4 ACQUISITION AND ANALYSIS OF REMOTE SENSING IMAGERY OF HARMFUL ALGAL BLOOMS

Raphael M. Kudela[1], Richard P. Stumpf[2], and Peter Petrov[3]

[1]University of California, Santa Cruz, Santa Cruz, CA USA
[2]National Oceanographic and Atmospheric Administration, Silver Spring, MD USA
[3]Regional Organization for the Protection of the Marine Environment, Kuwait

4.1 INTRODUCTION

Remote sensing was long considered an obvious tool for studying the distribution of harmful algal bloom (HAB) organisms over larger spatial and shorter time scales than is possible with ship-based sampling (Tester et al. 1991; Keafer and Anderson 1993). Legacy and next-generation instrumentation and sensors, including SeaWiFS, MODIS, MERIS, and the OLCI sensor on Sentinel-3, are dramatically improving the ability to determine constituents in the coastal ocean. Satellite altimeters and scatterometers also provide geophysical fields such as dynamic height (current patterns) and local winds (e.g. upwelling indices). Currently, MODIS Aqua and VIIRS are still operational, while the replacement for MERIS, OLCI, is now operational.

In some regions, remote sensing has already become a valuable tool for helping to predict the onset, location, and transport of HABs. For example, in the Florida Shelf and Gulf of Mexico, SeaWiFS and MODIS imagery has been incorporated into the U.S. NOAA HAB Bulletin reports to identify potential red tide events, while feature-tracking has been used to follow the spatial transport of these events (e.g. Tester et al. 1991; Tester and Steidinger 1997). Progress has also been made on the use of inherent optical properties, derived from ocean color inversion algorithms, to identify functional phytoplankton groups based on fundamental biophysical properties (e.g. Lohrenz et al. 2003; Schofield et al. 1999).

Although multi-spectral scanners (e.g. MODIS) can be used to detect the reflectance of chlorophyll *a* and other pigments with some accuracy, these efforts have been constrained by the inability of the sensors to discriminate phytoplankton populations at the species level.

This is, of course, a fundamental requirement of HAB programs. Instead, progress has been made by first linking specific water masses to HAB organisms and then identifying and tracking that water mass with an appropriate remote sensing technique. In particular, remotely-sensed sea surface temperatures (SST) have been used to follow the movement of fronts, water masses, or other physical features where HAB species accumulate. A fundamental problem for identifying HAB events, however, is that the imagery is still limited to identification of chlorophyll or other biomass proxies rather than individual organisms (at the genus or even functional group level).

Satellite imagery by itself will simply not provide the specificity needed to identify particular organisms. Recent advances have begun to extend our ability to use remote sensing beyond simple bulk chlorophyll measurements, however. For example, considerable work has gone into identifying phytoplankton functional groups, or groupings of optically similar organisms such as diatoms, dinoflagellates, and coccolithophorids. In some specific cases, optical estimates (either from in-water measurements or remote sensing) can be used to identify particular organisms, as some have unique optical properties. This includes *Karenia brevis*, *Trichodesmium* spp., and cyanobacterial (blue-green) algal blooms (Alvain et al. 2008; Stumpf et al. 2003; Westberry et al. 2005; Wynne et al. 2008). While diatoms and dinoflagellates are very similar optically, and both can cause high biomass events, there appear to be enough differences to discriminate between dinoflagellate- and diatom-dominated surface waters as well (Dierssen et al. 2006; Palacios 2012).

In addition to the limitations of optical methods (including remote sensing) for the identification of specific HAB organisms, another problem arises when imaging high biomass blooms. When the biomass exceeds ~50 mg/m^3 total chlorophyll, standard satellite algorithms (e.g. MODIS OC3 or MERIS Algal-2) often fail because the water-leaving radiances are high enough to trigger atmospheric correction failures. This results in consistent underestimates of high biomass events in coastal waters. This can be remedied relatively easily by the use of non-standard ocean color products. For example, Kahru and Mitchell (2008) showed that the 250 m resolution bands on the MODIS satellite can be used to develop a “particle index” that closely tracks red tides, while also providing the highest possible spatial resolution. Hu et al. (2005) advocated the use of fluorescence bands for the same reason; a second advantage is that only chlorophyll-containing particles strongly fluoresce, solving the issue of working in optically complex coastal waters. Chen et al. (2009) extended this by using multiple bands (fluorescence line height (FLH), backscatter, etc) to develop a “machine learning” algorithm that can detect red tides. Given enough data it is also possible to develop region-specific algorithms that work better than the global methods (Kahru et al. 2012).

To summarize, using modern methods and data freely available from several ocean color sensors, it is currently possible to identify high biomass HAB events (e.g., red tides), although this requires application of non-standard products. The biomass estimates can be further categorized into phytoplankton functional types, potentially useful for identifying subclasses of blooms such as high biomass dinoflagellate events. These methods require more effort and access to some laboratory or field optical measurements to parameterize the models. It is not currently possible (and is unlikely to become possible) to identify species of algae from space. When combined with other data streams such as currents, field measurements, and in-water monitoring programs, unusual events can be identified, tracked, and the subsequent impacts predicted if there are independent means of identifying the organisms. This is most effective when remote sensing is combined with in-water observations as part of an ocean observing program (see Chapter 3; Frolov et al. 2013; Kudela et al. 2013).

4.2 AVAILABILITY OF DATA AND SOFTWARE

A large amount of satellite data on ocean colour is freely available for users, though some expertise is needed to use and interpret it. Downloading data from the web sites of the ESA (European Space Agency) and NASA (U.S. National Aeronautics and Space Administration) is straightforward. Free software such as SeaDAS and SNAP makes it feasible to work with ocean color data on personal computers, and the NASA Ocean Biology Processing Group offers a forum for technical support. Data suitable for automated downloading are also available from sites such as the U.S. National Oceanic and Atmospheric Administration (NOAA) via ERDDAP. Here the focus is on the most common satellites and sensors described above. As of 2016, this limits data primarily to NASA MODIS (and VIIRS) sensors, and ESA MERIS (and OLCI) sensors. Expert users may also take advantage of Landsat8 (US Geological Survey), Sentinel-2 (ESA), and the various sea surface temperature sensors (e.g. AVHRR). The European Space Agency also supports SNAP for use with the Sentinel platform; it is based on the same system as SeaDAS. Some example links for those data products are provided here, but exhaustive descriptions of all sensors and products is beyond the scope of this chapter.

