Long term monitoring indicates changes in seasonal lake stratification, with potential impacts for the formation of Harmful Algal Blooms

NYSFOLA 2022

Moriarty, Vincent W. [1]
Swinton, Mark W. [2]
Kelly, Michael R. [1]
Auger, Guillaume A.R. [1]
Jane, Stephen F. [3]
Kolar, Harry R.[1]
Rose, Kevin C.[2]

Affiliations:
1. IBM Research, Yorktown Heights, New York
2. Rensselaer Polytechnic Institute, Troy, New York
3. Cornell University, Ithaca, New York

The Jefferson Project at Lake George

IBM Research

Outline

- Background: Stratification
- Lake George offshore chemistry program
- Stratification & cyanobacteria
- Late season stratification & HABs: November 2020

Lakes as Sentinels of Climate Change

Lakes are effective sentinels for climate change
(Adrian et al. 2009)

- Sensitive to climate
- Respond rapidly to change
- *Integrate* information about multiple types and sources of change over time (climate memory)
- Complex drivers → measurable signal
  - Lakes as a sensor

https://www.kurtgardnerphotography.com/print-store/art_print_products/lake-george-ny

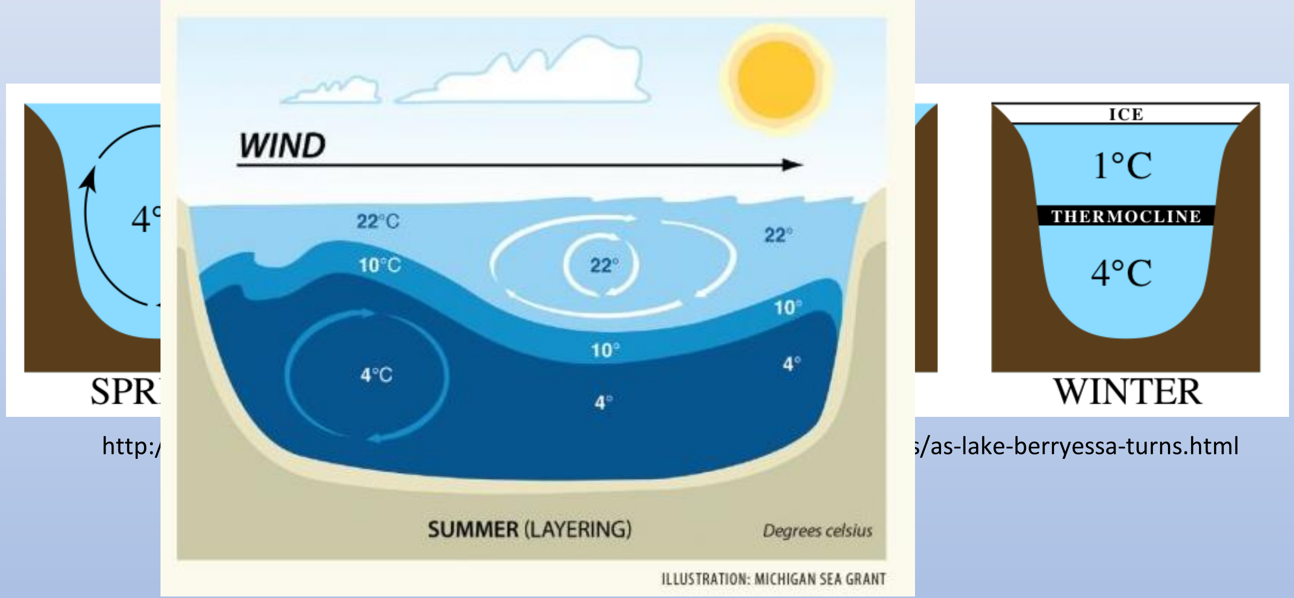
Dimictic Lakes & Seasonal Turnover

- Two lake system
  - Very different physical and chemical characteristics

- Thermocline becomes barrier preventing mixing
  - Hypolimnetic water is cut-off from atmospheric exchange
  - Epilimnetic water is cut-off from benthic nutrients

- Dimictic lakes are mixed 2x per year

- Late season: cold weather + high wind break down stratification, initiate fall turnover
  - Release of benthic nutrients



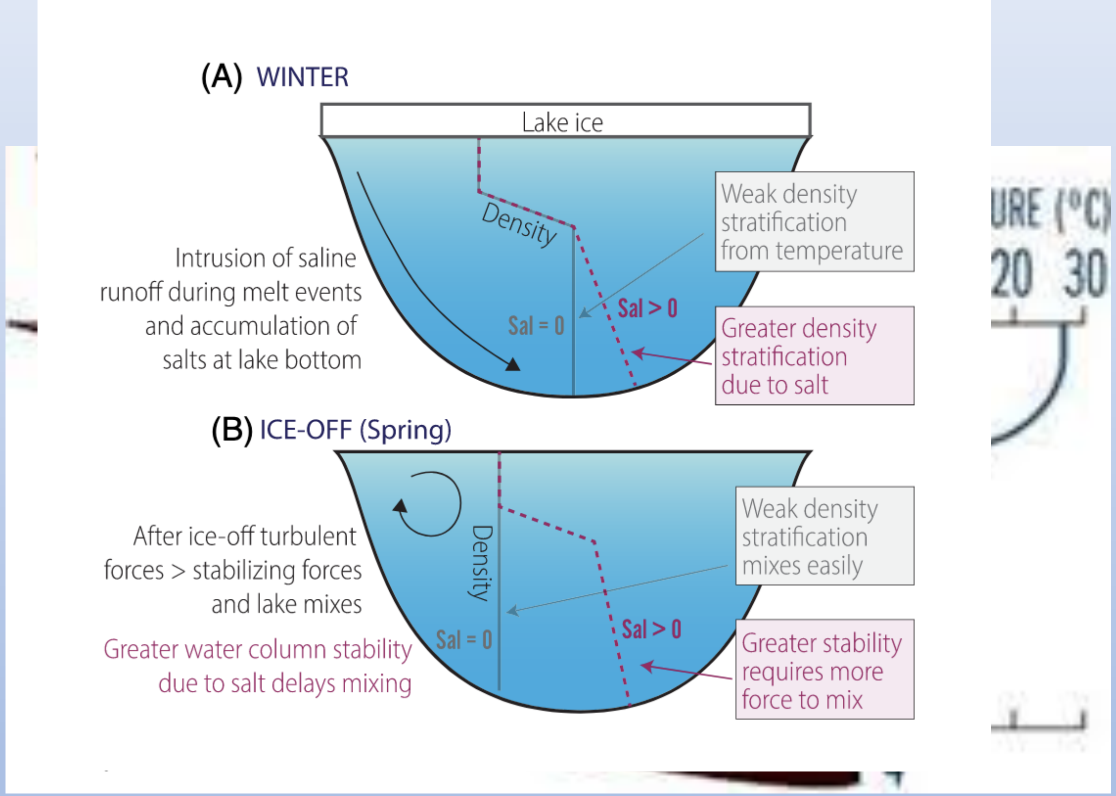
http:/ … /as-lake-berryessa-turns.html

https://www.michiganseagrant.org/lessons/lessons/by-broad-concept/physical-science/dissolved-oxygen-and-lake-stratification/

Lake Stratification

- Thermal stability
  - Resistance to mixing
  - Amount of energy required to mix lake to uniform density

- Strength of thermocline = Δ density



https://www.bccdpa.com/blog/lake-stratification-and-turnover

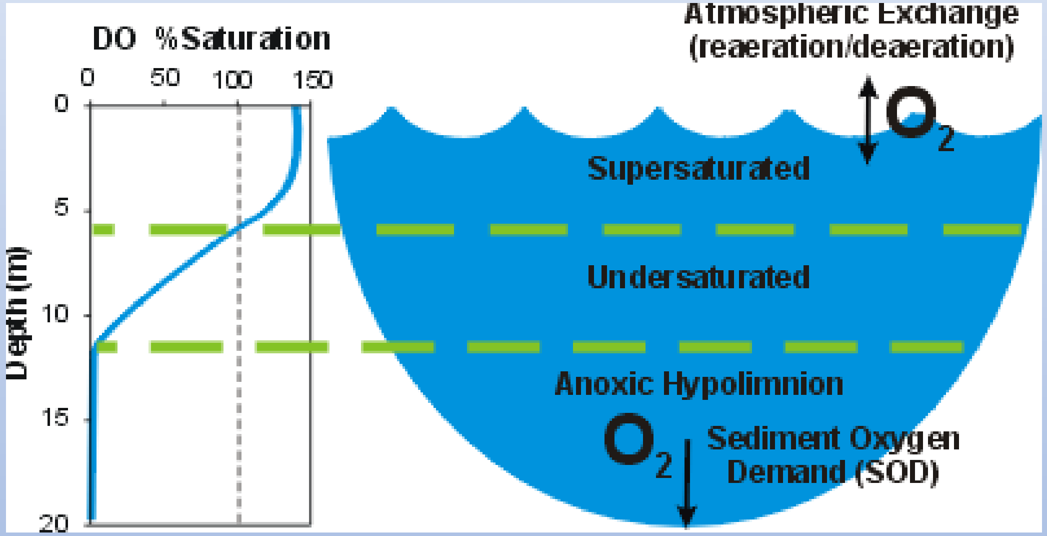
Impact of salinization on lake stratification and spring mixing
Ladwig et al, 2022

