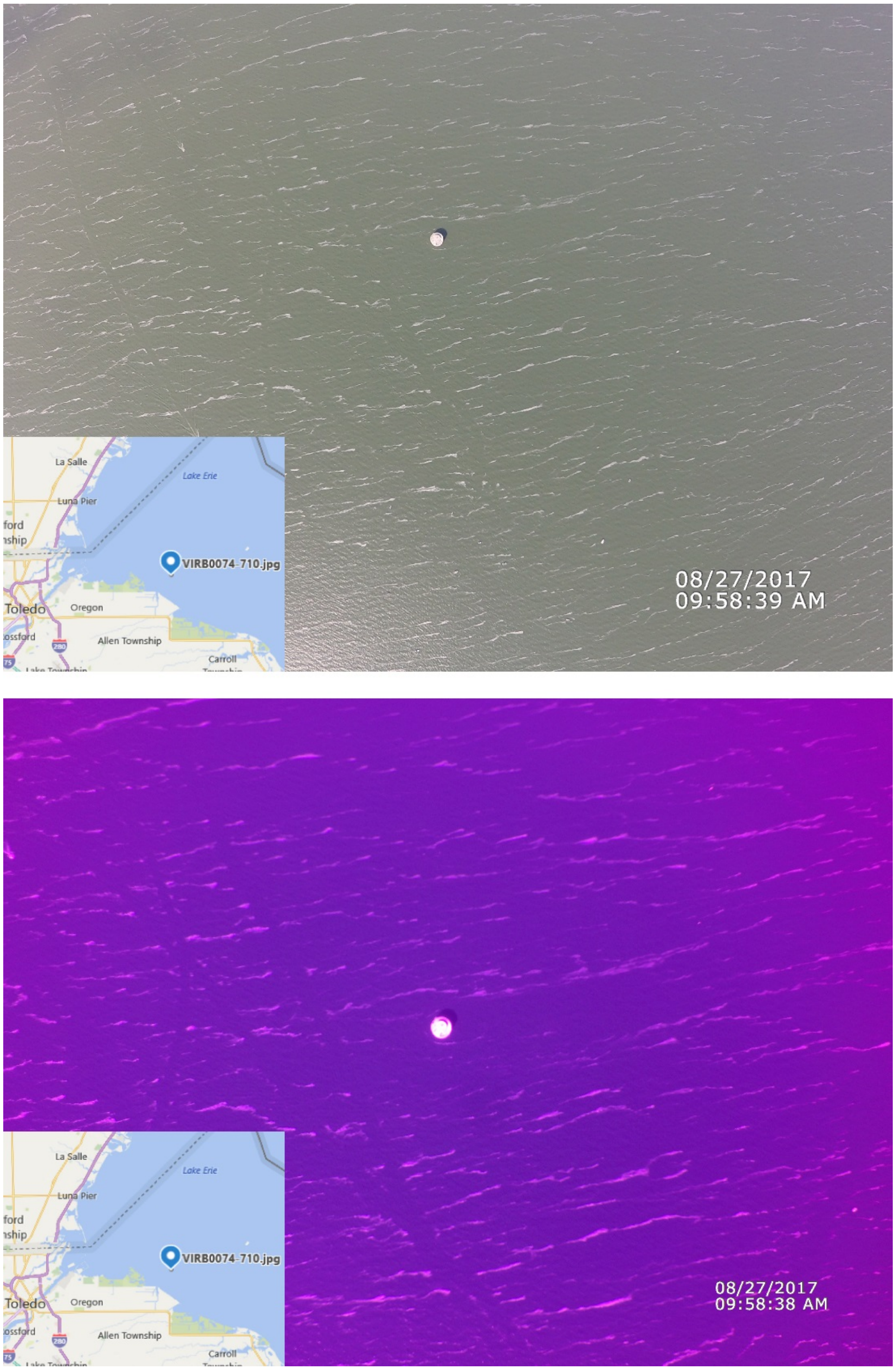


Figure 20.—Correlation with water-quality sensor data at the Toledo water intake crib for August 27, 2017. The Great Lakes Observing System in situ data shows a significant increase in turbidity and blue-green algae values, but less in chlorophyll values. However, these parameters do not represent the exact surface area shown in the aerial images as they are point measurements taken underwater. (a) RGB. (b) NIR.

relative numbers and do not represent absolute values. If the rfu number doubles, the amount of algae has roughly doubled. But the conversion of rfu to any absolute unit like chlorophyll ug/L or cells/ml is not very accurate and does not remain constant. The probes are near the surface, so if the algae migrate to the surface on a calm day, the numbers can go way up temporarily. It is all very rough and imperfect, but the best we have at this point (personal communication with Professor Thomas Bridegman, University of Toledo). This point is highlighted in Figure 21. The effectiveness of data buoys as early warning systems for HABs in Lake Erie are discussed in a project progress report by Chaffin and Kane (Ref. 16). This report is available at: https://water.usgs.gov/wrri/AnnualReports/2016/FY2016_OH_Annual_Report.pdf.

Our flight observations of August 26 and 27, showed massive amounts of foam engulfing the Toledo water intake crib (Figure 20). The winds were calm both days. The foam extended across a very large area, encompassing the entire western basin to the western edge of the islands (Figure 22). The NASA MODIS-Aqua data collected August 27, 2017, at 1:13 p.m. EST was issued on August 28. It shows a high cyanobacterial density index around Toledo (Maumee Bay). The algal mats and scum displaced by moving boats are visible in RGB and NIR nadir aerial images shown in Figure 23(a) and (b). Similar features are seen in aerial images taken over the Luna Pier and the shores of Monroe, Michigan.

The aerial image of the Maumee Bay State Park HAB infested water of August 24 is shown in the bottom middle panel (Figure 22). Similar features are seen in aerial images taken over the Luna Pier and the shores of Monroe, Michigan. According to the ODNR, this 1,336 acre park is one of the finest recreational facilities in the Midwest and also a unique natural environment created by the convergence of the land and Lake Erie. EPA advisories (http://epa.ohio.gov/habalgae.aspx) alert people to avoid water that looks like spilled paint, has surface scums, mats or films, is discolored or has colored streaks, and has green globs floating below the surface. Our aerial images document these very vividly. Our aerial observations corroborate NOAA’s HAB severity index for the 2017 season. It was very significant at level 8. Fortunately, the Toledo water intake crib remained open and the water was considered safe for human consumption.