4.3 INTERNET ACCESS TO IMAGERY

The simplest way to identify blooms with satellite imagery is to take advantage of standard (global) processing that makes both data and imagery available via web browsers. As described below, these standard products include RGB, chlorophyll, nFLH, and other products such as light attenuation depth, particulate backscattering (a useful indicator of particle load), colored dissolved organic material, and various other products. Data are typically divided into categories. Level-1 (L1) are “raw” data, suitable for reprocessing by the end-user. Level 2 (L2) include derived products such as chlorophyll, and have been atmospherically corrected. The L2 files may also be projected to a standard map. Level 3 (L3) are binned in space, time, or both. L3 imagery is often at reduced spatial resolution (typically 4 or 9 km). Standard L2 products are typically at 1 km resolution, and with some sensors (MODIS, MERIS) reprocessing of L1 data can generate imagery at 250-300 m resolution.

4.3.1 Access to L1, L2 and L3 images

NASA provides two portals that make it easy to access L1, L2 and L3 data. The WorldView site (http://worldview.earthdata.nasa.gov) provides a graphical interface that can display many types of satellite (and other) data using a graphical user interface. This is an excellent tool for quickly examining recent imagery, but the data are spatially binned and thus provide limited spatial resolution. Figure 4.1 provides a snapshot of MODIS chlorophyll for the same region used in section 4.3.

The NASA Ocean Biology Processing Group, OBPG, (http://oceancolor.gsfc.nasa.gov/cms/) provides the same data as WorldView, along with many other satellite products including MODIS Aqua and Terra, MERIS, and VIIRS. From this site it is possible to view L1, L2, and L3 imagery at various resolutions, and to download data directly for further processing. Figure 4.2 provides a screenshot of similar data as shown in Figure 4.1, but for the entire globe. These data (Figure 4.2) can be directly downloaded.

The ERDDAP site (http://coastwatch.pfeg.noaa.gov/erddap/griddap/documentation.html) provides access to a subset of the same data provided by WorldView and OBPG, but is set up primarily for machine-to-machine access. Using this site it is possible to set up automated extraction of a particular region, to download large amounts of data, and to create time-series.

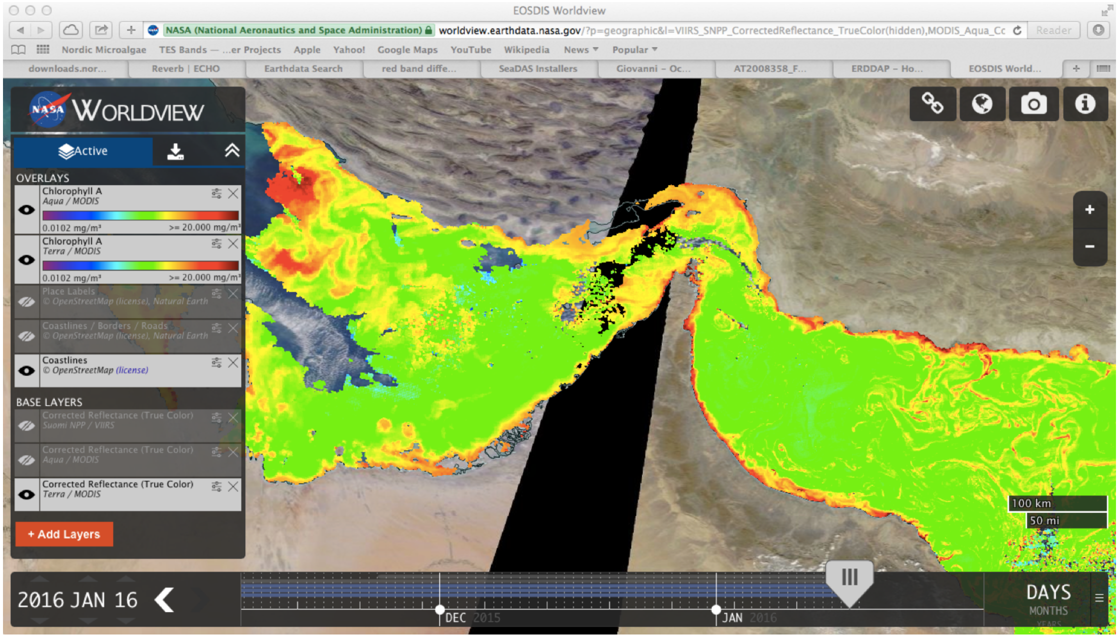

Figure 4.1. A screen shot of the NASA WorldView site.