Lake Stratification and Oxygen

Hypolimnion:

- Lack of exchange with atmosphere
  - Anoxic dead zones

- Stronger stratification associated with lower hypolimnetic O_2
  - 393 lakes (1941-2017)
  - Jane et al. (2021)



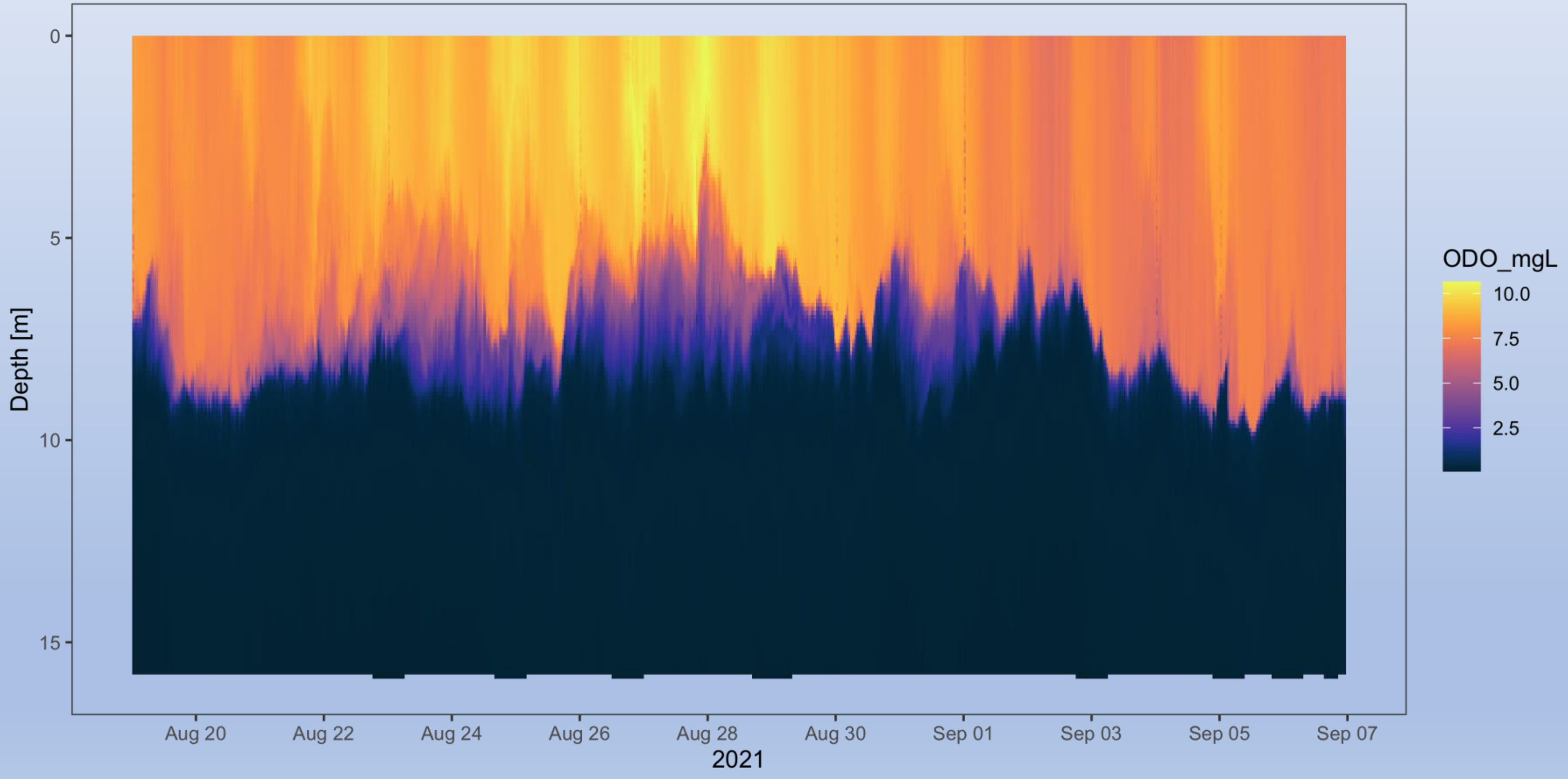
https://upstatefreshwater.org/NRT-Data/Data-Interpretation/data-interpretation.html

Internal Loading

- Phosphorus bonded to iron oxyhydroxides in sediments

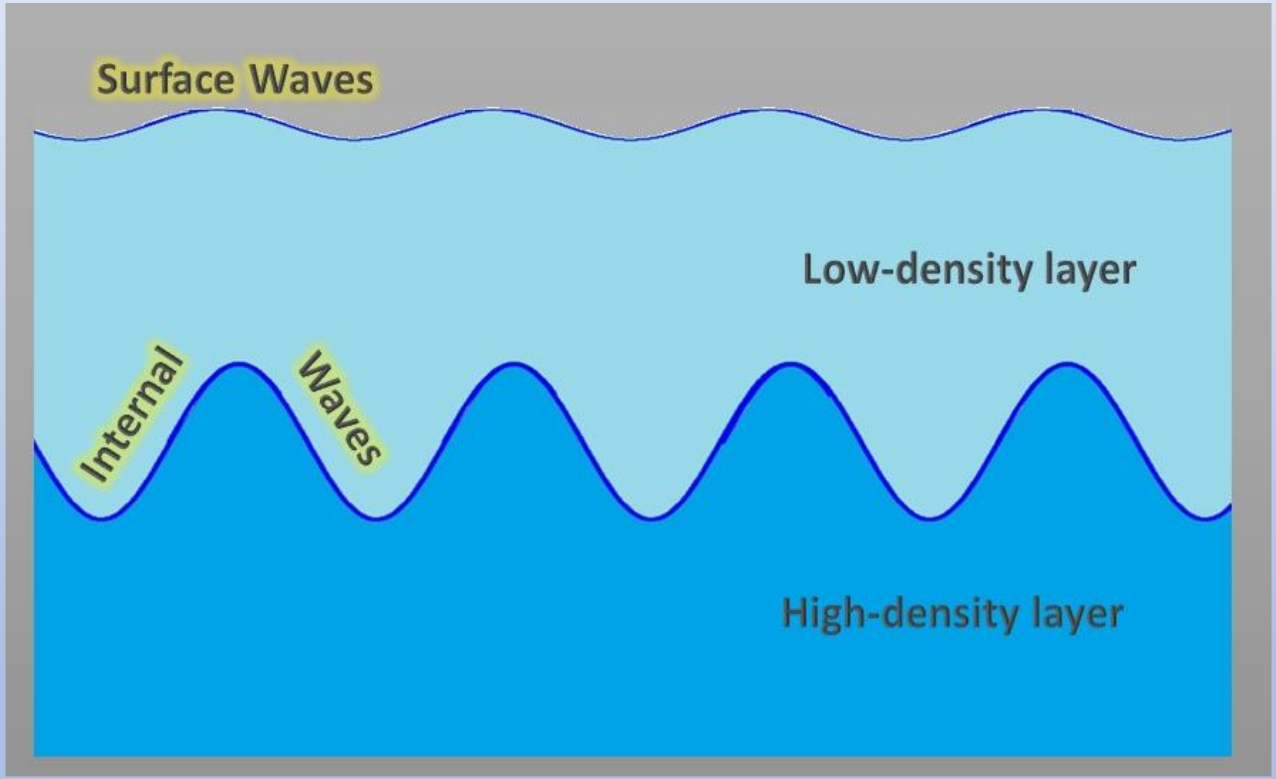
- Reductive dissolution in anoxic sediments → Release biologically available ortho-phosphate

- Majority of Lake George waters do not experience hypoxia



Lake Stratification and Internal Waves

- Propagation of internal waves
  - Requires density gradient
  - Stronger stratification = more energetic and more frequent internal waves