The Sandusky River in northern Ohio drains into the Sandusky Bay from Muddy Creek Bay to Cedar Point, which separates Sandusky Bay from Lake Erie. The average depth is around 10 to 12 ft. Some marshes, such as Sheldon Marsh, and several streams enter in this bay. The rectangular shaped bay is around 15 mi long and 2 to 3 mi wide. Our flight images from June to October 2017 consistently showed algal scums and/or chlorophyll-rich green color water. This is compared with satellite data and in situ measurements recorded on September 10 and shown in Figure 24. The algal mass is visible in the RGB aerial photograph. The MODIS data indicate a moderate to high level of toxicity (cyanobacterial density). The GLOS data collected using YSI-buoy sensors is shown in Figure 24(b) inset.

3.5 Unusual Harmful Algal Bloom (HAB) Outbreaks in Maumee River Upstream

The western basin of Lake Erie is known to have frequent HAB outbreaks in Maumee Bay. In early fall, we observed an unusually intense HAB outbreak in Maumee River upstream on September 24, 2017, as shown in Figure 25(a). It looked like green fluorescent paint had filled the river from the Maumee Bay upstream to past Toledo downtown about 6 to 8 mi in length. This event made headlines in the national news media (Ref. 8). On October 1, 2017, the Maumee River upstream bloom that looked like green fluorescent paint diminished (see Figure 25(b)).

Figure 26 shows in situ data from the USGS buoy located at Waterville, Ohio, a suburb of Toledo located upstream on the Maumee River. Corresponding to the dates of RGB aerial images (see Figure 25), a dramatic increase can be seen in chlorophyll values and its accessory pigment phycocyanin responsible for cyanobacteria (blue-green algae) production. The data is publically available at the USGS website:

https://nwis.waterdata.usgs.gov/usa/nwis/uv/?format=gif_default&site_no=04193490&period=&begin_date=2017-09-01&end_date=2017-10-05.

We observed the bloom and foam continued to spread from the Lake Erie Michigan coastline to the islands and from Toledo to Huron, a distance of about 65 mi (Figure 27(a)). Kelleys Island (Figure 27(b)) is located in Lake Erie about 4 mi north of Marblehead and 12 mi from Sandusky, Ohio. The entire island measures over 4 square miles and is the largest American island in Lake Erie.