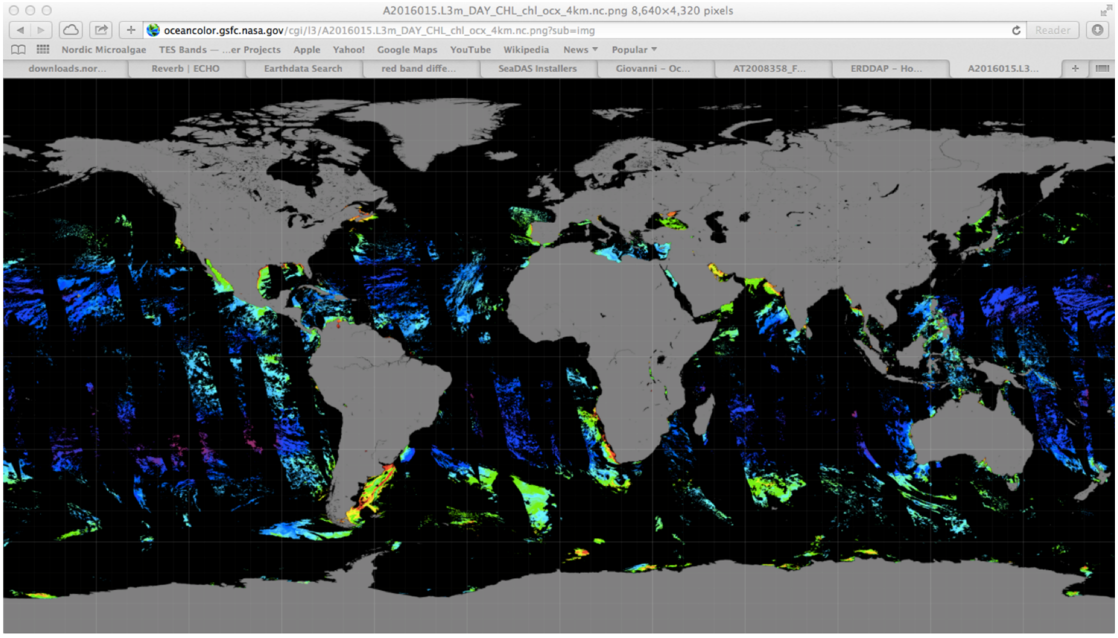

Figure 4.2. A screen shot of the NASA OBPG site showing L3 chlorophyll at 4 km resolution for 15 January 2016.

Finally, the Giovanni site, run by NASA (http://giovanni.sci.gsfc.nasa.gov/giovanni/) provides many options for accessing NASA data, including generation of individual images, time-series, and other specialized analyses. At this time (July 2017) Giovanni has not moved most reprocessing of NASA ocean color data to the system. While Giovanni only provides limited data (i.e. L3 data), it makes it simple to extract time series of several standard products for a given location. All of the processing and data extraction is completed on NASA servers, and the end-user is given both graphical images and the option of downloading the original data. Figure 4.3 provides an example of a chlorophyll time-series extracted from the Fujairah, UAE desalination intake site, for 1998-2015.

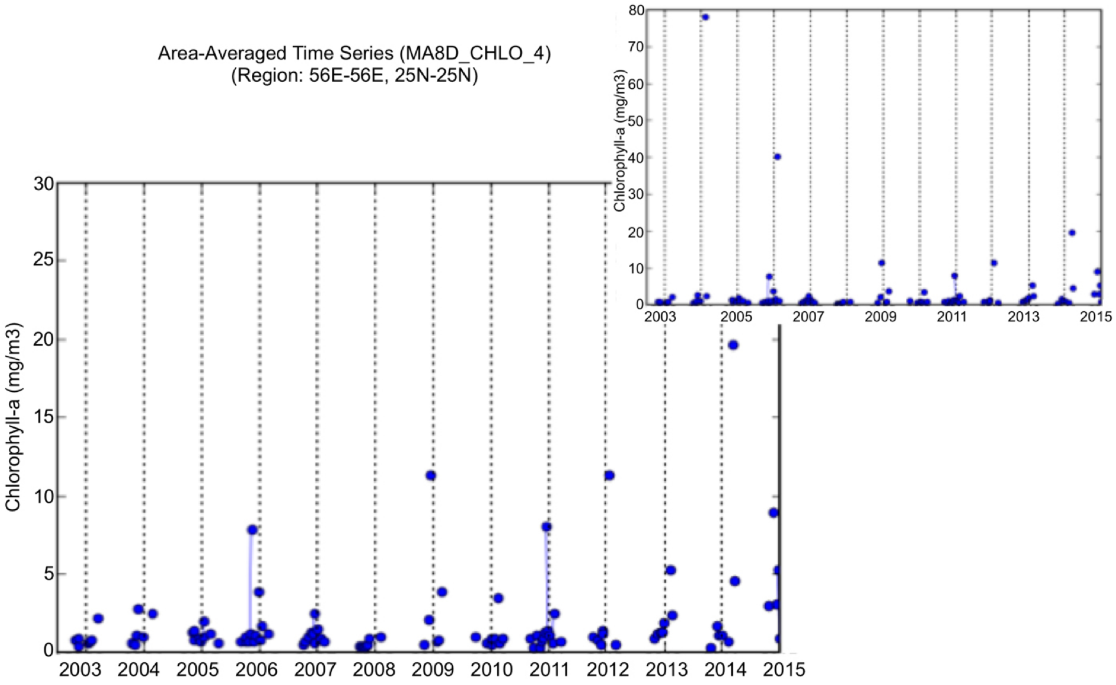

Figure 4.3. Time-series of chlorophyll extracted from the Fujairah, UAE desalination plant intake location. The inset shows the full range of the data, while the main graph was truncated at 30 mg/m^3.

4.3.2 Data subscription services

In addition to viewing/accessing data interactively, it is possible to define a specific region or regions and set up a data subscription with the NASA OBPG system. This requires the user to register with NASA, but the service is free and the registration process is straightforward. Access to the service is at this website:
http://oceancolor.gsfc.nasa.gov/sdpscgi/public/subscriptions_home.cgi

Once registered, the user can request either a non-extracted or extracted region globally. Currently MODIS Aqua, MODIS Terra, and VIIRS are available. Start and end dates are selected, along with a geographical region. Various products are available (depending on the sensor) including chlorophyll, nFLH, SST, and RGB. The user can request images (emailed to your account), data files, or both. For data, the user can further specify L1 or L2 files. This is particularly useful because the data will always be processed with the most current version of the OBPG processing routines.

4.4 SOFTWARE FOR PROCESSING SATELLITE DATA

NASA recently (~2015) changed formats from Hierarchical Data Format (HDF) to netCDF 4.0. ESA also generates data as netCDF 4.0. The advantages of these formats are that they are “self-contained”, including metadata and data within one “container”. Any software that can access netCDF or HDF files can be used to process satellite imagery, including (e.g.) Python and MATLAB, other programming languages, or specialized software designed to work directly with the imagery.

Freely available, commonly used, and highly recommended satellite processing software are provided by both ESA and NASA. These include SeaDAS software (NASA) and SNAP software, which recently replaced BEAM (Brockman Consulting, created for ESA). The most recent versions of SeaDAS are based on BEAM, so the two software sets are somewhat interchangeable. SeaDAS provides extra processing options specific to NASA processing (the OBPG), while BEAM/SBAP provides tools specific to ESA processing (MERIS, OLCI, Sentinel-2).