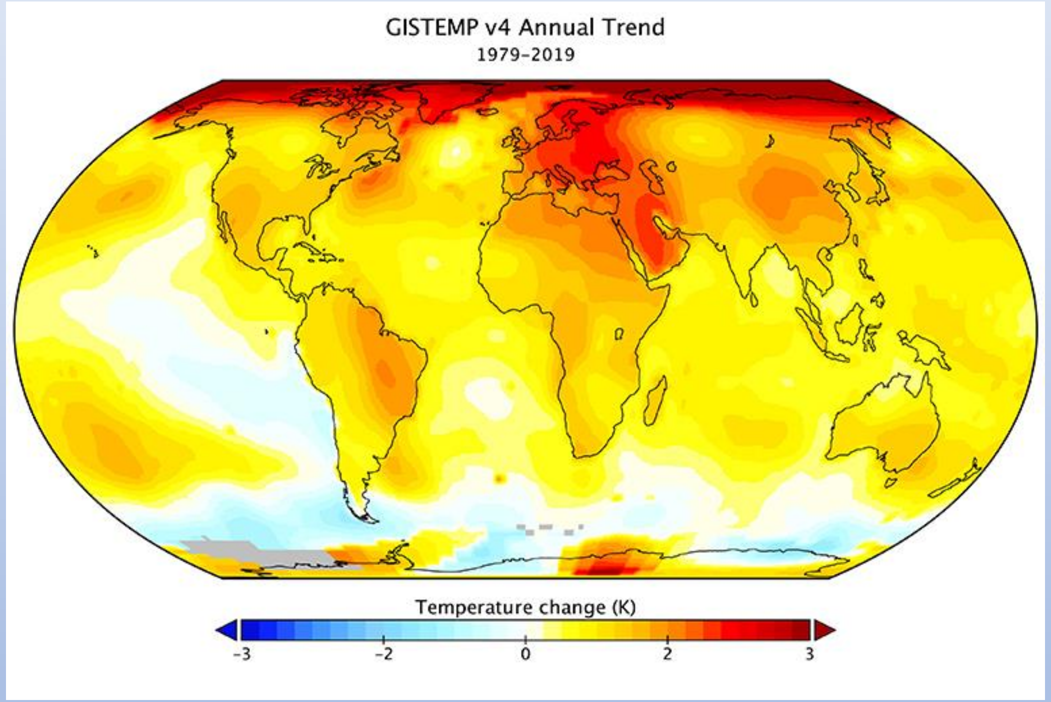


https://mlml.sjsu.edu/physoce/internal-waves-in-monterey-bay/

Climate Change Impacts

Surface water:

- Increased air temperature and shortwave radiation
- Global lake surface water temp warmed by 0.21 C per decade (Carrea et al. 2020)
    - Elevated surface temperature
    - Longer growing season (Swinton et al. 2015)
    - Earlier onset of summer stratification
    - Delay in fall turnover

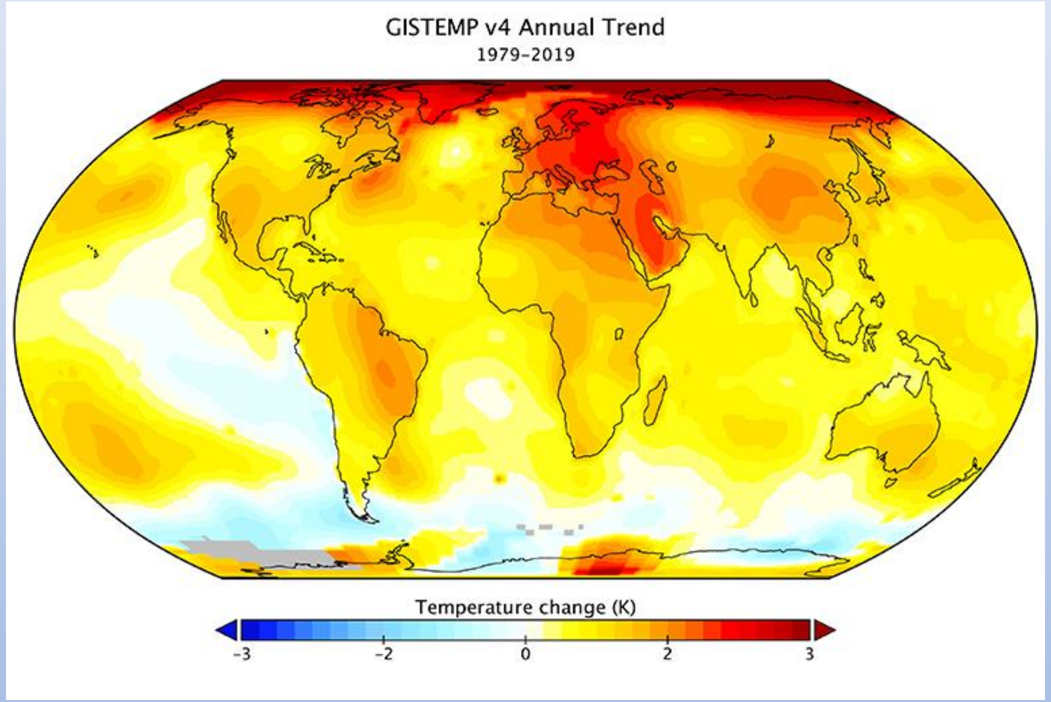


https://climate.nasa.gov/ask-nasa-climate/3017/making-sense-of-climate-sensitivity/

Climate Change Impacts

Deep water:

- Complex- not directly coupled to shallow water drivers
- Time between fall overturn and spring mixing is *only* cooling period experienced by deep waters
  - Hypolimnion heavily impacted by intensity and duration of this period.



https://climate.nasa.gov/ask-nasa-climate/3017/making-sense-of-climate-sensitivity/

Lake George Offshore Chemistry Program

- 1980 - present (40+ years)
- Eleven sites
- Twenty parameters
    - pH
    - Alkalinity
    - Specific Conductance
    - Secchi Depth
    - Chloride
    - Sulfate
    - Total Phosphorus
    - Total Soluble Phosphorus
    - Molybdate Reactive P
    - Nitrate
    - Ammonia
    - Soluble Silica
    - Chlorophyll
    - Total Nitrogen
    - Calcium
    - Magnesium
    - Sodium
    - Potassium
    - Iron
    - Temperature
    - Dissolved Oxygen

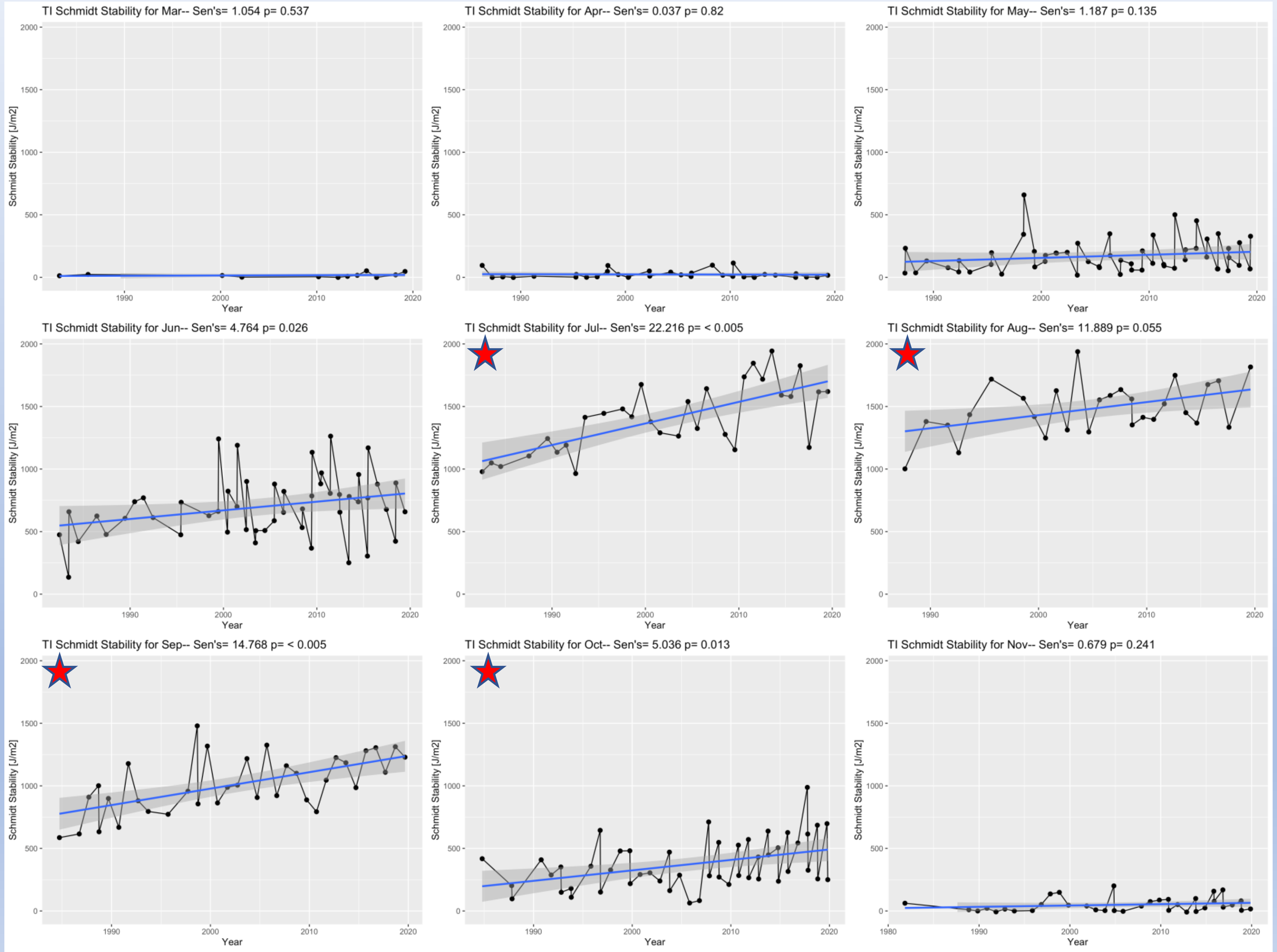
https://dfwi.rpi.edu/news/four-decades-data-sounds-early-warning-lake-george