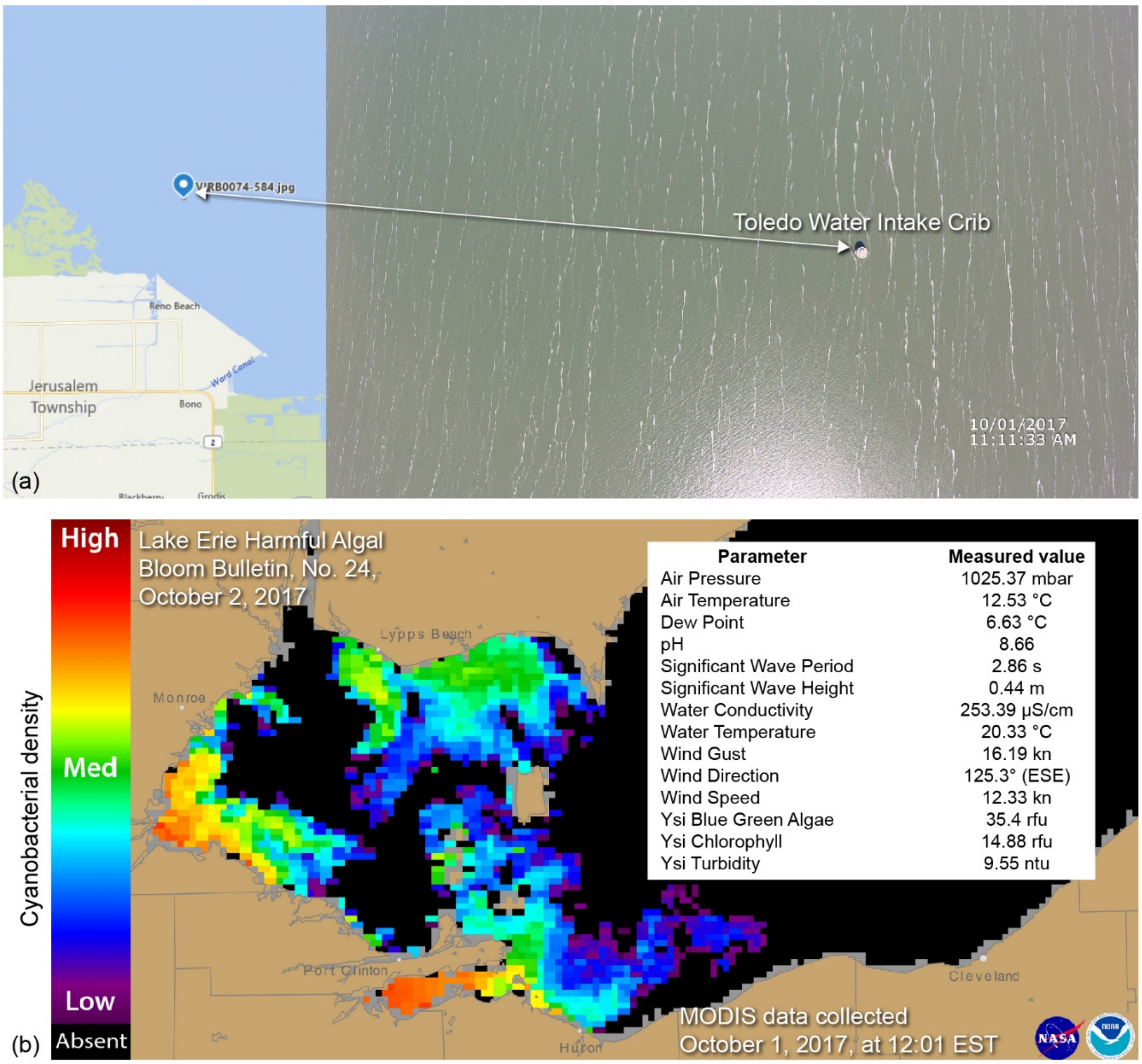


Figure 21.—(a) RGB nadir image of the Toledo water intake crib taken at 11:11:13 a.m. EST on October 1, 2017, indicates a submerged algal mat and foam around the crib. (b) MODIS data collected at 12:01 p.m. EST and the GLOS water quality data (inset) collected at 1:00 p.m. EST at the Toledo water intake crib buoy 45165. It shows high values for B-G algae (35.4 rfu) and chlorophyll (14.89 rfu). The MODIS data shows moderate levels of cyanobacterial density around this area.

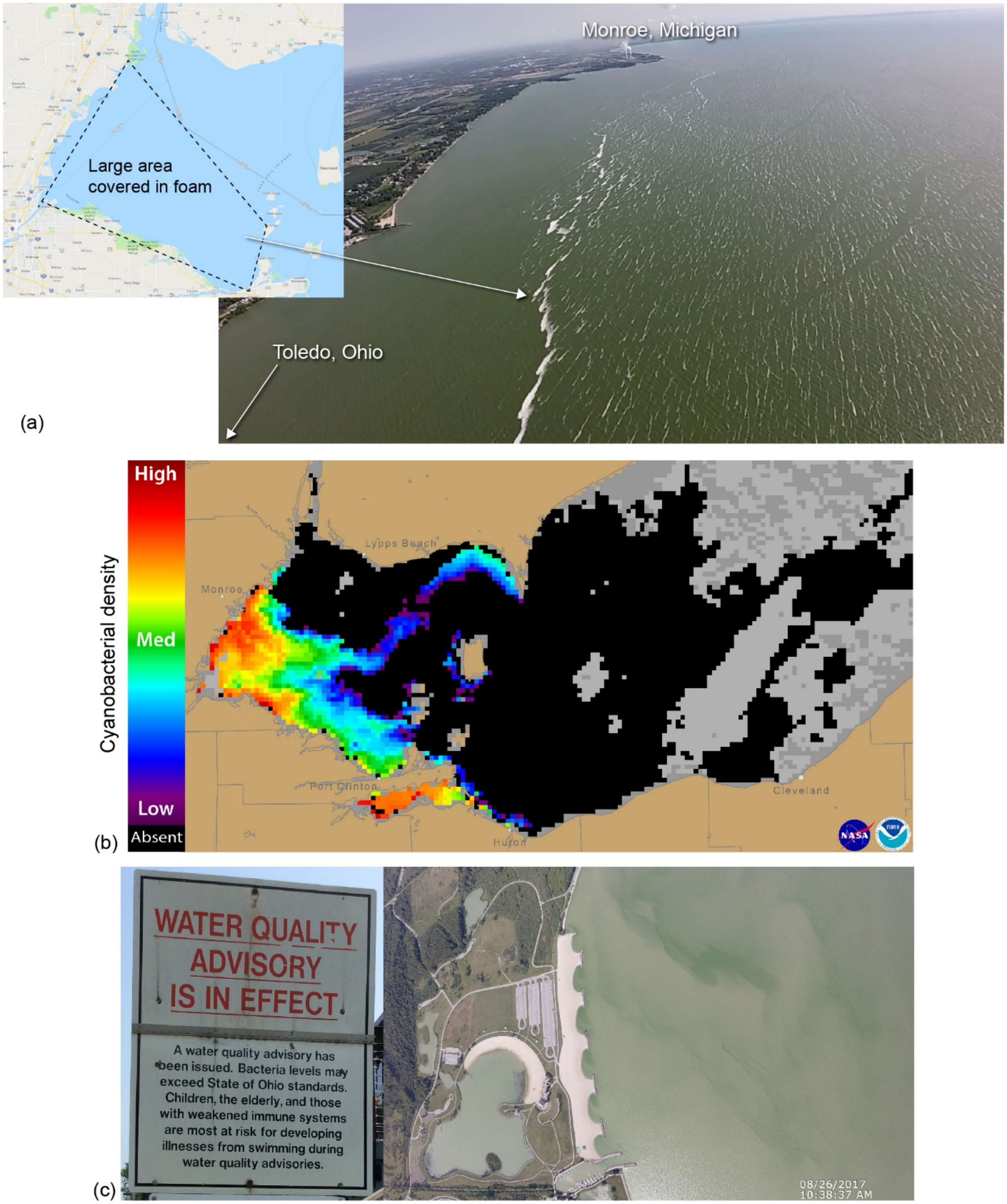


Figure 22.—Harmful algal bloom activity. (a) Screen shot of aerial video and Google maps with overlay of the approximate boundaries of the large foam-covered area. (b) Cyanobacterial index from MODIS data collected August 27, 2017, at 1:13 p.m. EST and posted on August 28, 2017. (c) RGB image taken August 26, 2017, while flying over Maumee Bay State Park, Ohio. These images can be helpful in informing the general public about water quality advisories.

Figure 23.—Georeferenced aerial nadir images in RGB (a) and (b) and NIR (c) and (d) taken on August 27, 2017 over Harbor View at Maumee Bay, Ohio showing thick algal mats and boat tracks.