4.4.1 Hardware requirements

Both SeaDAS and BEAM operate on standard personal computers (Windows, OS X, Linux). The only requirement is that Java is available. Satellite data are often very large, however, so it is recommended that a dedicated hard-drive be available for more extensive processing. Both SeaDAS and BEAM process much of the data "on the fly", as well, so they can tax systems with limited amounts of RAM. For routine processing 4-8 GB RAM is usually sufficient. For processing of time-series or very large (high resolution) imagery, it may be necessary to access up to 32 GB RAM, particularly if the computer is also being used for other tasks. Both programs provide rich processing capability that is beyond the scope of this Chapter. Either can be used to visualize and process satellite data obtained at L0 (completely unprocessed), L1, L2, or L3 levels.

4.4.2 SeaDAS software

SeaDAS is provided for free by the NASA OBPG group. It can be downloaded directly from NASA and comes precompiled for various operating systems. SeaDAS can be installed as a GUI (basic use) and as processing code (expert use) for processing of satellite data using low-level scripts. NOTE: the Windows version can be used to visualize data, but does not include the low-level processing programs.

The SeaDAS development released SeaDAS 7.4 in March 2017, which is built atop a modified version of BEAM. The science processing code has been updated to reflect changes recently implemented in production, providing bug fixes and support for the R2014.0 reprocessing for SeaWiFS. As long as the most recent version of SeaDAS is used, processing should be identical to the NASA OBPG products.

4.4.3 BEAM and SNAP software

BEAM is an open-source toolbox and development platform for viewing, analyzing and processing remote sensing raster data. Originally developed to facilitate the utilization of image data from Envisat's optical instruments, BEAM supports a growing number of other raster data formats such as GeoTIFF and NetCDF as well as data formats of other Earth Observation sensors such as MODIS, AVHRR, AVNIR, PRISM, and CHRIS/Proba. Various data and algorithms are supported by dedicated extension plug-ins. The primary tool is VISAT - an intuitive desktop application to be used for visualization, analyzing and processing of remote sensing raster data. As with SeaDAS, access to low-level processing scripts are also available for expert users. BEAM was replaced by SNAP, which is functionally similar but supports the most recent satellite platforms and processing methods.

4.5 ALGORITHMS USED TO DETECT BLOOMS

4.5.1 Atmospheric correction

Many regions where desalination is used, such as the Arabian Sea and Sea of Oman, are subject to severe dust and other atmospheric conditions that cause problems for the standard processing provided by NASA and ESA. These atmospheric correction issues are exacerbated by high-biomass events, which often trigger correction failures (Loisel et al. 2013). It is possible to recover much of the "lost" data by switching to non-standard atmospheric correction. This is time-consuming and requires optimization of the methodology. A more straightforward approach is to use algorithms that rely upon the shape of the ocean color spectra (spectral shape algorithms) that are applied with simple atmospheric corrections, or with no atmospheric correction at all. These rely on fairly standard products from the satellite processing, but are not routinely available without end-user processing. Some of the algorithms below take advantage of these methods, but "standard" products using NASA and ESA atmospheric correction are also discussed.

4.5.2 Algorithms

There is no HAB-specific remote sensing algorithm, but there are several methods that work well for identifying high-biomass bloom events. Most of these belong to a class called "spectral shape" algorithms. In contrast to chlorophyll methods, which generally use band ratios (typically the ratio of blue to green light), spectral shape methods rely on changes that occur over 3 or more bands (colors). The advantage of these algorithms is that they are much less sensitive to atmospheric correction issues, since it is the shape rather than the absolute values that identify the property of interest. These are also sometimes called linear baseline algorithms since, functionally, they are often calculated as the height of a peak above a baseline of two other wavelengths. This is how both FLH (fluorescence line height) and MCI (maximum chlorophyll index) are determined. Table 4.1 provides a list of algorithms commonly used for red tide detection.

Table 4.1. Commonly used remote sensing algorithms. The first three are available without additional end-user processing; the remainder require some expertise.

Target	***Method***	***Reference***
Biomass	Chlorophyll	*Standard product*
Chlorophyll fluorescence	Fluorescence line height (FLH), normalized fluorescence line height (nFLH)	*Standard product*
True-color image	Red-Green-Blue (RGB), Enhanced Red-Green-Blue (ERGB)	*Standard Product*
High biomass	Maximum chlorophyll index (MCI), Red band difference (RBD), maximum peak height (MPH)	Gower et al. 2005, Ryan et al. 2014; Amin et al. 2012; Matthews et al. 2012
High biomass	250 m band subtraction	Kahru et al. 2008
Floating Algae	Floating Algae Index (FAI)	Hu, 2009
Noctiluca	Spectral Shape	Astoreca et al. 2005
Trichodesmium	Spectral Shape	Hu et al. 2010

4.5.2.1 Standard algorithms

These algorithms are standard products provided by NASA and ESA, and do not require any special processing or effort. They are commonly available from multiple locations on the Internet.

4.5.2.2 High biomass algorithms

This group of algorithms relies upon changes in spectral shape as phytoplankton biomass increases. As described in Ryan et al. (2014), the primary issue with these algorithms is that they are sensitive to the biomass concentration. Below ~25 mg/m^3 chlorophyll, MODIS FLH works well. Above about 50 µg/L, MERIS MCI works well. It is possible to develop a single algorithm that works for all biomass levels (Ryan et al. 2014) given higher resolution spectral data, such as is available from HICO, but this will not be routinely available for 5-10 years, when the next-generation satellites launch. An alternative to these methods is to create an image of scattering (particles) from the "green" part of the spectrum. This is how the band-subtraction method (Kahru 2008) works. The advantage of this method is that it can use the high-resolution 250 m bands from MODIS, and is straightforward. This method can also be applied to either atmospherically corrected or non-atmospherically corrected data. The Floating Algal Index (FAI) is another variation on these methods that takes advantage of reflectance in the near-infrared caused by surface scums or floating algae.