Stratification Strength

- Schmidt stability index
  - Amount of work needed to mix lake to uniform temperature

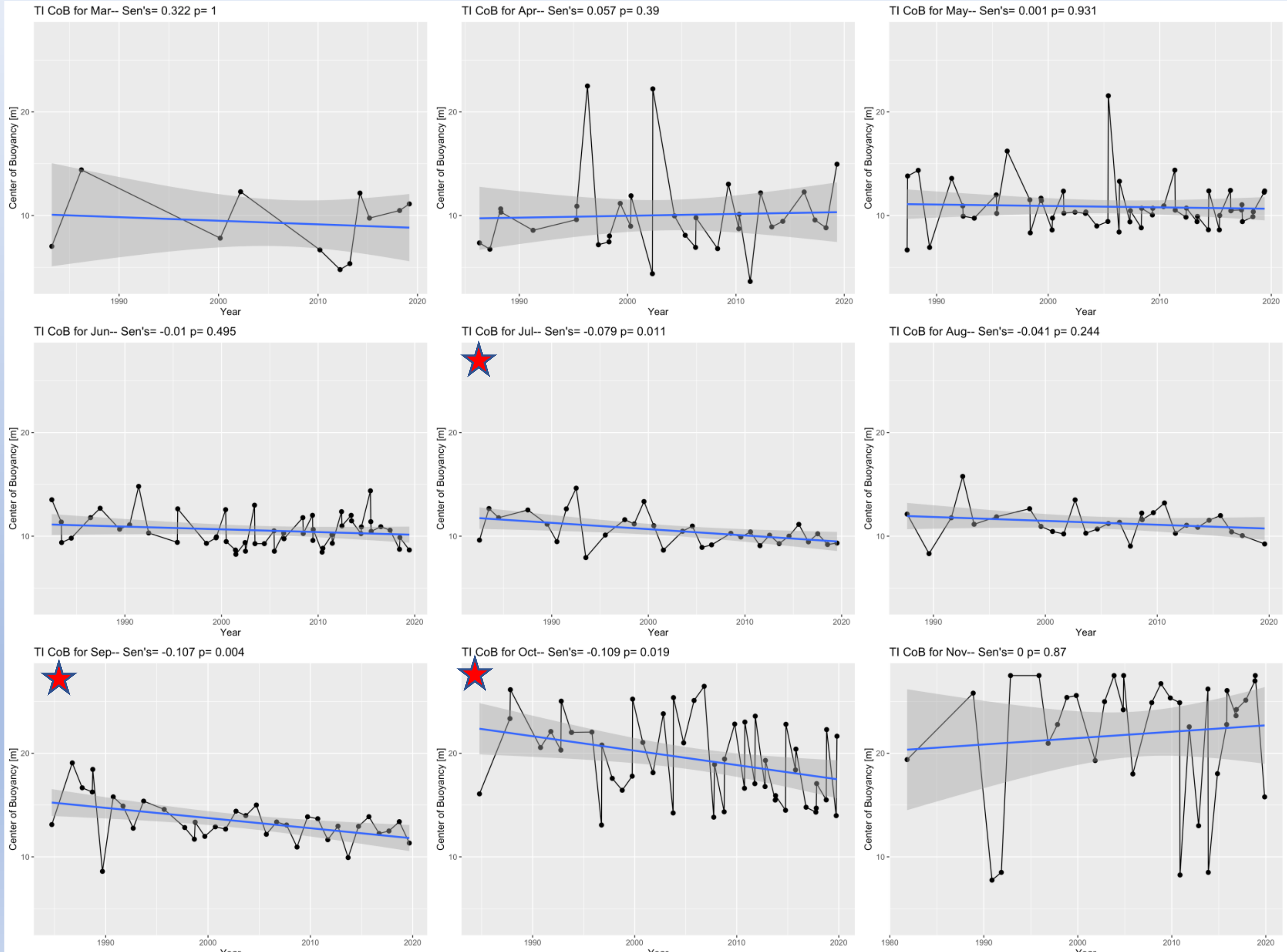
- Trend of increasing stratification strength
  - ~1000 J/m^2