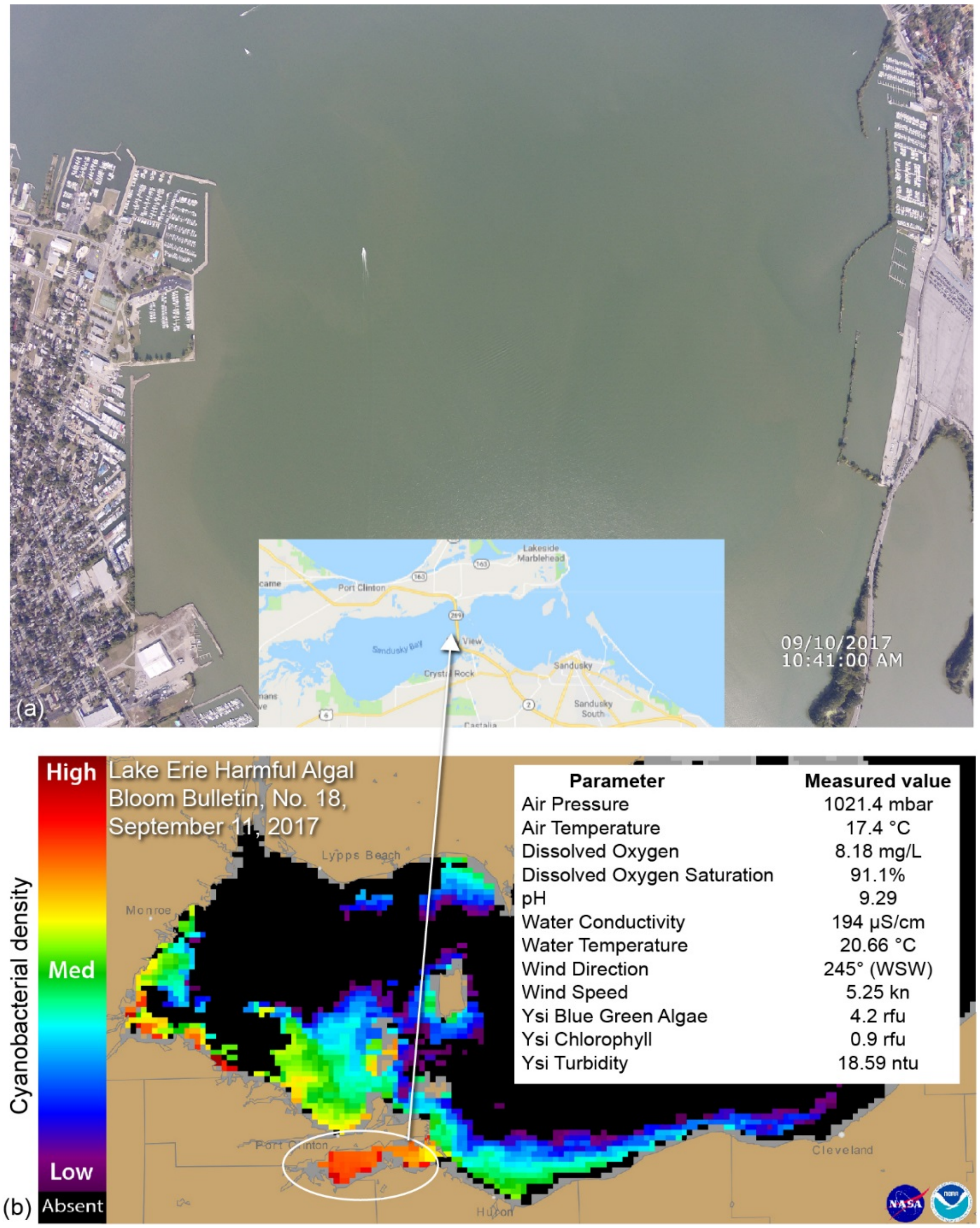


Figure 24.—RGB image (September 10, 2017, 10:41 EST) of algal mass at Sandusky Bay (a) in comparison with MODIS satellite and GLOS data (b). The NASA MODIS-Aqua data collected on 10 September, 2017, at 13:25 EST was posted on September 11, 2017. The GLOS data is shown in the inset was collected at 8:00 a.m. on September 10, 2017. The area shown inside the black circle at the bottom is the shallow (10 to 12 ft deep, about 15 mi long, and 2 to 3 mi wide) Sandusky Bay.

