Climate Change Impacts on Harmful Algal Blooms in U.S. Freshwater: A Screening-Level Assessment

Steve Chapra

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Harmful Algal Blooms (HABs)

Red tides (Dinoflagellates) - Marine

Bluegreen Algae (Cyanobacteria) - Freshwater and Estuaries
Lake Taihu
China
A cow killed by consuming Cyanobacteria
Toledo Water Supply Shut Down Due To Lake Erie Microcystis bloom
Climate Change Impacts on Harmful Algal Blooms in U.S. Freshwaters: A Screening-Level Assessment

Steven C. Chapra,† Brent Boehlert,*,§ Charles Fant,‡ Victor J. Bierman, Jr.,∥ Jim Henderson,⊥
David Mills,‡ Diane M. L. Mas,⊥ Lisa Rennels,‡ Lesley Jantarasami,⊥ Jeremy Martinich,⊥
Kenneth M. Strzepek,§ and Hans W. Paerl‡

†Tufts University, Medford, Massachusetts United States
‡Industrial Economics, Inc., Cambridge, Massachusetts United States
§Massachusetts Institute of Technology, Cambridge, Massachusetts United States
∥LimnoTech, Oak Ridge, North Carolina United States
⊥Corona Environmental Consulting, Louisville, Colorado United States
§Abt Associates, Boulder, Colorado United States
⊥Fuss & O’Neill, Inc., West Springfield, Massachusetts United States
⊥U.S. Environmental Protection Agency (EPA), Washington, D.C. United States
⊥Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, North Carolina United States

Supporting Information

ABSTRACT: Cyanobacterial harmful algal blooms (CyanohABs) have serious adverse effects on human and environmental health. Herein, we developed a modeling framework that predicts the effect of climate change on cyanobacteria concentrations in large reservoirs in the contiguous U.S. The framework, which uses climate change projections from five global circulation models, two greenhouse gas emission scenarios, and two cyanobacterial growth scenarios, is unique in coupling climate projections with a hydrologic/water quality network model of the contiguous United States. Thus, it generates both regional and nationwide projections useful as a screening-level assessment of climate impacts on CyanohAB prevalence as well as potential lost recreation days and associated economic value. Our projections indicate that CyanohAB concentrations are likely to increase primarily due to water temperature increases tempered by increased nutrient levels resulting from changing demographics and climatic impacts on hydrology that drive nutrient transport. The combination of these factors results in the mean number of days of CyanohAB occurrence ranging from about 7 days per year per waterbody under current conditions, to 16–23 days in 2050 and 18–39 days in 2090. From a regional perspective, we find the largest increases in CyanohAB occurrence in the Northeast U.S., while the greatest impacts to recreation, in terms of costs, are in the Southeast.
SCREENING ASSESSMENT

- Intentionally simplified
- Built entirely on well-established and accepted process formulations, and transport and fate mechanisms, rather than in developing new modeling methods or conducting site-specific, data-intensive calibration.
- Not intended to inform management of individual waterbodies
- Applications:
  - Support planning, policy, and identify data or methodological gaps to guide future research on an inherently uncertain issue
  - Intended to quantify and monetize the multisector risks of inaction on climate change and the benefits to the U.S. of global reductions in greenhouse gas emissions.
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TEAM
Steve Chapra    Tufts University
Hans Paerl     Univ. North Carolina
Ken Strzepek    MIT
Lesley Jantarasami  U.S. EPA (DC)
Jeremy Martinich    U.S. EPA (DC)
Vic Bierman     LimnoTech
Brent Boehlert  Industr. Econ./MIT
Chas Fant       Industr Econ.
Jim Henderson   Abt Assoc.
David Mills     Abt Assoc.
Diane M.L. Mas  Fuss & O’Neill
Lisa Rennels    Industr. Econ.