- July, August, September, and October



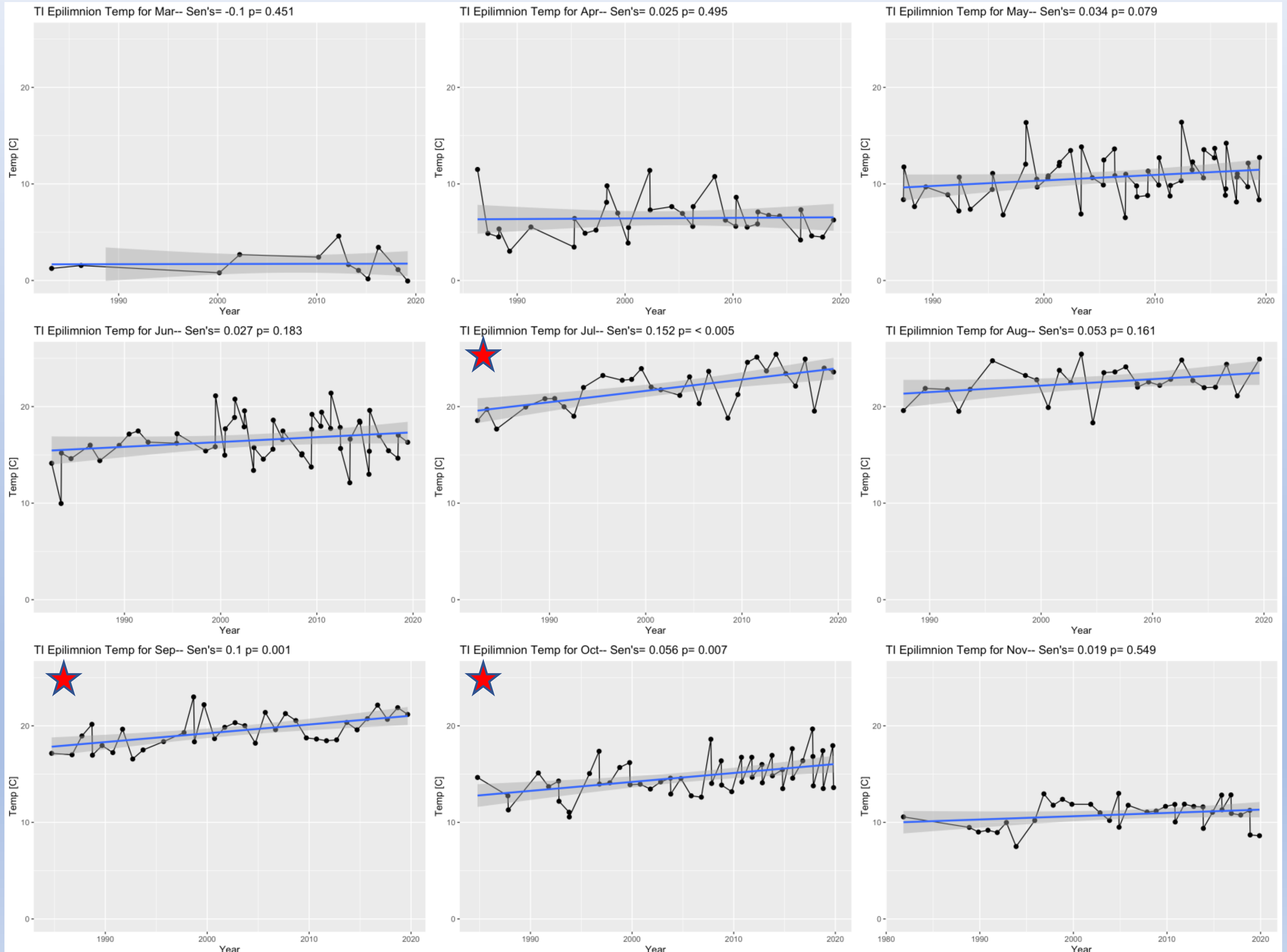
Depth of Epilimnion

- Epilimnion is shallowing



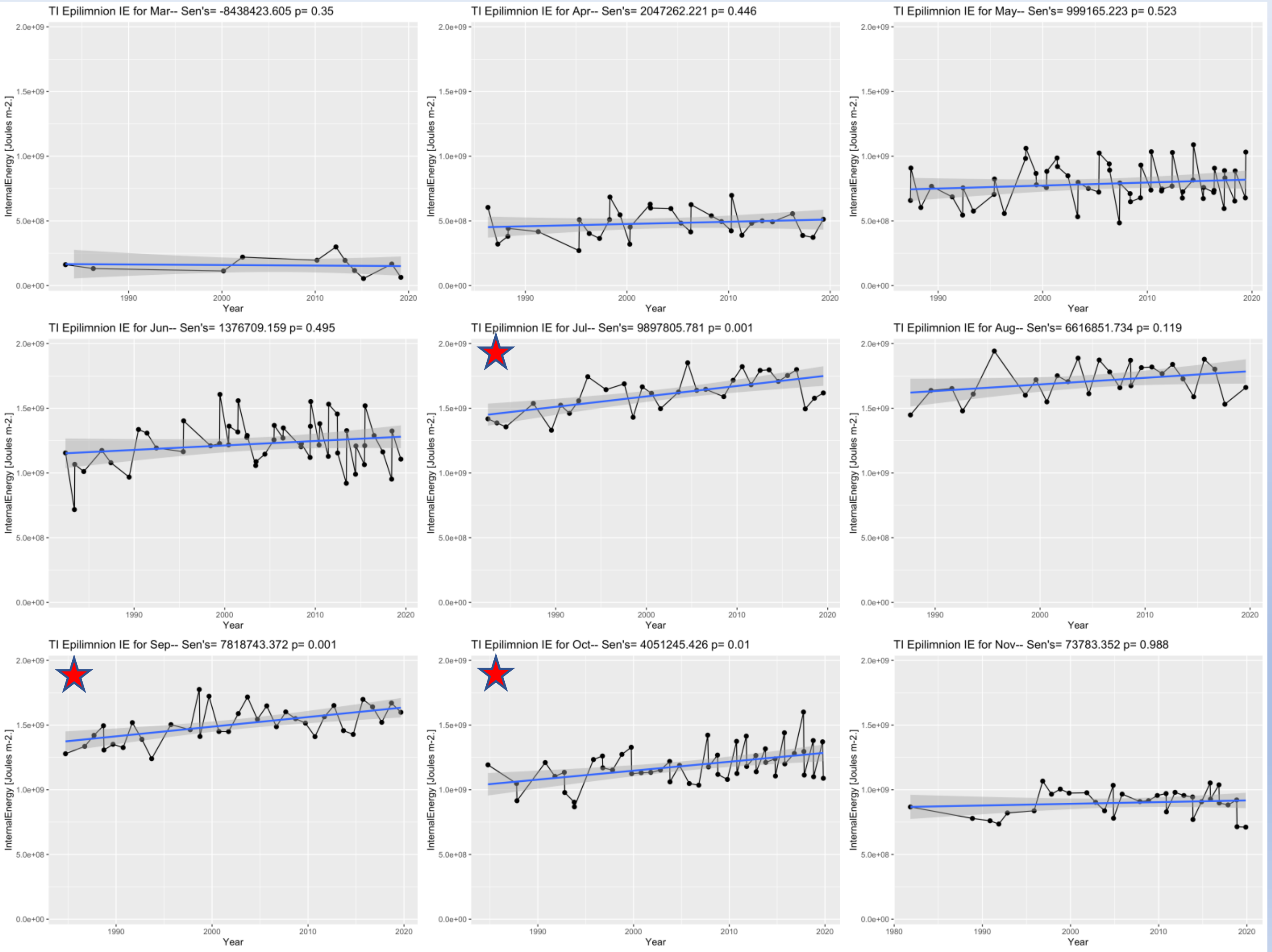
Temperature of Epilimnion

- Epilimnion is warming



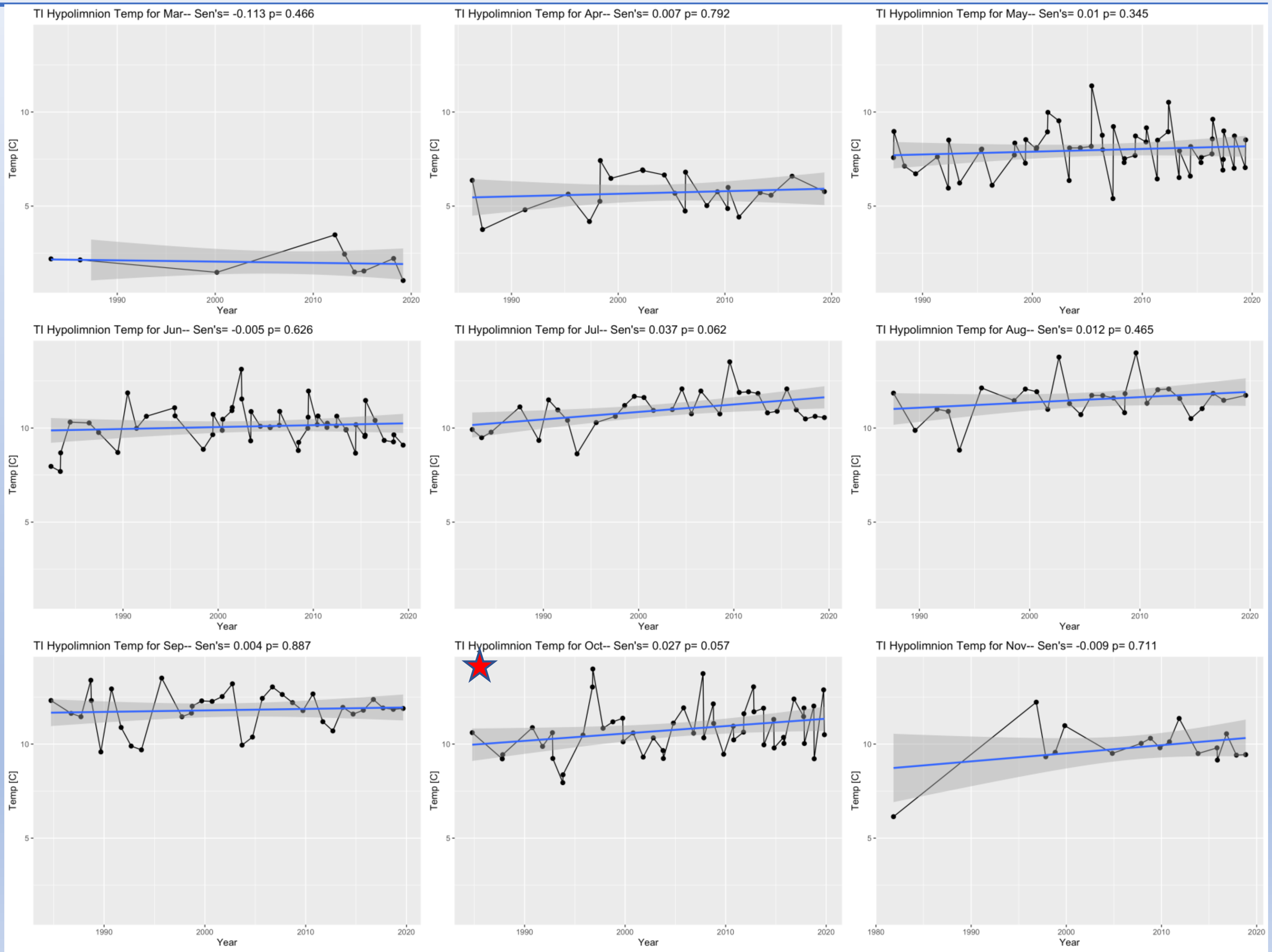
Internal Energy of Epilimnion

- Even though shallowing reduces the volume of the epilimnion, we see an increase in thermal energy of epilimnetic waters



