Using Satellite Data for the Prediction and Detection of Harmful Algal Bloom Outbreaks

Richard Stumpf, NOAA National Centers for Coastal Ocean Science
Fundamentals of Satellite RS for Health Applications, Week 4
Outline

Harmful algal blooms (HABs)

- What are HABs
  - Cyanobacterial HABs specifically
    - The problem

- Satellites and cyano HABs

- Algorithms

- Applications

California sea lion undergoing stomach pumping after poisoning (photo courtesy Dr. Francis Guindal, Marine Mammal Center, Sausalito, CA)
Marine HABs

HAB Occurrences Worldwide

Global problem with many species

Image from whoi.edu/redtide
Impacts of Harmful Algal Blooms

- Molluscan shellfish losses
- Fish kills (threat to aquaculture)
- Endangered species
- Tourism
- Public health
- US $1 billion in loss over 10 years
- $1 billion industries at risk in East Asia, Europe, South America.
### Marine HABs
Species monitoring and response can be helped by Remote Sensing

<table>
<thead>
<tr>
<th>HAB Species</th>
<th>Region</th>
<th>Sensing Type</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Pseudo-nitzschia</em> spp.</td>
<td>Upwelling regions</td>
<td>SST, chlorophyll</td>
<td>ASP, variable</td>
</tr>
<tr>
<td><em>Karenia brevis</em></td>
<td>Gulf of Mexico</td>
<td>Chlorophyll, optical ratio, absorption spectra</td>
<td>NSP, respiratory, fish toxin</td>
</tr>
<tr>
<td><em>Karenia mikimotoi</em></td>
<td>Coastal ocean (Hong Kong, Ireland, New Zealand)</td>
<td>SST chlorophyll</td>
<td>NSP</td>
</tr>
<tr>
<td><em>Gymnodinium catenatum</em></td>
<td>Estuaries, coastal ocean, upwelling</td>
<td>SST chlorophyll</td>
<td>PSP</td>
</tr>
<tr>
<td><em>Alexandrium</em> spp.</td>
<td>Coastal ocean (Gulf of Maine, Gulf of Alaska)</td>
<td>SST</td>
<td>PSP</td>
</tr>
<tr>
<td><em>Gonyaulax</em></td>
<td>Upwelling regions</td>
<td>Chlorophyll, possible UV absorption</td>
<td>Fish toxin</td>
</tr>
<tr>
<td><em>Cochlodinium</em></td>
<td>Coastal ocean (British Columbia, Korea)</td>
<td>SST, color</td>
<td>Shellfish toxin</td>
</tr>
<tr>
<td><em>Nodularia, Microcystis</em></td>
<td>Enclosed Brackish</td>
<td>Color</td>
<td>Hepatotoxin</td>
</tr>
<tr>
<td><em>Dinophysis</em> (not monitored by RS)</td>
<td>Ireland, Portugal, Norway</td>
<td>Maybe SST, however, optical in situ</td>
<td>Shellfish toxin</td>
</tr>
</tbody>
</table>
Freshwater Cyanobacterial “HABs”

Put-in Bay, July 24, 2015
By Dr Justin Chaffin, Stone Laboratory, OSU
Issues with cyano blooms

Deaths at dialysis center in Brazil in 1996

Drinking water issue, cyano-toxins must be removed, risk of liver & kidney damage
Risks to Pets and Animals

- Dog & cattle deaths occur annually in U.S. **Toxins**!