4.5.2.3 Noctiluca *algorithms*

The heterotrophic dinoflagellate genus *Noctiluca* is a relatively common bloom-forming organism in many areas of the world, including the Gulf[1] and Sea. It occurs as both "red" and "green" varieties, with the less common green variety colored by a prasinophyte symbiont (Harrison et al. 2011). Red *Noctiluca* is the unpigmented heterotrophic version, but it often discolors the water (reddish, or "tomato soup" color) due to a combination of its ingested prey items, internal symbionts, and high reflectance in the red and near-infrared. Remote sensing has been used successfully in previous studies (e.g. Gomes et al. 2008; Piontkovski et al. 2011) to infer bloom dynamics of *Noctiluca* by combining general products such as chlorophyll climatologies and anomalies with in-water data and observations of currents, sea surface temperature, and mixed-layer depth.

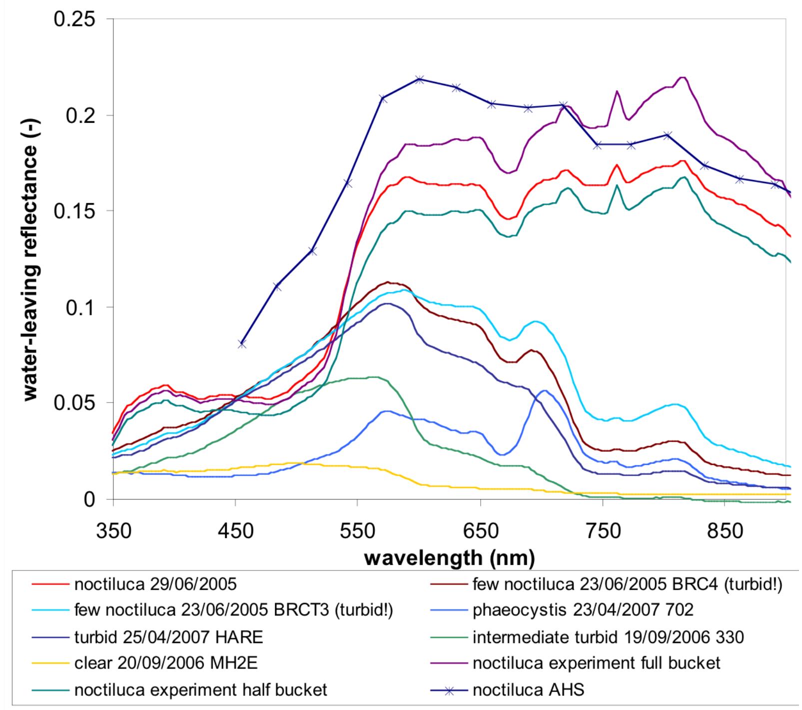

Figure 4.4. Red *Noctiluca* exhibits unusual optical properties, including the inflection at around 530 nm, the sharp increase from 480-580 nm, and the extremely high reflectance in the red and near-infrared. Adapted from Astoreca et al. 2005.

Red *Noctiluca* has somewhat unique properties (Figure 4.4), particularly the strong absorption feature between 480-530 nm leading to a sharp increase in reflection from 520-580 nm (similar to the "red edge" effect in kelp and higher plants). It also exhibits very strong reflectance in the red and

---

[1] Here the Gulf refers to the shallow body of water bounded in the southwest by the Arabian Peninsula and Iran to the northeast. The Gulf is linked with the Arabian Sea by the Strait of Hormuz and the Gulf of Oman to the east and extends to the Shatt al-Arab river delta at its western end.

near-infrared (NIR; 650-850 nm). While this makes it relatively easy to identify *Noctiluca* from high-resolution in-water or even airborne data, the lower spatial and spectral resolution of most satellites is problematic. The strong NIR reflectance is qualitatively similar to suspended sediments, making it easy to misinterpret imagery, while the edge effect in the ~580 nm region requires increased spectral resolution.

4.5.2.4 Trichodesmium *algorithms*

Colonial cyanobacterium (blue-green algae) *Trichodesmium* blooms (mostly *Trichodesmium erythraeum*) occur regularly in the Arabian Sea, Sea of Oman, Indian Ocean, Gulf of Mexico, and Atlantic, and have been proposed to serve as a significant nitrogen source for some regions. Detection of *Trichodesmium* blooms from space has been of interest since the 1980s. Early attempts used empirical algorithms developed for the Coastal Zone Color Scanner (CZCS). More recent efforts focused on the inherent and apparent optical properties (spectral absorption, backscattering, and reflectance) of *Trichodesmium* and on the development of empirical (Subramaniam et al. 2002) and semianalytical algorithms (Westberry et al. 2005) for application to multispectral data from SeaWiFS and MODIS.

These algorithms were developed for optically simple open ocean waters, and frequently over- and underestimate *Trichodesmium* blooms in more complex coastal waters. To address this problem, Hu et al. (2010) proposed to use a spectral shape algorithm derived from the same processing used for the Floating Algal Index (FAI). The algorithm is based on the unique scattering and absorption properties of *Trichodesmium*, but is more complicated than simple linear baseline methods in that it uses multiple wavelengths in the visible. While it works well with atmospherically corrected data, as with most spectral shape approaches it is relatively robust to errors in the correction, since the diagnostic is the shape of the spectra rather than the absolute values of the wavelengths. Hu et al. (2010) demonstrated that this method works well in coastal waters, although it does require manual processing of the data (necessary for inspection of the spectral shape). The processing steps start with simple atmospheric correction of the satellite data to remove the effects of Rayleigh scatter. The FAI is then calculated. For pixels with positive FAI, the spectral shape is then examined (Figure 4.5).