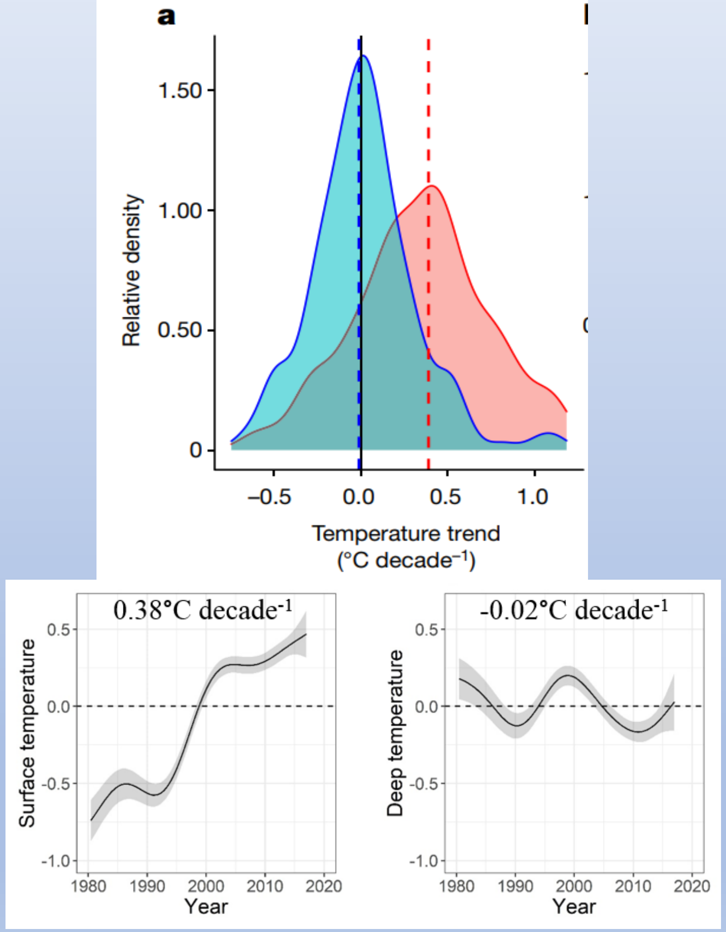
Temperature of Hypolimnion

- Hypolimnion *may* be warming, but not at same rate of epilimnion
- Differential warming is potential source of increased stratification strength



Temperature of Hypolimnion

- Hypolimnion *may* be warming, but not at same rate of epilimnion
- Differential warming is potential source of stratification strength
- 393 temperate lakes
- 1941-2017



