Remote Sensing of Cyanobacterial Blooms: from Monitoring to Forecast

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Remote Sensing of Cyanobacterial Blooms: from Monitoring to Forecast

- A worldwide phenomenon: algae blooms
- Blooming distribution in China
- Spatial-temporal distribution of cyanobacteria blooms in Lake Taihu and Lake Chaohu
- Formation process of cyanobacteria bloom
- PC retrieval in surface waters
- Phytoplankton biomass estimation
- Cyanobacterial bloom forecast
The cyanobacterial blooms exist in waters worldwide (lake, reservoir, river, coastal waters in Asia, Europe, Africa, America, ……).
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It is the third largest lake in the U.S. state of Florida, 124 km², blooms happened in 1940s-1950s
Lake Madison is a reservoir in King George, Virginia, United States, with an area of about 4.5 km².
It is the largest lake in the southeastern United State, with a surface area of about 1900 km², blooms happened since 1980s.
It is situated in Germany, Switzerland and Austria near the Alps, third largest in central Europe, area of 538km², max. depth of 252m, blooms happened in 1950s-1970s
It is an artificial lake in Australia, 202.5 km², mesotrophic, blooms happened since 1960s.
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The cyanobacterial blooms exist in waters worldwide (lake, reservoir, river, coastal waters in Asia, Europe, Africa, America, ……)

Lake Kasumigaura, Japan

It is the second-largest lake in Japan, an area of 220 km²
The cyanobacterial blooms exist in waters worldwide (lake, reservoir, river, coastal waters in Asia, Europe, Africa, America, ……)

It is the largest in Africa and the second largest freshwater lake in the world, an area of 69000 km²
So the lake blooms is a worldwide phenomenon, from the developed to the developing, to the undeveloped economic countries, from America, to Europe, Australia, Asia, and to Africa.
A worldwide phenomenon: algae blooms

Blooming distribution in China

Spatial-temporal distribution of cyanobacteria blooms in Lake Taihu and Lake Chaohu

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Algae blooming site since 1985

Five blooming dominance algae: Cyanophyta (Microcystis, Anabaena, Oscillatoria, Aphanizomenon), Euglenophyta (Euglena), Chlorophyta (Chlorella), Bacillariophyta (Cyclotella), Pyrrophyta (Peridinium)

Blooming main occurrence month: Mar.-Sep.


The relationship ($P<0.001$) between nitrogen and phosphorus during algal bloom events

Eastern China Southern China

Inner Mongolia-Xinjiang Lake-zone
Tibetan Plateau Lake-zone
Yunnan-Guizhou Plateau Lake-zone
Eastern Plain Lake-zone
Northeast China Plain and Mountain Lake-zone

Nanhu Island

Lake
Main river
Key river
National boundary
Watershed boundary
Provincial boundary
Inner Mongolia-Xinjiang Lake-zone
Tibetan Plateau Lake-zone
Yunnan-Guizhou Plateau Lake-zone
Eastern Plain Lake-zone
Northeast China Plain and Mountain Lake-zone

0 400 800 km
0° N
40° N
20° N
20° E 90° E 120° E 150° E

70° E 80° E 90° E 100° E 110° E 120° E 130° E 140° E
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Three representative typical eutrophic lakes

Lake Chaohu

Lake Taihu

Lake Dianchi
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In each year of 2001-2016

In each month of Jan.-Dec.

Algal blooms frequency distribution in pixel

\[ F_{i,j} = \frac{C_{i,j}}{TC_j} \]

\( F_{i,j} \) is the relative frequency of bloom occurrence in the \( i \)th pixel during time \( j \).

\( C_{i,j} \) is the count of bloom occurrence in the same pixel.

\( TC_j \) is the total count of MODIS images.
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The formation process of cyanobacteria bloom

There are different dominant ecological factors at different stages:

- **Sinking & Sleeping**
  - Nov.-Feb.

- **Recovering & floating**
  - Mar.-Apr.

- **Mass growth**
  - Apr.-Sep.