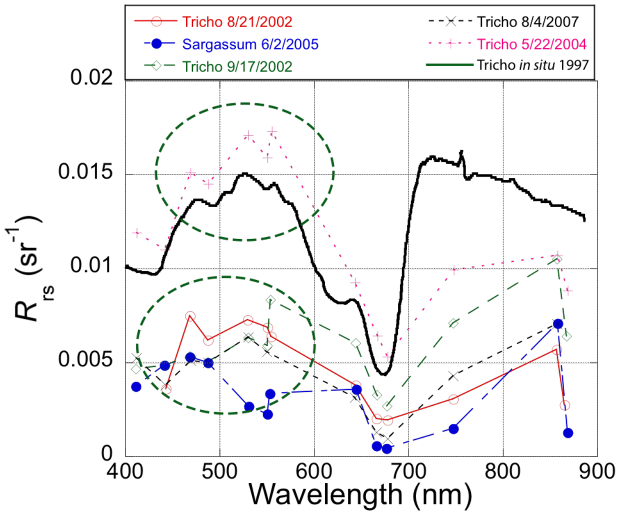

Figure 4.5. Spectral remote sensing reflectance from the MODIS sensor for *Trichodesmium* on the West Florida Shelf (WFS), with corresponding high-resolution data from the Florida Keys collected on 7/1/1997. For comparison, *Sargassum* is shown from the Western Gulf of Mexico (WGOM). All of these blooms show up as positive FAI (as would dense blooms of *Noctiluca* and *Cochlodinium*). *Trichodesmium* has a unique spectral shape, however, with a high-low-high-low-high pattern at 469-488-531-555 nm (MODIS bands, dashed circles). Other sensors with bands in this range would detect the same pattern. Figure adapted from Hu et al. 2010.

4.6 EXAMPLES OF ALGORITHMS

The algorithms discussed above can generally be divided into two categories. Those that are provided by NASA and ESA and do not require any extra effort, and those that require the end-user to conduct additional processing. In practice it is common to use several algorithms (images) and to compare the results from each to develop an informed understanding of the dynamics of a region. Here an example from the Arabian Sea and Sea of Oman is used to highlight how these algorithms compare. Abbreviations are given in Table 4.1.

Figure 4.6 provides an image from the Oman/UAE region for 23 December 2008, using the NASA MODIS Aqua satellite. At the time, a massive red tide of the dinoflagellate *Cochlodinium* had extended throughout the region. Standard products available from NASA include truecolor, or RGB (panel A), Chlorophyll (panel C), Sea Surface Temperature (panel D; note that MODIS Terra was used, and that some data are missing, denoted by the black region), and normalized Fluorescence Line Height, nFLH (panel F). End-user processing of the files produced an Enhanced RGB image (panel B), the RBD (panel E) and FAI (panel G) images, and spectra (panel H) were extracted using the SeaDAS processing program.

Starting with the RGB and ERGB, it can be seen that it was a cloud-free day with little to no dust in the atmosphere. Shallow regions where bottom-reflectance occurs can be seen in the Strait of Hormuz and around the UAE coastline—these areas show up as “bright” areas in the water, and can result in artificially high (false) chlorophyll values. The ERGB does better at highlighting the extent of the bloom (compare A, B, C). In the chlorophyll image (C) there are several regions with missing data (white). Since there were no clouds, this indicates a failure of the chlorophyll algorithm, typically in very high (red tide) patches. This is also apparent in nFLH (F). In contrast, RBD (E) does not have those missing data; this is particularly important along the coast where impacts are likely to occur, since relying solely on the chlorophyll (or nFLH) imagery would suggest that there are no data available. Comparing C and F, some places where there is supposedly high chlorophyll have little or no fluorescence, suggesting that the “chlorophyll” was contaminated by bottom reflectance. Finally, FAI (G) picks out the most intense surface patches of chlorophyll. Two regions are circled (dashed lines) and the spectra are shown in panel H. The southern patch, offshore of Oman, shows the characteristic up-down-up spectral shape of *Trichodesmium*, suggesting that in addition to the *Cochlodinium* red tide along the coast, there were also patches of floating algae offshore. The other region (north) has a spectra indicative of dinoflagellates, with a pronounced green peak and another red/near-infrared peak.

These images show why it is useful to compare several products in order to understand the dynamics of the region. Any single product (algorithm) provides similar patterns, but does not provide all the information available from the satellites. Of course, data are only available when it is not cloudy, and it is critical to have local validation of the satellite products to ensure that interpretation is correct.

4.7 SUMMARY FOR END-USERS

Numerous free data products are available that provide useful and relevant information for tracking algal blooms in coastal waters, with many new sensors coming online. For new users, an excellent starting-point is one of the web-based systems to routinely visualize the region of interest and become familiar with the general oceanographic patterns and data availability. From there, basic data analysis, such as generation of time-series for a given location, can be attempted. If in-water or plant-based data are available it is straightforward to extract data using, for example, the Giovanni website to explore correlations between satellite observations and local conditions. As the end-user becomes more familiar with the available