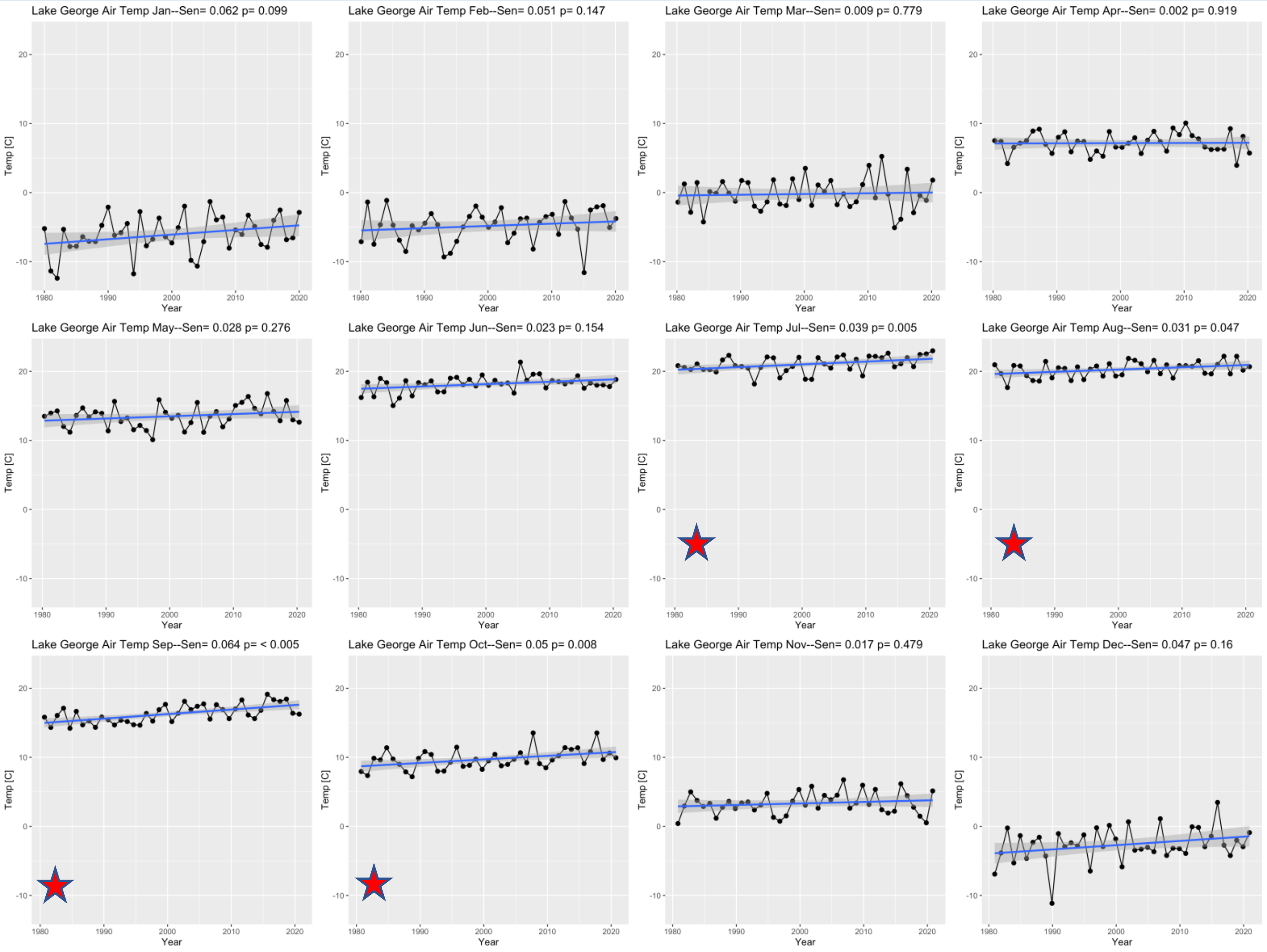
Jane et al., 2021, Nature

Air Temperature

- Warming air temperatures in mid-late summer driving changes in epilimnion

- Warming of epilimnion driving changes in stratification

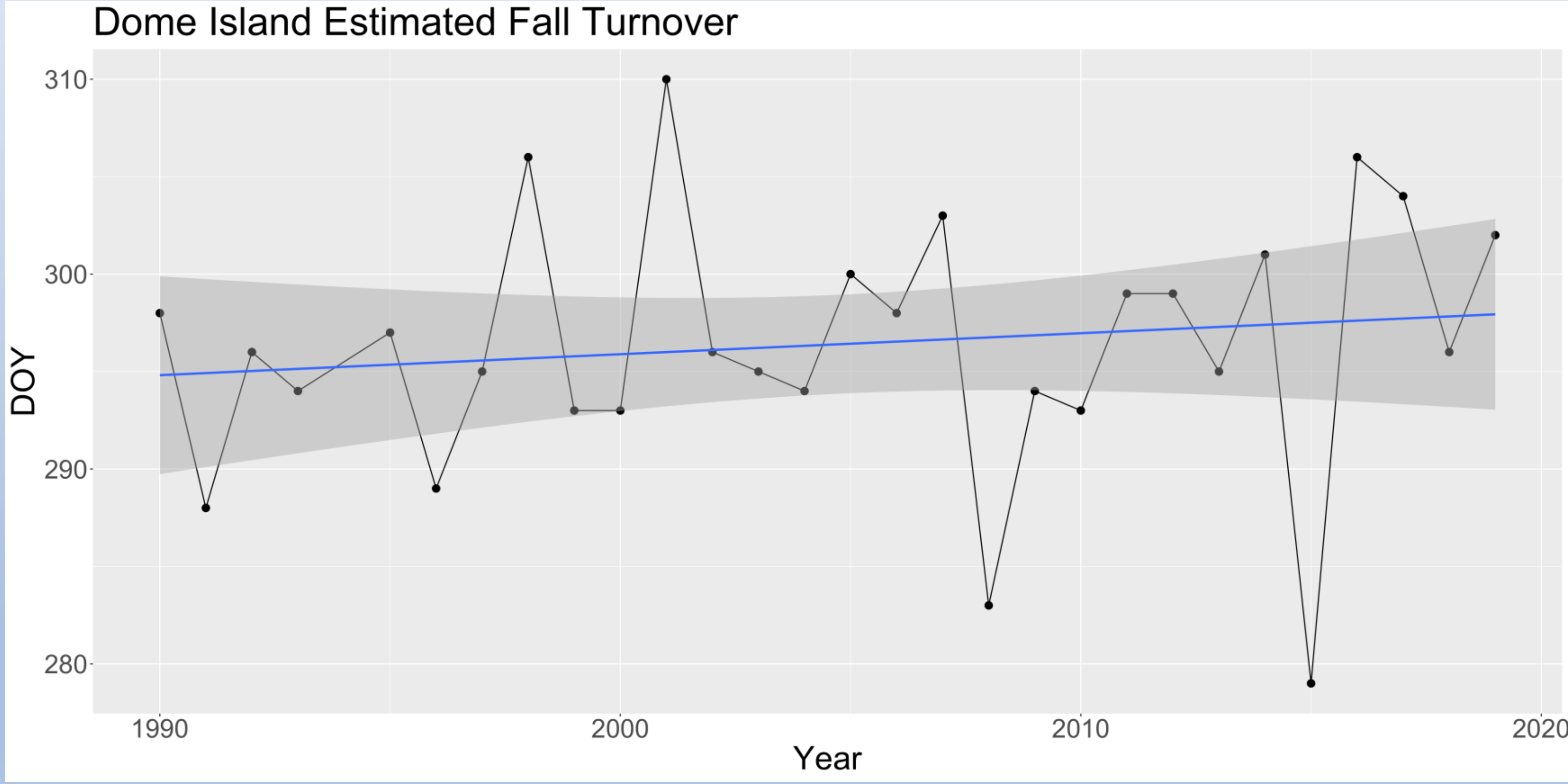
- 40-year trend of epilimnion getting warmer, shallower, with more heat energy, and stronger stratification in late summer- fall



National Center for Environmental Prediction Reanalysis data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA

Stratification Duration

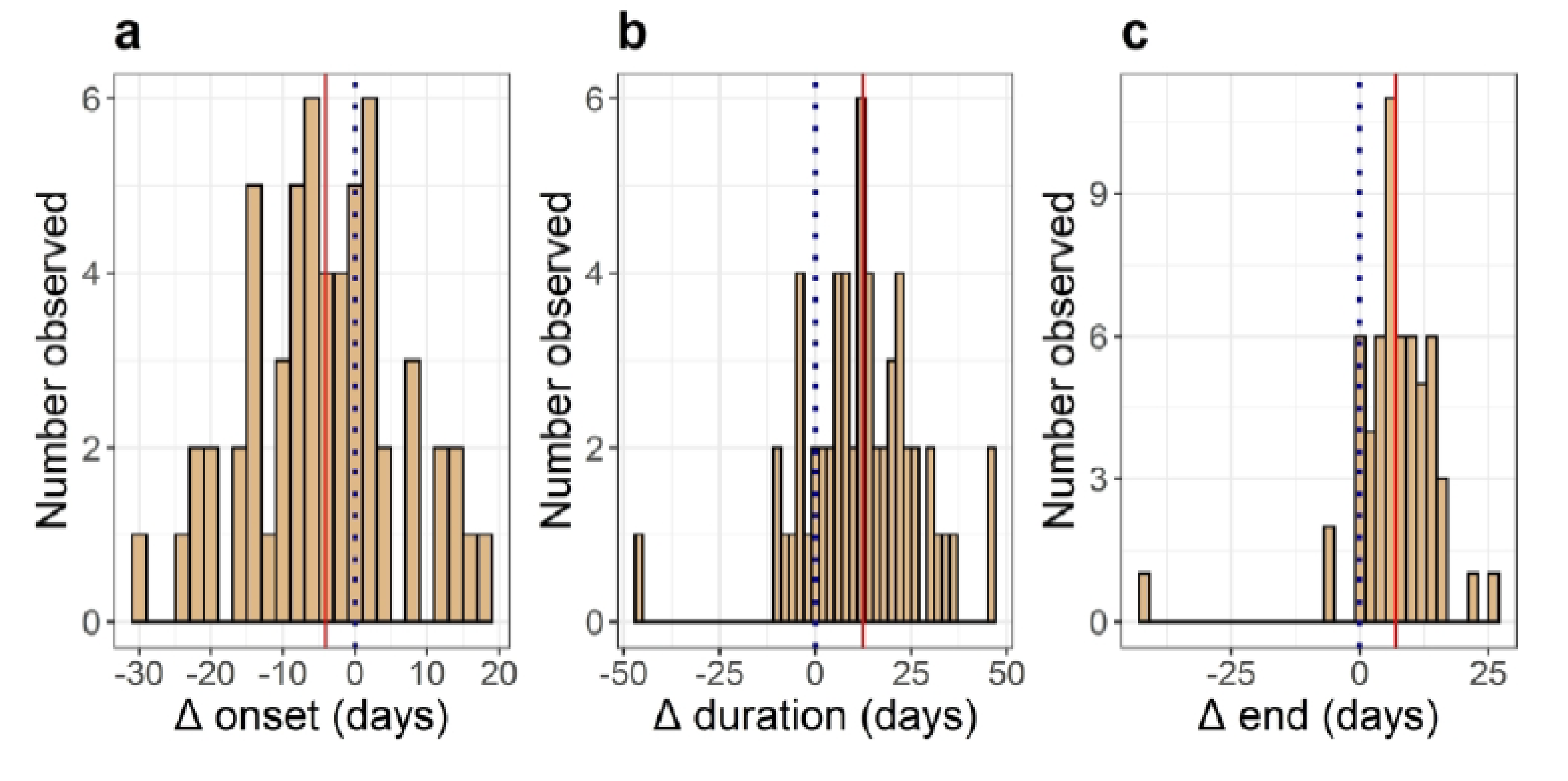
- Weak trend: delay of fall turnover
- Temporal resolution (2 weeks) is >= change in turnover



Stratification Duration is increasing

- 139 lakes

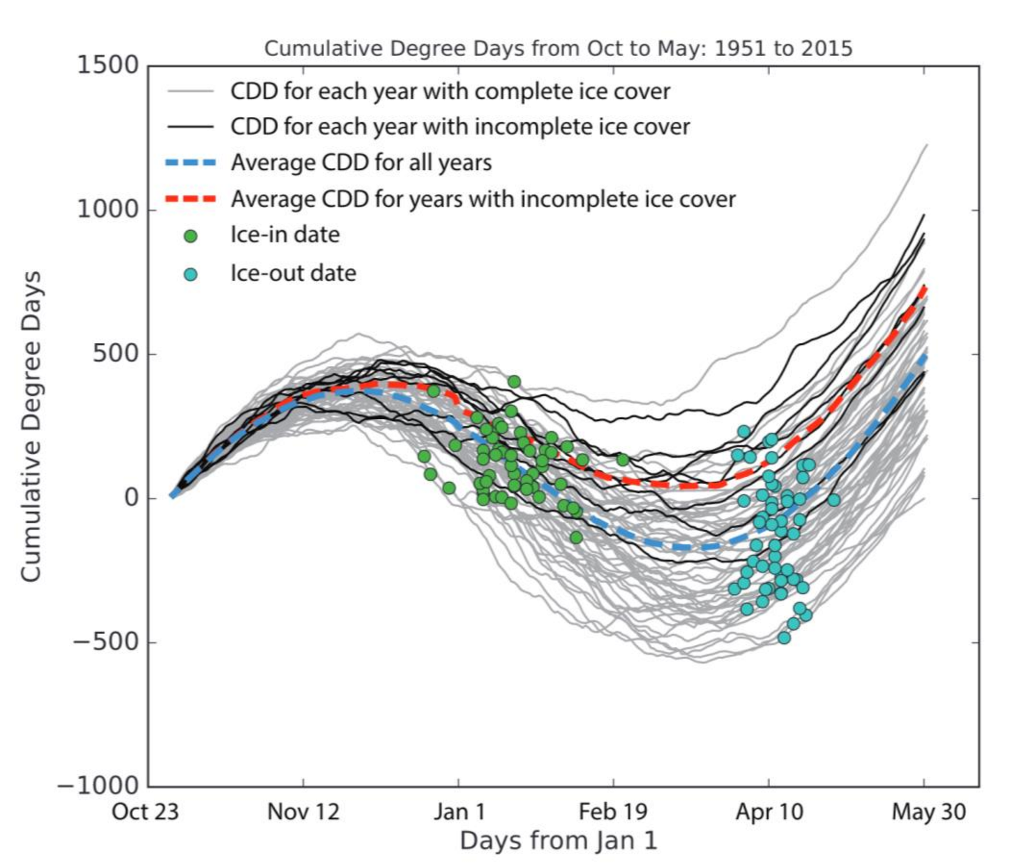
- A= Start of stratification
- B= Duration of stratification
- C= End of stratification