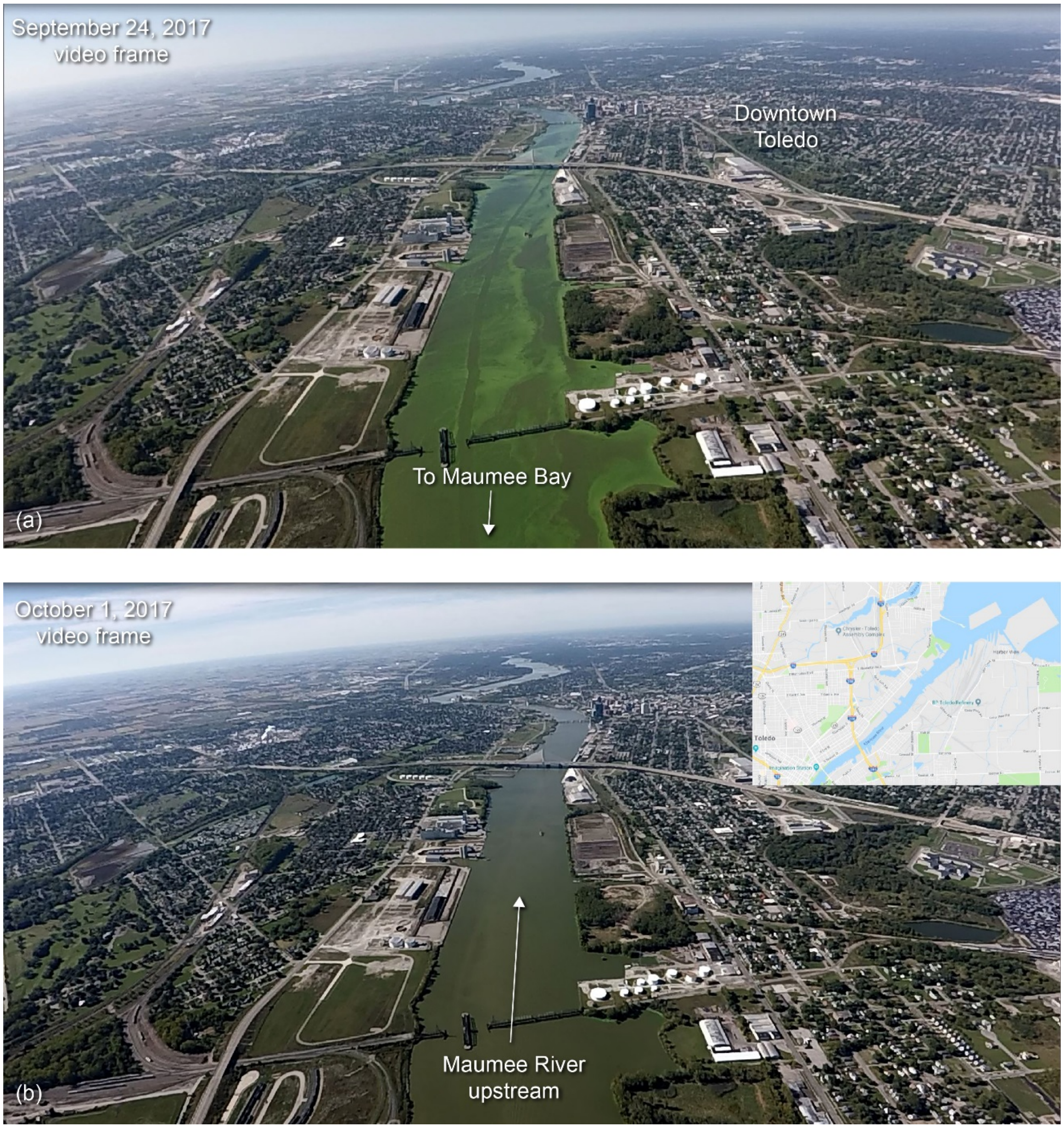
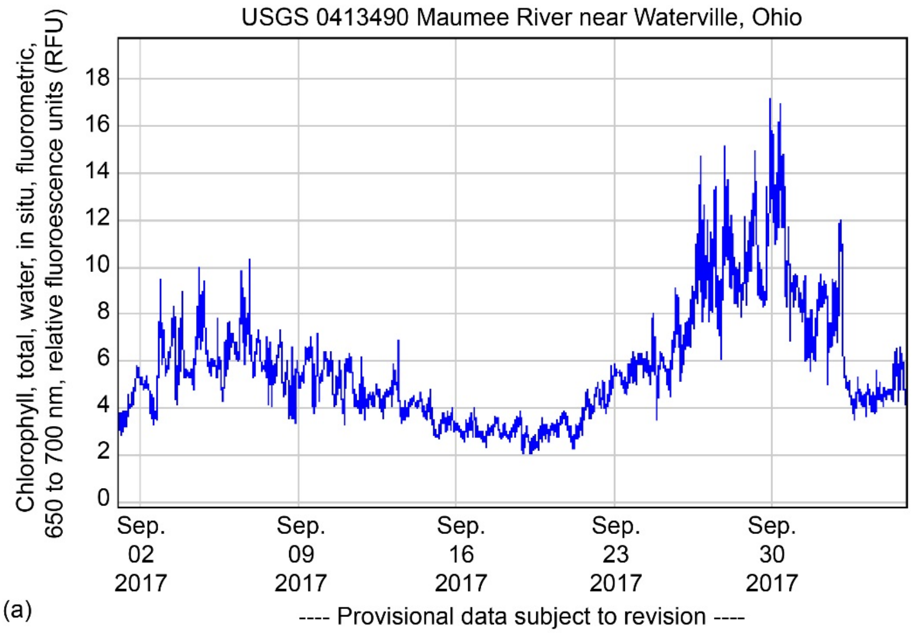
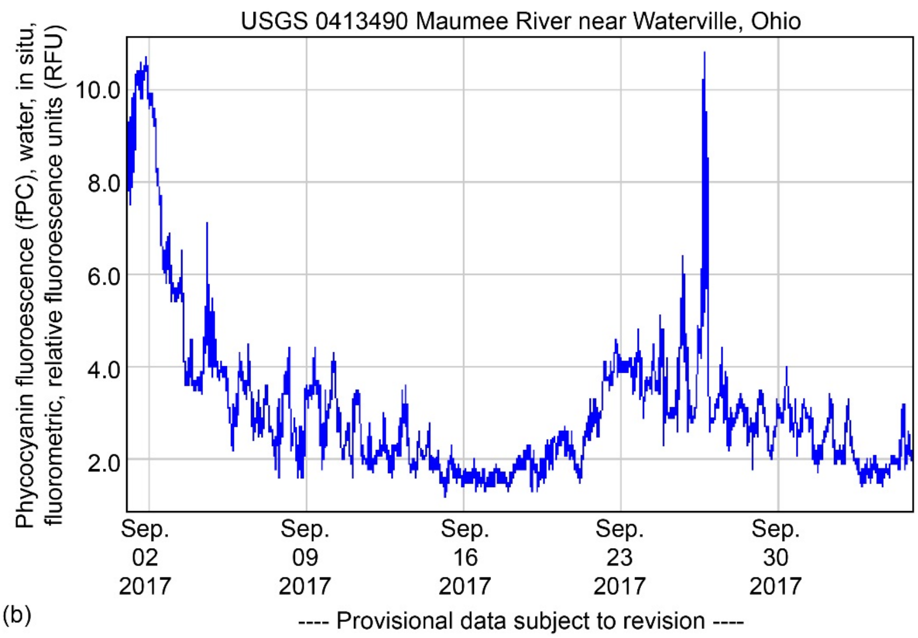


Figure 25.—(a) Intense algae outbreak in Maumee River upstream about 6 to 8 mi from the Maumee Bay to past downtown Toledo. This unusual outbreak was videotaped while flying over the Maumee River at an altitude of 3,000 ft AGL on September 24, 2017. (b) The bloom started to subside on October 01, 2017. Photos like these are preferred by water quality managers as they show them the extent of a bloom that they cannot see by boat or by standing on shore.