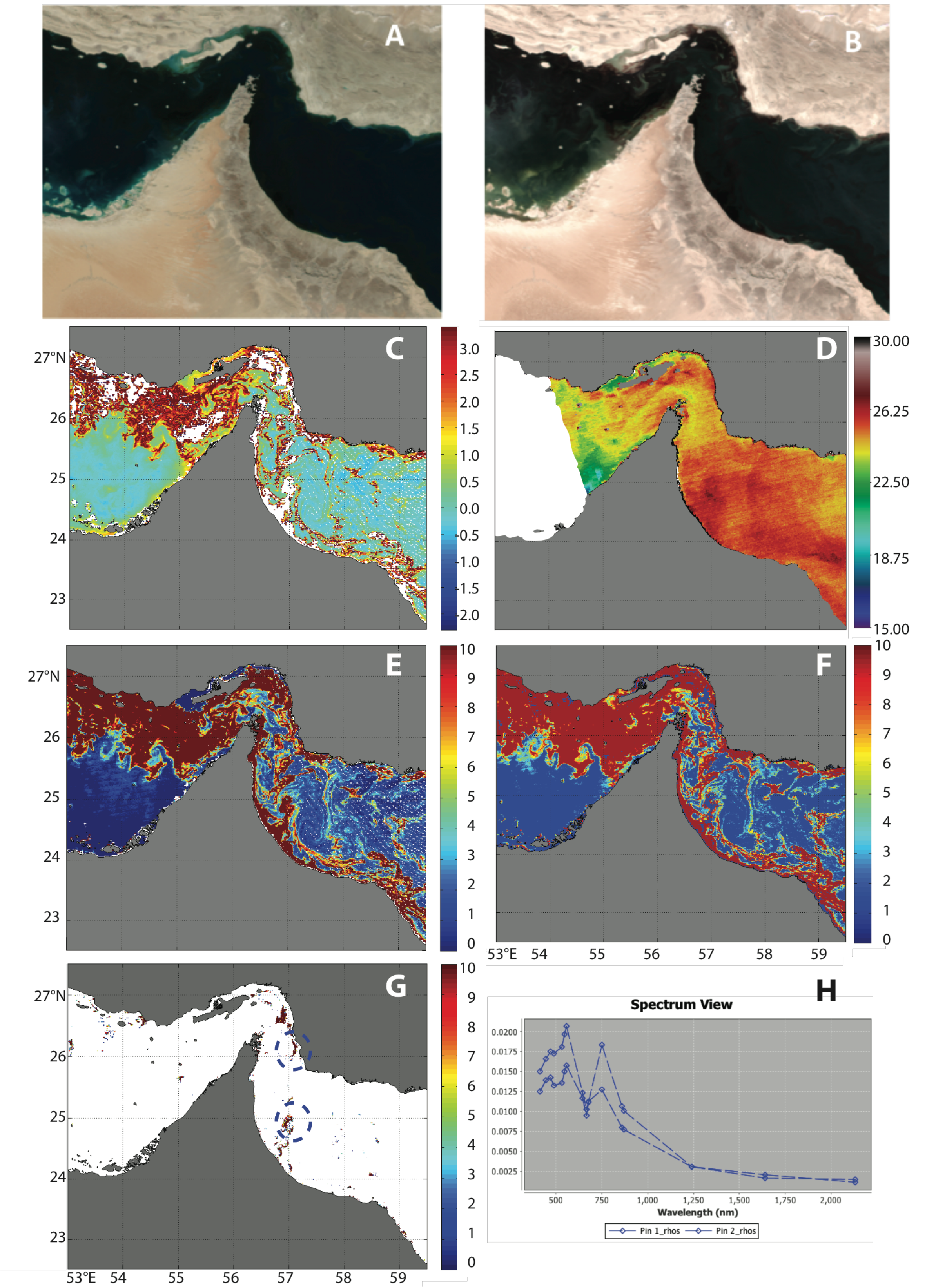

Figure 4.6. MODIS Aqua data from 23 December 2008 during a red tide event. A: RGB; B: ERGB; C: chlorophyll; D: SST; E: RBD; F: nFLH; G: FAI; H: spectra from the circled region in G. See the text for a full description.

data and limitations, the final step is to acquire and process data directly, using either standard algorithms, or taking advantage of the tools available in both SeaDAS and BEAM for non-standard algorithms. An excellent resource for this last step are self-guided tutorials available online (https://www.youtube.com/results?search_query=seadas). At the time of publication, the main satellite processing tools (SeaDAS, BEAM, SNAP) are all based on the same underlying computer code, so an end-user familiar with SeaDAS will quickly be able to use any of these packages. With the basic information provided in this chapter, an end-user can quickly progress from casual use of satellite images to routine production of regionally-adjusted datasets suitable for research and monitoring.

4.8 USEFUL LINKS TO SATELLITE BASED OCEAN COLOR DATA

General

European Space Agency: http://sentinel.copernicus.eu

NASA: http://oceancolor.gsfc.nasa.gov/cms/

USGS: http://earthexplorer.usgs.gov

Data Access

NASA WorldView: https://worldview.earthdata.nasa.gov

NASA Ocean Biology Processing Group: http://oceancolor.gsfc.nasa.gov

NASA Data Subscriptions:
http://oceancolor.gsfc.nasa.gov/sdpscgi/public/subscriptions_home.cgi

Old Giovanni Site: http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_8day

New Giovanni Site: http://giovanni.sci.gsfc.nasa.gov/giovanni/

NOAA ERDDAP:
http://coastwatch.pfeg.noaa.gov/erddap/griddap/documentation.html

SST and other Data Visualization: http://podaac-tools.jpl.nasa.gov/soto-2d/soto.html?layers[]=jpl_ourocean_l4___sst___36000_x_18000___daynight&date=2016-01-11

SST Data: https://podaac.jpl.nasa.gov/GHRSST

Software

NASA SeaDAS: http://seadas.gsfc.nasa.gov

ESA BEAM: http://www.brockmann-consult.de/cms/web/beam/

ESA SNAP: http://step.esa.int/main/toolboxes/snap/

4.9 REFERENCES

Alvain, S., Moulin, C., Dandoneau, Y., and Loisel, H. 2008. Seasonal distribution and succession of dominant phytoplankton groups in the global ocean: A satellite view. *Global Biogeochemical Cycles,* 22: GB3001.

Amin R., Zhou J., Gilerson A., Gross B., Moshary F., and Ahmed, S. 2012. Novel optical techniques for detecting and classifying toxic dinoflagellate *Karenia brevis* blooms using satellite imagery. *Optics Express,* 17: 9126-9144.

Astoreca, R., Rousseau, V., Parent, J.-Y., Lancelot, C., Ruddick, K., and Van Mol, B. 2005. Optical properties of algal blooms in an eutrophicated coastal area and its relevance to remote sensing. Proc. SPIE 5885, doi:10.1117/12.615160.

Chen, W. W., Hall, L. O., Goldgof, D. B., Soto, I. M., and Hu, C. 2009 Automatic red tide detection from MODIS satellite images. *Proceedings of the 2009 IEEE International Conference on Systems, Man and Cybernetics*, 1864-1868.

Dierssen, H., Kudela, R., Ryan, J., and Zimmerman, R. 2006. Red and black tides: Quantitative analysis of water-leaving radiance and perceived color for phytoplankton, colored dissolved organic matter, and suspended sediments. *Limnology and Oceanography* 51, 2646-2659

Frolov, S., Kudela, R. M., and Bellingham, J. G. 2013. Monitoring of harmful algal blooms in the era of diminishing resources: A case study of the U.S. West Coast. *Harmful Algae,* 21-22, 1-12.