- **Floating & accumulating**
  - Apr.-Nov.

- **Hydrometeorological**
- **Temperature & Oxygen**
- **Material & Energy**

The period in a year:
- November-February
- March-April
- April-September
- April-November

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1st period: Sleeping

2nd period: Accumulated temperature

3rd period: Mass growth

4th period: Blooms

热红外波段
Almost all optical sensors:

- NOAA AVHRR
- Nimbus-7 CZCS
- Seastar SeaWiFS
- Terra ASTER
- Aqua/Terra MODIS
- NPP VIIRS
- Envisat MERIS
- Landsat MSS/TM/ETM/OLI
- IRS-P6 LISS-3/-4/ AWIFS
- EO-1 Hyperion&ALI
- Sentinel OLCI
- Beijing-1 CCD
- Huanjing-1 CCD
- Gaofen-(1-4) CCD
- ...
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Single band threshold
NDVI
EVI

FAI: the difference between Rayleigh-corrected reflectance in the NIR and a baseline formed by the red and SWIR bands

\[
R'_{rc,NIR} = R_{rc,RED} + (R_{rc,SWIR} - R_{rc,RED}) \times \frac{\lambda_{NIR} - \lambda_{RED}}{\lambda_{SWIR} - \lambda_{RED}}
\]

\[
FAI = R_{rc,NIR} - R'_{rc,NIR}
\]

To decompose algal bloom coverage to sub-pixel level in order to improve the area precision of algal blooming by a novel algorithm APA (Algae Pixel-growing Algorithm).

A 3x3 pixels window

FAI$_{max}$: maximum FAI.
FAI$_{min}$: minimum FAI.

For growing points: $\alpha_{pixel} = \begin{cases} \frac{1}{FAI_{pixel} - FAI_{non-algae}} & FAI \geq FAI_{algae} \\ \frac{1}{FAI_{algae} - FAI_{pixel}} & FAI_{algae} > FAI_{pixel} > FAI_{non-algae} \\ 0 & FAI < FAI_{non-algae} \end{cases}$

$FAI_{center} = \gamma \cdot FAI_{max} + (1 - \gamma) \cdot FAI_{min}$

$FAI = \alpha \cdot FAI_{algae} + (1 - \alpha) \cdot FAI_{water} = (FAI_{algae} - FAI_{water}) \cdot \alpha_{center} + FAI_{water} \cdot \alpha_{center}$

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A retrieval model for phytoplankton pigment concentration, respectively, including phycocyanin and chlorophyll-$a$:

$$a = a_d + a_{ph} + a_g + a_w$$

2nd & 3rd period growing

Absorption due to phytoplankton pigment:

$$a_{ph}$$

Absorption due to suspended particulate matter:

$$a_d$$

Absorption due to colored dissolved organic matter:

$$a_g$$

Total backscattering:

$$b_b$$

Remote sensing reflectance

$$R_{rs} = \left(0.070 + 0.155u \cdot 0.752u\right)u$$

$$u = b_k / (a + b_k)$$
To develop a quantitative inversion model for chlorophyll-a and phycocyanin:

\[
R_{rs} = f' \frac{b_b}{a + b_b} - a_w (\lambda_i) \frac{R(\lambda_i)}{f'(\lambda_i)} + b_{bw} (\lambda_i) \left( 1 - \frac{R(\lambda_i)}{f'(\lambda_i)} \right) = \sum a'_i (\lambda_i) \frac{R(\lambda_i)}{f(\lambda_i)} - b'_i (\lambda_i) \left( 1 - \frac{R(\lambda_i)}{f(\lambda_i)} \right) c_i
\]