(a)



(b)

Figure 26.—In-situ data from USGS buoy located at Waterville, Ohio; suburb of Toledo located on the Maumee River upstream. An increase in chlorophyll values and its accessory pigment phycocyanin matches with aerial images shown in Figure 25. (Graph courtesy of the U.S. Geological Survey.)

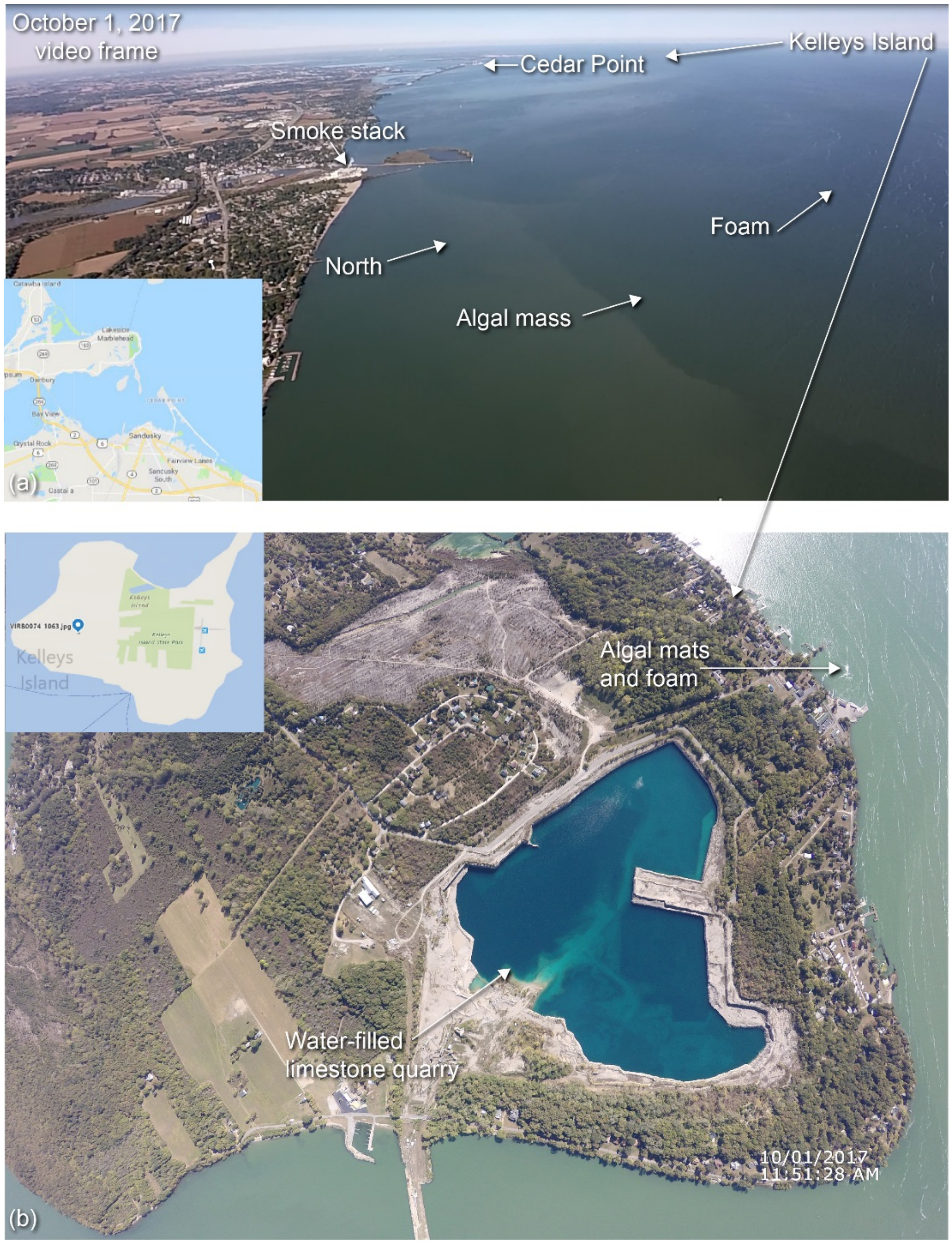


Figure 27.—(a) Continued spread of bloom and foam from the Lake Erie Michigan coastline to the islands and from Toledo to Huron (distance of approximately 65 mi). (b) High-resolution (1.3 ft/pixel) image of Kelleys Island in Lake Erie taken at an altitude of 3,000 ft AGL clearly delineates fine particulates of limestone floating in the 200 acre water filled limestone quarry, different water colors, vegetation, and other structures. The distinct blue color of water in the quarry is perhaps due to Rayleigh scattering in which the light scattered by small particles is dominant.

3.6 Scientific Understanding of the Role of Estuaries and Wetlands in Harmful Algal Bloom (HAB) Prevention

According to a recent study the destruction of small wetlands is directly linked to algal blooms in the Great Lakes (https://uwaterloo.ca/earth-environmental-sciences/news/destruction-small-wetlands-directly-linked-algal-blooms). In addition to HAB monitoring in near shore and open water, our approach of high-resolution RGB and NIR imaging provided by volunteer GA pilots can serve and compliment a multitude of other applications, such as observations of agriculture farm lands (moisture and tile drainage), vegetation, flooding, inland, coastal oil spills, inventory of water levels, and shore erosion. As an example, the Old Woman Creek (OWC) National Estuarine Research Reserve (NERR) is a coastal wetland system along the southern shore of Lake Erie near the city of Huron in Ohio. The ODNR is using this wetland as a model to study contributing factors to the loss of Great Lakes wetland biological diversity due to the presence of invasive plants such as *Phragmites australis*, an aggressive invader that displaces the native vegetation. It was first observed at OWC in the mid-1980s. Whyte et al. have shown that this species has expanded in the area surrounding Star Island, the northwest embayment, and the southeast corner of the lower wetland. In each area, it has replaced large, monospecific stands of *Nelumbo* (lotus) (Ref. 17). The RGB and NIR aerial photographs taken frequently can facilitate delineation of the vegetation boundaries and patterns and the development and spread of *Phragmites*. GA-CS images taken frequently will allow wetland and natural resource managers to better understand vegetation dynamics enabling proper management strategies. Presently, OWC's vegetation monitoring focuses on the area north of the Railroad Bridge and south of Route 6 (see Figure 28(a)). Kristin Arend, Research Coordinator and Fisheries Biologist is conducting a project relating shoreline vegetation along the central and western basins of Lake Erie to nearshore fish communities. Currently, the USDA NAIP aerial images are being used to document changes in plant species composition and community structure in response to *Phragmites* expansion and other invasive species. However, the frequency of these images is every 2 to 3 years with only one flight. Our GA-CS images taken every week over OWC can be beneficial in this effort. The images shown in Figure 28 show changes in plant communities of OWC. We are providing aerial imagery in support of quantitative ground data collected by OWC researchers to study changes in the plant community as a function of time and seasons.