Gomes, H. R., Goes, J. I., Prabhu Matondkar, S. G., Garab, S. G., Al-Azri, A. R. N., and Thoppil, P. G. 2008. Blooms of *Noctiluca miliaris* in the Arabian Sea—An *in situ* and satellite study. *Deep-Sea Research* 55, 751-765.

Gower, J., King, S., Borstad, G., and Brown, L. 2005. Detection of intense plankton blooms using the 709 nm band of the MERIS imaging spectrometer. *International Journal of Remote Sensing,* 26, 2005-2012.

Harrison, P. J., Furuya, K., Glibert, P. M., Xu, J., Liu, H. B., Yin, K., Lee, J. H. W., Anderson, D. M., Gowen, R., Al-Azri, A. R., and Ho, A. Y. T. 2011. Geographical distribution of red and green *Noctiluca scintillans. Chinese Journal of Oceanology and Limnology* 29, 807-831.

Hu, C., Muller-Karger, F. E., Taylor, C. J., Carder, K. L., Kelble, C., Johns, E., and Heil, C. A. 2005. Red tide detection and tracing using MODIS fluorescence data: A regional example in SW Florida coastal waters. *Remote Sensing of Environment* 97, 311-321.

Hu, C. 2009. A novel ocean color index to detect floating algae in the global oceans. *Remote Sensing Environment* 113, 2118-2129.

Hu, C., Cannizzaro, J., Carder, K. L., Muller-Karger, F. E., and Hardy, R. 2010. Remote detection of *Trichodesmium* blooms in optically complex coastal waters: Examples with MODIS full-spectral data. *Remote Sensing of Environment* 114, 2048-2058.

Kahru, M., and Mitchell, B. 2008. Ocean color reveals increased blooms in various parts of the world. *EOS* 89:170-171.

Kahru, M., Kudela, R. M., di Lorenzo, E., Manzano-Sarabia, M., and Mitchell, B. G. 2012. Trends in the surface chlorophyll of the California Current: Merging data from multiple ocean color satellites. *Deep-Sea Research II* 77-80, 89-98.

Keafer, B. A., and Anderson, D. M. 1993. Use of remotely-sensed sea surface temperatures in studies of *Alexandrium tamarense* bloom dynamics. In: Smayda, T. J., Shimizu, Y. (eds) *Toxic phytoplankton blooms in the sea.* Elsevier Science, Amsterdam, pp 763-768.

Kudela, R. M., Frolov, S. A., Anderson, C. R., and Bellingham, J. G.. 2013. Leveraging ocean observatories to monitor and forecast harmful algal blooms: A case study of the U.S. West Coast. IOOS Summit. Available at http://www.iooc.us/summit/white-paper-submissions/community-white-paper-submissions/

Lohrenz, S. E., Weidemann, A.D., and Tuel, M. 2003. Phytoplankton spectral absorption as influenced by community size structure and pigment composition. *Journal of Plankton Research* 25(1), 35-61.

Loisel, H., Vantrepotte, V., Jamet, C., and Dat, D. N. 2013. Challenges and new advances in ocean color remote sensing of coastal waters. In: *Topics in Oceanography*, E Zmbbianchi (Ed.), InTech.

Matthews, M.W., Berard, S., and Robertson, L. 2012. An algorithm for detecting trophic status (chlorophyll-*a*), cyanobacterial-dominance, surface scums and floating vegetation in inland and coastal waters. *Remote Sensing of Environment*, 124, 637-652.

Palacios, S. L. 2012. Identifying and tracking evolving water masses in optically complex aquatic environments. Ph.D. Thesis, University of California, Santa Cruz, 207 pp.

Piontkovski, S., Al-Azri, A., and Al-Hashmi, K. 2011. Seasonal and interannual variability of chlorophyll-*a* in the Gulf of Oman compared to the open Arabian Sea regions. *International Journal of Remote Sensing* 32, 7703-7715.

Ryan, J. P., Davis, C. O., Tufillaro, N. B., Kudela, R. M., and Gao, B.-C. 2014. Application of the hyperspectral imager for the coastal ocean to phytoplankton ecology studies in Monterey Bay, California. *Remote Sensing* 6, 1007-1025.

Schofield, O., Grzymski, J., Bissett, W. P., Kirkpatrick, G. J., Millie, D. F., Moline, M., and Roesler, C. S. 1999. Optical monitoring and forecasting systems for harmful algal blooms: possibility or pipe dream? *Journal of Phycology*, 35(6), 1477-1496.

Stumpf, R. P., Culver, M. E., Tester, P. A., Tomlinson, M., Kirkpatrick, G. J., Pederson, B. A., Truby, E., Ransibrahmanakul, V., and Soracco, M. 2003. Monitoring *Karenia brevis* blooms in the Gulf of Mexico using satellite ocean color imagery and other data. *Harmful Algae* 2, 147-160.

Subramaniam, A., Brown, C. W., Hood, R. R., Carpenter, E. J., and Capone, D. G. 2002. Detection of *Trichodesmium* blooms in SeaWiFS imagery. *Deep-Sea Research II* 49, 107-121.

Tester, P. A., and Steidinger, K. A. 1997. *Gymnodinium breve* red tide blooms: Initiation, transport, and consequences of surface circulation. *Limnology and Oceanography* 42,1039-1051.

Tester, P. A., Stumpf, R. P., Vukovich, F. M., Fowler, P. K., and Turner, J. T.1991. An expatriate red tide bloom: Transport, distribution, and persistence. *Limnology and Oceanography* 36, 1053-1061.

Westberry, T. K., Siegel, D. A., and Subramaniam, A. 2005. An improved bio-optical model for the remote sensing of *Trichodesmium* spp. blooms. *Journal of Geophysical Research* 110: C06012.

Wynne, T. T., Stumpf, R. P., Tomlinson, M. C., Warner, R. A., Tester, P. A., Dyble, J., and Fahnenstiel, G. L. 2008. Relating spectral shape to cyanobacterial blooms in the Laurentian Great Lakes. *International Journal of Remote Sensing* 29, 3665-3772.