\[
b_{bw} (\lambda_1) \left( 1 - \frac{R(\lambda_1)}{f'(\lambda_1)} \right) - a_w (\lambda_1) \frac{R(\lambda_1)}{f'(\lambda_1)} \\
b_{bw} (\lambda_2) \left( 1 - \frac{R(\lambda_2)}{f'(\lambda_2)} \right) - a_w (\lambda_2) \frac{R(\lambda_2)}{f'(\lambda_2)} \\
\vdots \\
b_{bw} (\lambda_n) \left( 1 - \frac{R(\lambda_n)}{f'(\lambda_n)} \right) - a_w (\lambda_n) \frac{R(\lambda_n)}{f'(\lambda_n)} =
\]

\[
\begin{bmatrix}
\frac{R(\lambda_1)}{f'(\lambda_1)} a'^*_d (\lambda_1) & \frac{R(\lambda_1)}{f'(\lambda_1)} a'_g (\lambda_1) & \frac{R(\lambda_1)}{f'(\lambda_1)} a'_ph (\lambda_1) \\
\frac{R(\lambda_2)}{f'(\lambda_2)} a'^*_d (\lambda_2) & \frac{R(\lambda_2)}{f'(\lambda_2)} a'_g (\lambda_2) & \frac{R(\lambda_2)}{f'(\lambda_2)} a'_ph (\lambda_2) \\
\frac{R(\lambda_n)}{f'(\lambda_n)} a'^*_d (\lambda_n) & \frac{R(\lambda_n)}{f'(\lambda_n)} a'_g (\lambda_n) & \frac{R(\lambda_n)}{f'(\lambda_n)} a'_ph (\lambda_n)
\end{bmatrix}
\begin{bmatrix}
b^*_bp (\lambda_1) \\
b^*_bp (\lambda_2) \\
b^*_bp (\lambda_n)
\end{bmatrix}
\]
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A quantitative inversion model for lake water surface temperature

\[
T_s = A_0 + A_1 T_{31} - A_2 T_{32}
\]

\[
T_i = \frac{C_2}{\lambda_i \ln(1 + \frac{C_1}{\lambda_i^2 I_i})}
\]

\[
I_i = \left(\frac{\alpha - \ln(\frac{\rho_{32}}{\rho_2})}{\beta}\right)^2
\]

\[
p_i = \frac{NDVI - NDVI_s}{NDVI_s - NDVI_i}
\]

\[
NDVI = \frac{B_2 - B_1}{B_2 + B_1}
\]
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A novel phycocyanin index (PCI) for MERIS

PC has a local absorption peak at ~620 nm.

PCI is defined as remote-sensing reflectance ($R_{rs}$, sr$^{-1}$) at 620 nm normalized against a baseline formed linearly between $R_{rs}(560)$ and $R_{rs}(665)$.

PCI is a monotonic functional relationship with PC concentration

$$PCI = R'_{rs}(620) - R_{rs}(620)$$

$$R'_{rs}(620) = R_{rs}(560) + \frac{620-560}{665-560} \times (R_{rs}(665) - R_{rs}(560))$$

To change PC: 1-100 µg/L, how about PCI?

In-water and atmospheric simulations

It is sensitive to PC, but insensitive to CDOM or atmospheric perturbations, thus can be applied to satellite data.
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PCI Algorithm development and evaluation

PCI is nearly immune to sun glint, thick aerosols, thin clouds, CDOM, and turbidity.
Advantages

(1) PCI is insensitive to perturbations due to sun glint, thick aerosols, and thin clouds.

(2) PCI is insensitive to perturbations due to sun glint, thick aerosols, and thin clouds.

(3) PCI is insensitive to turbidity changes induced by sediment re-suspension.

The valid satellite data rate is increased from <1% to 50%
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**BNDBI (Baseline Normalized Difference Bloom Index)** by MODIS band 1 and band 4

\[
BNDBI = \frac{(R'_{rs}(555) - R'_{rs}(645))}{(R'_{rs}(555) + R'_{rs}(645))}
\]

\[
R'_{rs}(555) = R_{rs}(555) - \left[ R_{rs}(469) \times \frac{(859-555)}{(859-469)} + R_{rs}(859) \times \frac{(555-469)}{(859-469)} \right]
\]

\[
R'_{rs}(645) = R_{rs}(645) - \left[ R_{rs}(469) \times \frac{(859-645)}{(859-469)} + R_{rs}(859) \times \frac{(645-469)}{(859-469)} \right]
\]

\[
Chla = 982.3 \times BNDBI^4 + 71.86 \times BNDBI^3 + 562.4 \times BNDBI^2 + 79.05 \times BNDBI + 6.6
\]