4.0 Discussion

The objective of this proof-of-concept study was to explore a new aerial monitoring method that is low cost, flexible, can be deployed rapidly, cover a wide area, and provide high-quality data in near real time, free of charge, to end users. This effort generated data on bloom and plume extent and dynamics that complements the data obtained by large-scale formal studies of HABs. It can help researchers and hydrology modelers understand questions posed by the interaction of the factors controlling various parameters influencing HABs.

The images reveal enormous information delineating important features. These images easily spot algal blooms as they look like a scum, foam, or mat on top of the water or like paint that has been spilled on the water's surface. The RGB and NIR images reported above can be further analyzed with advanced computational tools if necessary by expert researchers. Professor Joseph Ortiz of Kent State University, in a NASA internal project report, demonstrated that the aerial RGB and NIR images discussed previously can be processed to a degree usable for scientific analysis and modeling. His image analysis employed free open-source algorithms for band ratio calculations and NASA-developed SeaDAS for ocean color products. The SeaDAS tutorials are available at NASA: https://seadas.gsfc.nasa.gov/tutorials/. The preliminary analysis performed on a few images showed that first-look qualitative and perhaps semi-quantitative information can be obtained on the NDVI, normalized differential water index (NDWI), pigment concentration, vegetation fraction, water clarity, and possibly cyanobacteria and/or algae. This unpublished report is available to researchers upon request. This approach may provide scientists one more very low-cost complimentary tool to assist in HAB monitoring and modeling in their geographical area of interest. The water toxicity, however, can only be ascertained by onsite field testing.