- Freshwater ecologists
- Computer Scientists
- Economists
- Environ. Engineers
- Government regulators
- Hydrologists
- WQ Modelers
- Limnologists

PET, historical runoff
Reservoirs, hydropower, water management, flow routing
Costs based on recreational visitation losses
BOD, Heat, N, P

Historical Temperature & Precipitation
Projected Temperature & Precipitation
Changes in Temperature & Precipitation
Soil characteristics, PET, crop phenology, Kc, Ky, population projections

General Circulation Models

Rainfall Runoff Model
Water Demand Model

Runoff
Demand

Water Resources Systems Model
US Basins

Flows
Volumes

Water Quality Model
QUALIDAD HABs
Human Impacts Assessment
Water supply implications Implications for recreation
WQ impacts
“Models should be simple as possible, but no simpler”

Einstein

• A parsimonious water quality model framework
• River basins (with impoundments)
• Conventional pollution (not toxics)
• Incorrect everywhere but generally correct
• “Educated guess” model
• Done all the time for prediction
PHYSICS: HEAT BALANCE

GCM

- solar shortwave radiation
- atmospheric longwave radiation
- water longwave radiation
- conduction and convection
- evaporation and condensation
## WATER QUALITY: MASS BALANCES

### STATE VARIABLES

- \( c_p \): particulate organic C
- \( c_d \): dissolved organic C
- \( o \): dissolved oxygen
- \( n_o \): organic N
- \( n_a \): ammonia N
- \( n_n \): nitrite/nitrate N
- \( p_o \): organic P
- \( p_i \): inorganic P
- \( a_d \): diatoms
- \( a_g \): greens
- \( a_f \): cyanobacteria (N fixing)
- \( a_n \): cyanobacteria (non-N fixing)

- **Organic carbon (CBOD)**
- **Dissolved oxygen**
- **Nitrogen**
- **Phosphorus**
- **Phytoplankton**
QUALIDAD KINETICS

**Processes:**
- h: hydrolysis
- s: settling
- p: photosynth.
- gz: grazing
- rea: reaeration
- x: oxidation
- n: nitrification
- dn: denitrification
- re: respiration

**State Variables:**
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- \(p_o\): organic P
- \(p_i\): inorganic P
- \(a\): algae
# Blue-green algae

"Annie, Phannie, Mike & Oscar"

<table>
<thead>
<tr>
<th>Name</th>
<th>N-fixation</th>
<th>Toxic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anabaena</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Aphanizomenon</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Microcystis</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Oscillatoria</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
Functional Groups

(a) Diatoms  
(b) Greens  
(c) N-fixing Bluegreens  “Oscillatoria”  
(d) non-N-fixing Bluegreens  “Microcystis”

“Good Algae”  
i.e., nontoxic, edible phytoplankton

Cyanobacteria  
(HABs)  
(AKA Blue Green Algae)

“The cockroaches of the water”
Seasonal Succession of Phytoplankton in Lakes

(a) Oligotrophic

(b) Hypereutrophic
Principal Components Governing Seasonal Succession Patterns

What makes cyanobacteria win?

- Temperature
- Nutrient limitation
- Grazing
- Settling/buoyancy
Diatoms

Greens

Bluegreens

Temperature (°C)
All species need phosphorus
Only diatoms need silica
Nitrogen-fixing cyanobacteria (blue-greens) can obtain atmospheric nitrogen ($N_2$) directly from the water
Cyanobacteria are not grazed by zooplankton or other planktivorous organisms (e.g., fish, zebra mussels, etc.)
Blue-greens settle slowly and can actually rise

Negative settling velocity

Gas vacuoles

Primarily during stagnant periods

Implications:

Multi-layer vertical segmentation

Might require diel time scale
NUTRIENT LIMITATION, SETTLING & GRAZING

Total phytoplankton chlorophyll

Diatoms → Greens/ Others → Bluegreens (Non N-fix) → Bluegreens (N-fix) → Zooplankton → Total phytoplankton chlorophyll

Silica → Nitrogen → Phosphorus
Seasonal Predictions

Different Climate Models & Emission Scenarios

Cyanobacteria Cell Count (thousands)

No Climate Change
RCP4.5-2090
RCP8.5-2090

No Climate Change
Future Temperature Rise

GISS-E2-R
RCP 8.5

HadGEM2-ES
RCP 8.5

2050

2090

< 0.5  1.0  1.5  2.0  2.5  3.0  3.5  4.0  4.5  >
Nonpoint loadings for the baseline scenario