Advantages: (1) to reduce the effect of atmosphere; (2) to reduce the effect of turbid water
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Obviously, cyanobacterial blooms are heterogeneous in horizontal and the coverage area can be estimated;

However, how is it in vertical and how many is the biomass?

It is necessary for forecast warning to acquire the spatial information both in horizontal and in vertical.
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To determine the vertical distribution type by the field

Sampling in vertical
Underwater light field by TriOS

Lake Chaohu

<table>
<thead>
<tr>
<th>CV of vertical profile</th>
<th>E_u (W/m²)</th>
<th>E_d (W/m²)</th>
<th>L_u (W/m²)</th>
<th>Chl, SPM, DOC, POC, PC, a, bb, Kd</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean (%)</td>
<td>74</td>
<td>41</td>
<td>64</td>
<td>Chl, SPM, DOC, POC, PC, a, bb, Kd</td>
</tr>
<tr>
<td>max (%)</td>
<td>9.5</td>
<td>17.47</td>
<td>23.27</td>
<td>Chl, SPM, DOC, POC, PC, a, bb, Kd</td>
</tr>
<tr>
<td>min (%)</td>
<td>41</td>
<td>10.00</td>
<td>13.29</td>
<td>Chl, SPM, DOC, POC, PC, a, bb, Kd</td>
</tr>
<tr>
<td>SD (%)</td>
<td>67.13</td>
<td>26.00</td>
<td>13.94</td>
<td>Chl, SPM, DOC, POC, PC, a, bb, Kd</td>
</tr>
</tbody>
</table>

CV = SD/mean × 100%

Kun Xue, Yuchao Zhang, Hongtao Duan, Ronghua Ma, Steven Loiselle, Minwei Zhang. A remote sensing approach to estimate vertical profile classes of phytoplankton in a eutrophic lake Remote Sensing. 2015, 7, 14403-14427.
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To estimate the total biomass in Lake Chaohu by MODIS imageries

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To develop a cyanobacteria bloom prediction model including cyanobacteria growth, hydrodynamic and nutrient distribution.
Observation data: automatic and artificial in Lake Taihu
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A water quality automatic monitoring system for Lake Taihu
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FTP (Field Test Platform) in Lake Taihu for lake color remote sensing

Simulation field

- HeadWall HyperSpec® VNIR (400-1000nm)
- Flow velocity and direction instrument
- On-line water quality monitoring system/Cyclops-7 Submersible Sensors (chl-a, turbidity, water temperature, DO, conductivity, blue-green algae, etc.)
- RAMSES Underwater Hyperspectral (RAMSES-ARC/ACC-UV/VIS)
- HS-6P
- AC-S absorption attenuation meter

Control system on the platform

Wind speed/direction instrument

In situ photo

HyperSpec® VNIR (400-1000nm)
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A lake cyanobacterial blooms monitoring software/system by MODIS

the MODIS satellite broadcasting and relay system

the lake cyanobacterial blooms MODIS monitoring system

the data assimilation system for cyanobacterial blooms forecast in Lake Taihu
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Data Assimilation in Ecological Processes of Cyanobacterial Bloom in Taihu Lake

To couple the hydrodynamic model with remote sensing inversion data, automatic and artificial monitoring data to implement multi-source data assimilation of cyanobacterial blooms.
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A model/software integrating cyanobacteria growing, water dynamic, and nutrient distribution model
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Only eight hours from MODIS data acquiring, model forecasting, to the local government informing.
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Lake Taihu cyanobacteria blooming forecast report for local government and public

To forecast the cyanobacteria blooming occurrence site, probability/area and spatial distribution