- Novel Marine Harmful Algal Bloom: Cyanotoxin (Microcystin) transfer from land (freshwater) to sea otters

Credit: James Brooks / Flickr / CC BY-2.0

Credit: Centers for Disease Control and Prevention
Microcystins and cylindrospermopsins

US EPA Drinking Water Guidelines

- Technical guidance (10-day average):
  - Microcystins: 0.3 μg/L (ppb) for children under 6, 1.6 ppb for older and adults
  - Cylindrospermopsins: 0.7 ppb for children under 6, 3 ppb for older and adults
Recreational

• WHO Recommendations
• Microcystin-LR:

<table>
<thead>
<tr>
<th></th>
<th>Microcystin</th>
<th>chlorophyll-a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;10 ppb</td>
<td>&lt;10 µg/L</td>
</tr>
<tr>
<td>Moderate</td>
<td>10-20</td>
<td>10-50</td>
</tr>
<tr>
<td>High</td>
<td>20-2,000</td>
<td>50-5,000</td>
</tr>
<tr>
<td>Very High</td>
<td>&gt;2,000</td>
<td>&gt;5,000</td>
</tr>
</tbody>
</table>

• Different states have variations

2009 Documented States

Graham et al., 2009, Lakelines
Toxicity varies across species and within species
From WHO (Chorus and Bartram, 1999 after Fastner, 1998)

Satellites cannot detect toxins
Cyanos of Concern for toxicity

Heterocysts: **nitrogen fixing do not require abundant nitrogen**

Gas Vacuoles: **flotation, concentrate at surface or mix with winds**

- **Microcystis**
  - Colony, no heterocysts, gas vac., T&O, toxins
- **Aphanizomenon**
  - Filament, heterocysts (N-fixer), gas vac., T&O, toxins
- **Dolichospermum (Anabaena)**
  - Filament, heterocysts, gas vac., T&O, toxins
- **Planktothrix (Oscillatoria)**
  - Filament, no heterocysts, gas vac. ?, T&O, toxins
- **Cylindrospermopsis**
  - Filament, heterocysts, no gas vac. ?, no T&O, toxins
- **Lyngbya (sometimes attached)**
  - Filament, no heterocysts, no gas vac., no T&O, toxins
*Microcystis* most common toxic cyanobacteria

Lake Erie, Aug 2010
Aphanizomen and Microcystis examples
California

Aphanizomenon flos-aquae

Microcystis spp.

Photos from R. Kudela, UCSC
Planktothrix argardhii
Ohio, consistently dispersed
Environmental Factors
Nutrients, freshwater is usually phosphorus-limited

> 100 µg/L phosphorus associated with cyanobacterial blooms

Intensity of toxicity may be influenced by nitrogen,
but also by turbidity and other factors still being determined

Downing et al. 2001
Cyanobacteria Like Warm Water, unlike “good” algae
Many have strongest growth > 20ºC and minimal growth < 15ºC

Paerl et al., 2011 (Science of the Total Environment)
Wind Matters for Buoyant Blooms, identified in the earliest remote sensing studies.

The use of remote sensing to detect how wind influences planktonic blue-green algal distribution

A. J. Horne and R. C. Wrigley

With 4 figures in the text
Cyanos thrive in low wind, many float to the surface.

- Cyanos (Microcystis in this case) tend to float (green)
- Diatoms sink (olive)

Credit: Tom Archer
Satellite Remote Sensing
Where We Are With Satellites

- We can find algal blooms
- Cyano blooms are detectable, but usable methods currently produce many false positives
  - We are examining strategies to reduce these
  - We bias against false negatives
- All sensors can find scum
- Most sensors have limitations
  - Resolution trade-offs: spatial, spectral, temporal
Satellite Imagery. True color is useful but not best.

Two severe blooms that look different in true color

Lake Erie, 28 July 2015, Landsat OLI

Lake Erie, 5 October 2011, Landsat 5 TM
## Satellite Comparison for Cyano Applications

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Spatial</th>
<th>Temporal</th>
<th>Key Spectral</th>
</tr>
</thead>
<tbody>
<tr>
<td>MERIS (2002-12) OLCI Sentinel-3, 2016</td>
<td>300m</td>
<td>2 day</td>
<td>10 (5 in red edge)</td>
</tr>
<tr>
<td>MODIS high res Terra, 1999; Aqua 2002</td>
<td>250/500m</td>
<td>1-2 day</td>
<td>4 (1 red, 1 NIR)</td>
</tr>
<tr>
<td>MODIS low res Sea WiFS</td>
<td>1km</td>
<td>1-2 day</td>
<td>7-8 (2 in red edge)</td>
</tr>
<tr>
<td>Landsat</td>
<td>30m</td>
<td>8 or 16 day</td>
<td>4 (1 red, 1 NIR)</td>
</tr>
<tr>
<td>Sentinel-2</td>
<td>20m</td>
<td>10 day</td>
<td>5 (1 red, 2 NIR, 1 in red edge)</td>
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</tbody>
</table>