Total Nitrogen

Total Phosphorus
Diatoms

Fraction of total (%)
CyanoHAB non-fixers
Critical HABs blooms

2050

2090
Regional Climate Change Projections

Water Resources Regions

Map showing water resources regions across the United States, with specific regions highlighted.
Climate Change Projections
New England (01)

CYANOBACTERIA

Baseline

DIATOMS

2050
Climate Change Projections Southeast (03)

CyanoBacteria

Baseline

Diatoms

2050
Change in Cyanobacteria Concentrations (1000 cells / ml)

2050

2090
Change in Cyanobacteria Concentrations
(1000 cells / ml)
Conclusions

- Climate change will increase duration, magnitude, and spatial extent of CyanoHABs
- Climate impacts go well beyond temperature rise (and we are only scratching the surface)
- National or regional screening level models are useful for guiding planning strategies
- Impact of very high temperatures on cyanobacteria needs further study
- Interdisciplinary teams & systems approaches are critical for informing policy regarding HABs
CONCLUSIONS

🌟 All models are wrong
  (and possibly evil)

🌟 All models are right
  (especially if they are animated
  and in vivid colors)

🌟 "All models are wrong, but some are useful"

G.E.P. Box
## Major Differences Between “Good” Algae & HABs

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<tr>
<th>Factor</th>
<th>“Good” Algae</th>
<th>Cyanobacteria</th>
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<tbody>
<tr>
<td></td>
<td>Diatoms</td>
<td>N₂ Fixers</td>
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<tr>
<td></td>
<td>Greens</td>
<td>non N₂ Fixers</td>
</tr>
<tr>
<td>Settling</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Edible</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>Need</td>
<td>Need</td>
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<tr>
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<td>Need</td>
<td>Need</td>
</tr>
<tr>
<td>Silica</td>
<td>Need</td>
<td>Need</td>
</tr>
<tr>
<td>Max growth rate</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Min light</td>
<td>High</td>
<td>Low</td>
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<tr>
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Research Issues

- High temperature kinetics
- Scum formation
- Model modifications
- Toxin modeling
TEMPERATURE DEPENDENCY

\[ k_g(T) = 2.1 \times 1.066^{T-20} \]

Rate doubles for 10°C rise
Very High Temperature???
Sensitivity Analysis: Effects of Nutrient Levels and IN/IP Ratios

- **oligotrophic**
  - IP = 5 µgP/L

- **eutrophic**
  - IP = 25 µgP/L

- **hypereutrophic**
  - IP = 50 µgP/L

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<table>
<thead>
<tr>
<th>N limited</th>
<th>IN/IP = 2</th>
<th>IN = 10 µgN/L</th>
<th>IN = 50 µgN/L</th>
<th>IN = 150 µgN/L</th>
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<tbody>
<tr>
<td>IN/IP = 7.2</td>
<td>IN = 36 µgN/L</td>
<td>IN = 180 µgN/L</td>
<td>IN = 540 µgN/L</td>
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<tr>
<td>P limited</td>
<td>IN/IP = 25</td>
<td>IN = 125 µgN/L</td>
<td>IN = 625 µgN/L</td>
<td>IN = 1875 µgN/L</td>
</tr>
</tbody>
</table>
END OF SUMMER LEVELS

INCREASING PHOSPHORUS

INCREASING NITROGEN

Key:
- Diatoms
- Greens
- BG fixers
- BG non-fixers

Temperature (°C)

“GOOD”

BAD
High Temperature Growth

$\kappa_{g,\text{max}} (\text{/d})$

- High-Growth
- Plateau
- Temperature inhibition

Temperature (°C)

$k_{g,max}$ (d)

0 0.5 1 1.5
SCUM FORMATION

SEDIMENTS

WIND

SEDIMENTS

WIND

SEDIMENTS
Model Modifications

- Build on existing
- Open source
- Functional groups (easy)
- Kinetics (easy)
- Scum formation (???)
- Thin surface layer
Seasonal Profile of aggregate cyanobacteria concentration (1000 cells / ml) in 2090