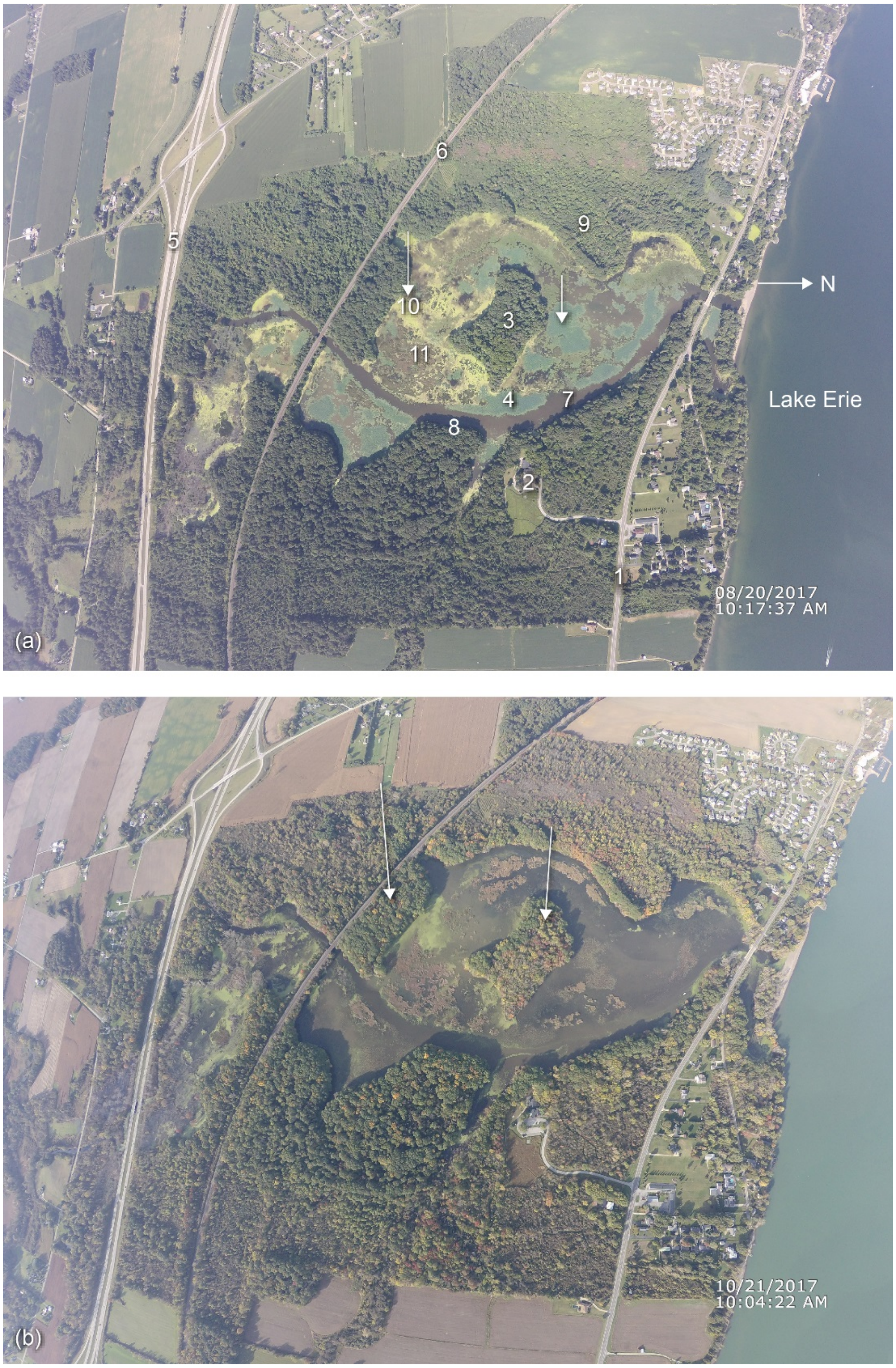


Figure 28.—Images over Old Woman Creek (OWC) looking west. (a) Image taken on August 20, 2017, at 10:17:37 a.m. (1) U.S. Route 6, (2) OWC visitor center, (3) Star Island, (4) lotus, (5) State Route 2, (6) railway line, (7) open water, (8) trees' shadow (sun from E–SE), (9) broad-leaved deciduous trees, (10) duckweed (*Lemna minor*), and (11) Cattails (*Typha angustifolia*) and *Phragmites australis*. (b) Image taken 2 months later on October 21, 2017 at 10:04:22 a.m. shows significant changes in vegetation. The distinct fall foliage is clearly visible along with a marked decrease in the population of duckweed and *Nelumbo lutea* (lotus) pointed by arrows. The aerial photographs facilitate delineation of the vegetation boundaries and patterns.

The GA-CS images presented contain intricate detail, can be processed quickly, and are easy to understand by everyone. However, we should point out that although the RGB and NIR images provide high-resolution images (1.3 ft/pixel) they are limited in their bandwidth and do not provide information on specific chemical or biological constituents causing water toxicity. Glenn engineers (Lekki et al.) are developing a compact hyperspectral imager (HSI) (Ref. 18) for HAB remote sensing at the cyanobacterial level suitable for UAV or drone flights. Once this imager capable of acquiring data in approximately a 200- to 1020-nm spectrum range is fully tested and validated, perhaps in the future it can be mounted on GA airplanes for CS flights. We think a camera system discussed above along with the miniaturized HSI camera will result in providing both high-resolution visual photographs and data on water toxicity.

The GA-CS flight operations and aerial imaging worked flawlessly. The major limitation in this project was uploading data up to one central location in a timely manner. The high-resolution images take up several gigabytes of space. This requires high-speed internet connections, which are not available to every pilot. Efforts to upload images just for one flight took at least 6 to 8 h on a home computer to transfer to a server. The availability of web developers due to lack of resources was another roadblock in processing and distributing georeferenced data to end users. Because timing is everything in HAB monitoring, the individual pilots devised another way to distribute data in a timely manner to end users. They prepared brief reports with images within a couple of hours post-flight and sent them in PDF files to several agencies and researchers. The original images were emailed upon request to individual researchers or uploaded to their Dropbox or Google Drive accounts. The research community appreciated the reports and images. The digital technology is literally moving forward at the speed of light. In not too distant future, it may be possible to livestream the CS data (images and videos) in real time.

In this report, in the interest of page limitations, we only described work on Western Lake Erie performed by the authors (RA and TS). However, the GA-CS HABs monitoring approach can be easily upscaled. Our approach attracted interest in expanding this effort to other parts of the U.S. (coast-to-coast and Alaska) as HAB outbreaks are occurring more frequently. Over 100 pilots and/or airplane owners expressed interest and their willingness to participate in this volunteer work. As an example, water bodies in three states shown in Table II were covered under this CS initiative. In 2017, 12 more states in the U.S. requested help to expand this effort in their areas.

We demonstrated that GA-CS aerial imaging provides an effective means to visualize the entirety of an algal bloom and to observe it in its context as it develops from open lake water to a toxic algal mat. We complemented HAB research efforts of state, federal, and university researchers by providing them with data they cannot generate themselves and by using the results they do generate. Improving our understanding of the complex interactions that promote blooms and toxin production will enable greater comprehension of root causes and the development of preventive strategies.

TABLE II.—EXAMPLE OF PILOT NETWORK IN AREAS OTHER THAN LAKE ERIE COVERED BY CITIZEN SCIENTIST PILOTS

State	Pilot	Water system
California	Robert Dismukes	Monterey Bay, Pinto Lake, Lake Cunningham, Quarry Lakes, Lake Del Valle
	Mokhtar Chamli	Salton Sea
Minnesota	Dave Nelson	Mississippi River
Utah	Jody Patterson	Scofield Reservoir

5.0 Conclusion

In conclusion, our initiative showed GA pilot volunteers and citizen scientists could be vitally important in the effort to monitor HABs. We achieved the project goals of helping to develop an early warning system to alert communities of ensuing algal bloom along coastlines and waterways and of providing near real-time data access to anyone (free of charge) interested in water quality. The fact that 12 states asked for help from this initiative clearly shows the widespread demand and value of this approach. This effort bridged the HAB monitoring imaging gaps on some days when satellite and other airborne data were not available. The CS data makes it possible for the scientists to study issues related to HABs, water quality managers use them in their decision making process, and students use them in advance learning and image processing.

Appendix—Acronyms and Abbreviations

AGL	above ground level (in feet)
AOPA	Aircraft Owners and Pilots Association
ATC	air traffic control
CS	citizen science
d	day(s)
EPA	Environmental Protection Agency
ETD	Environmental, Transportation, and Decision Support
FAA	Federal Aviation Administration
FOV	field of view
GA	general aviation
GLOS	Great Lakes Observing System
GPS	Global Positioning System
HAB	harmful algal bloom
HD	High definition
HSI	hyperspectral imager
KLPR	Lorain County Regional Airport
MODIS	Moderate Resolution Imaging Spectroradiometer
MP	megapixel
MTRI	Michigan Tech Research Institute
NAIP	National Agriculture Imagery Program
NERR	National Estuarine Research Reserve
NDVI	normalized differential vegetation index
NDWI	normalized differential water index
NIR	near-infrared
NOAA	National Oceanic and Atmospheric Administration
NTU	Nephelometric Turbidity Units
ODNR	Ohio Department of Natural Resources
OW	Old Woman Creek
rfu	relative fluorescence units
RGB	red, green, and blue
s	second(s)
SD	Secure Digital
UAV	unmanned aerial vehicle
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VFR	visual flight rules (a set of FAA regulations under which a pilot operates an aircraft in clear weather conditions with visual references)
YSI	Yellow Springs Instrument

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