- ok: good
- poor: poor
- Potential with 2nd satellite
- Potential with 2nd satellite in 2017
Radiation and Water Bodies

- False color sharpens distinction between land and water
- Reddish pixels at right include land
- Mixed pixels limit our ability to monitor small water bodies
- 3 pixel rule for individual scenes

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<tr>
<td>Land</td>
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A different resolution factor: sampling scale

- Field samples against satellite have some uncertainty:
- Compare the contents of any cup at random to the average of all cups in San Francisco Stadium
- Satellites tell you the average in the entire stadium; a water sample is akin to one cup

300 m
Spectral resolution: Satellite spectral bands & turbid blooms

Landsat

MERIS

MODIS 250/500m

SeaWiFS
MERIS (and Landsat) Bands on Water Spectra for Microcystis phycocyanin (indicator) absorbs about 620 nm; Chl-a about 680 nm.
Types of Algorithms, I
Analytical, Semi-Analytical (Ratio), Biological-Empirical

Analytical (based on solving simple physics equations)

- Water Reflectance $\sim a/(b_b + a)$ where $a$ is absorption and $b_b$ is backscatter
- Phycocyanin absorption at 620 nm;
- Chl-a absorption at 667 nm;
- Backscatter at 709 nm and 779 nm.
- Studies by Simis, Gons, Mithra and others
- Also QAA for absorption (Lee and others)

If water reflectance is retrieved and accurate, quite effective; demonstrated to work with in situ radiometry

HOWEVER: satellites depend on excellent atmospheric correction
Types of Algorithms, II

Analytical, Semi-Analytical (Ratio), Biological-Empirical

Semi-analytical (ratio, changes in absorption change ratios)

- Ratios such as 709 nm to 620 nm for PC, 709 to 665 for chl-a

With good data, quite effective; demonstrated to work with radiometry

HOWEVER: satellite depends on excellent atmospheric correction
Types of Algorithms  III
Spectral Shape Biological-Empirical

Spectral shape (derivative), based on biological characteristics, but empirical
• CI (Wynne and Stumpf; Lunetta)
• MCI (Gower et al.)
• MPH (Matthews and Odermatt)

Can be used without atmospheric correction, do not require water “reflectance”. These are currently the most robust for routine monitoring.

We use CI as it may be less sensitive to sediment and water vapor.
“CI” Derivative for Intense Blooms, More Cyano Sensitive

- Chl-a biomass, phycocyanin (PC) as indicators.
Example quantification for CI

Lake Erie Transferred to Many Other US Lakes

Relationship to Chl-a

Microcystis cells

Method also used for lakes in Europe and in Caspian Sea
Cyanobacteria Index “CI”
Extra Wavelengths Give CI – Equates to Concentration

MODIS True Color, 9 Oct 2011
Cyano Index (Cl) 8 Oct 2011

Surface concentration (up to 1 m).
Does not require scum, and works with scum
Biomass Indicator, comparison to satellite data

Florida Lakes, remember water sample against 300 m satellite pixel.

Data from LakeWatch and MERIS
Tomlinson et al., 2016
What about Scum? Spectra of *Microcystis* “Scum”

High in NIR, Low in Red; useful with all “color” satellites. Calm wind needed.
True Color

Find the Scum

• Side Note: true color is valuable but hard to interpret
NIR band reveals the scum
Applications
Monitoring cyanoblooms in real time. Lake Erie twice/weekly

Experimental Lake Erie Harmful Algal Bloom Bulletin
National Centers for Coastal Ocean Science and Great Lakes Environmental Research Laboratory
27 July 2015, Bulletin 04

The Microcystis cyanobacteria bloom continues in the western basin. The bloom extends from west of West Sister Island, veering southward to the coast, then curving to the northeast through the islands toward the central basin and up to the Canadian coast.

Observed
Forecast

Figure 1. Cyanobacterial Index from NASA’s MODIS-Terra data collected 24 July 2015 at 12:00 pm EDT. Grey indicates clouds or missing data. Black

Figure 2. Nowcast position of bloom for 27 July 2015 using GLCFS modeled currents to move the bloom from the 24 July 2015 image.

http://coastalscience.noaa.gov/research/habs/forecasting
Bloom Analysis

October 2011

Sept 2013

October, ESA MERIS

September, NASA MODIS
Tracking biomass in Florida

Over 3 Years

High

Med-Low

Variable

Lake Apopka

Lake Harris

Lake Dora

100 µg/L

60 µg/L

2009 2011
Potomac River, Maryland, extent of *Microcystis* bloom, 2011

Improved CI

New collaboration with MD-DNR, George Mason Univ. and NOAA Phytoplankton Monitoring Network

Courtesy of Dr. Chris Jones
George Mason Univ.
Phenology, Klamath River (CA) Reservoirs

Iron Gate Reservoir

<table>
<thead>
<tr>
<th>Date</th>
<th>CHL (µg/L)</th>
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<tbody>
<tr>
<td>4/14/2010</td>
<td>10</td>
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<tr>
<td>7/14/2010</td>
<td>20</td>
</tr>
<tr>
<td>10/14/2010</td>
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</tr>
<tr>
<td>1/14/2011</td>
<td>50</td>
</tr>
<tr>
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<td>20</td>
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Iron Gate Reservoir

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<th>Date</th>
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<tbody>
<tr>
<td>4/14/2010</td>
<td>40</td>
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<tr>
<td>7/14/2010</td>
<td>60</td>
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<td>1/14/2011</td>
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</tr>
<tr>
<td>1/14/2012</td>
<td>10</td>
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MERIS Composites

Iron Gate

Gopco

Aug 11-20, 2010

Feb 1-10, 2011

20 µg/L

50 µg/L
Wind Matters for Buoyant Blooms

The use of remote sensing to detect how wind influences planktonic blue-green algal distribution

A. J. Horne and R. C. Wrigley

With 4 figures in the text
Conceptual Diagram

No Wind

Optical depth
Conceptual Diagram

With Wind

Optical depth
Lake Erie Bloom

- Satellites see either surface scum or surface concentration
- Caution on “averaging” buoyant blooms
Use of Long-term patterns. Lake Erie 2015 Was Bad

Lake Erie's green monster returns
Algae back with a vengeance in Lake Erie a year after Toledo's water crisis; prognosis poor
Phosphorus as a Driver of Cyano Blooms in Lakes
Lake Erie, Spring Load from Maumee River

Downing et al., 2011

Lauran Johnson, NCWQR
Last information
Some last thoughts on freshwater cyanobacterial blooms

- Cyanobacterial blooms occur in eutrophic waters, they usually have high Chl-a.
- Not all satellites are the same.
  - Algorithms need to be suitable for cyanobacteria (MERIS & new OLCI are best)
    - Need algorithms as robust as the application (monitoring or characterization?)
    - Need other environmental information for other sensors (Landsat, Sentinel-2, etc.)
    - Scum is easiest to see (near infrared vs red), but only works with calm winds
- Not all blooms are toxic.
  - Satellite cannot detect toxicity.
    - (See Stumpf et al. 2016 Harmful Algae, on strategies for toxin mapping)
- Other insights can be gained
  - Monitoring blooms in real-time
  - Which lakes have problems and when
  - Role of nutrients in producing blooms
  - Inter-annual variability
Places for Information on Phytoplankton

http://oceandatacenter.ucsc.edu/PhytoGallery/index.html

http://botany.si.edu/references/dinoflag/

http://www.dnr.state.md.us/bay/cblife/algae/index.html

https://pubs.er.usgs.gov/publication/ofr20151164/