Jane et al., in review @ Global Change Biology

Ice Phenology

- Lake George ice cover record (1912 - 2022)
  - Lake George Association
  - 1912-1990: Only one year Lake George did not completely freeze over (1919)
  - 1990-2020: Thirteen years Lake George did not completely freeze over
    - Lake Sentinel!
  - 1912-1990 ice cover = Jan 24th – Apr 10th
  - 1990-2020 ice cover = Jan 20th- Apr 12th
  - Six-day reduction in ice cover
  - 2040-2060: loss of complete ice coverage (RCP8.5)
- Mirror Lake – Ice cover avg 24 days shorter since 1903

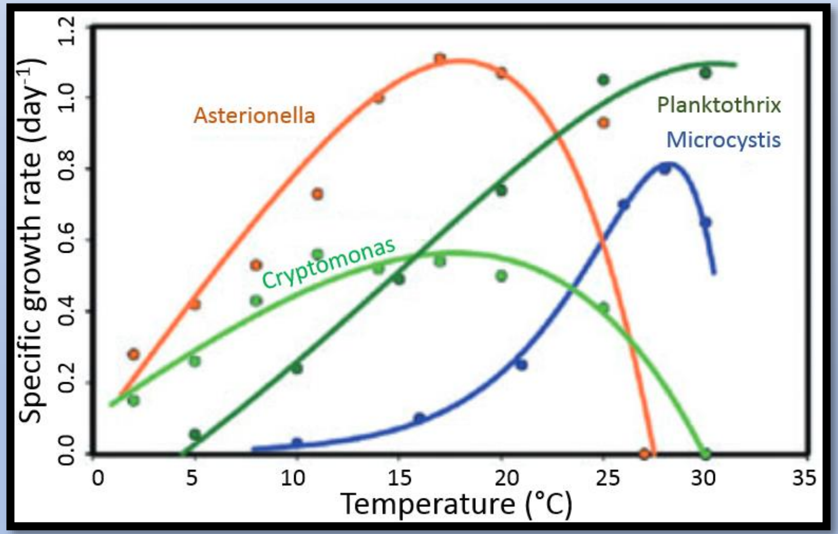


Watson et al. 2020

Stratification, Cyanobacteria and HABs

Potential impacts of change in lake stratification strength/duration:

- Warmer epilimnion → Longer growing season → Increased overall productivity



Paerl and Huisman 2009, Environmental microbiology reports

Stratification, Cyanobacteria and HABs

Potential impacts of change in lake stratification strength/duration:

- Warmer epilimnion → Longer growing season → Increased overall productivity
- Stronger stratification → Decreased dissolved oxygen → Increased internal P loading
- Longer stratification periods → Longer periods of anoxia driven internal P loading

- Stronger stratification → Segregation of benthic derived nutrients

Mobility and Speed

- *Microcystis aeruginosa* migration speed = 140m d-1
  (Reynolds & Walsby, 1975)

- Sinking phytoplankon or flagellar motion = 0.4m d-1
  (Smayda, 1970)

- Thermocline becomes barrier to weak swimmers

- Strong buoyancy allows BGA colonies to travel through thermocline

- BGA can access *both* increased nutrients (hypolimnion) and increased PAR (photic zone)
  - Weak stratification reduces competitive advantage

Dervaux et al. 2015

Stratification, Cyanobacteria and HABs

Potential impacts of changes in lake stratification strength and duration:

- Warmer epilimnion → Longer growing season → Increased overall productivity
- Stronger stratification → Decreased dissolved oxygen → Increased internal P loading
- Longer stratification periods → Longer periods of anoxia driven internal P loading

- Stronger stratification → Segregation of benthic derived nutrients
  - Stronger stratification and increased periods of stratification may benefit BGA that can control buoyancy

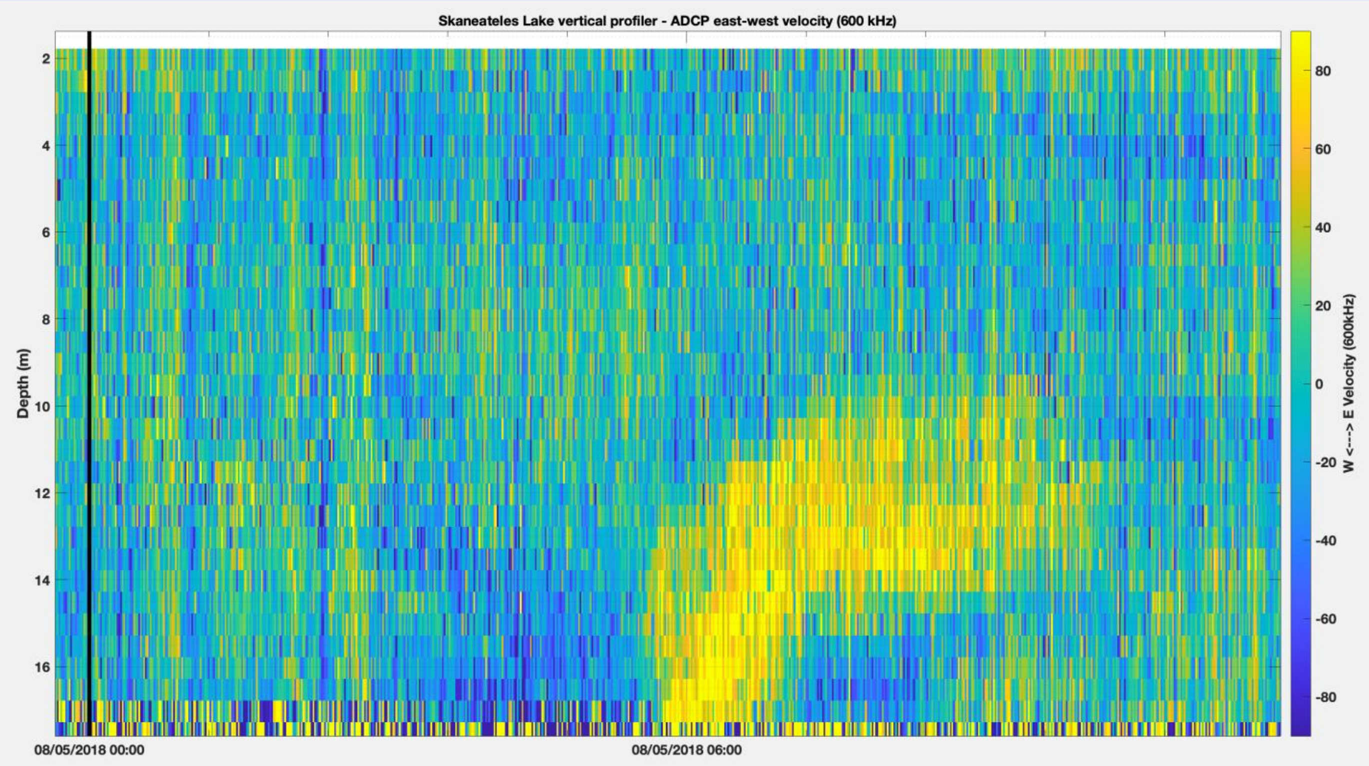
- Increased stratification strength leads to stronger internal wave action, and longer periods of internal wave activity

Skaneateles Lake – Benthic Interactions and HABs

- Internal waves & wind driven vertical mixing (Langmuir circulation)

- Importance of benthic disturbance for resuspension of nutrients and entrainment of cyanobacteria into water column

- “A sequence of weather-driven hydrodynamic events stimulates the formation of harmful algal blooms on an oligotrophic lake” (submitted)
    - Michael R. Kelly, Vincent W. Moriarty, Harry R. Kolar, Guillaume A. R. Auger, Michael E. Henderson, Campbell D. Watson, Rick A. Relyea, Christopher A. Scholz, Charles T. Driscoll, and Kevin C. Rose

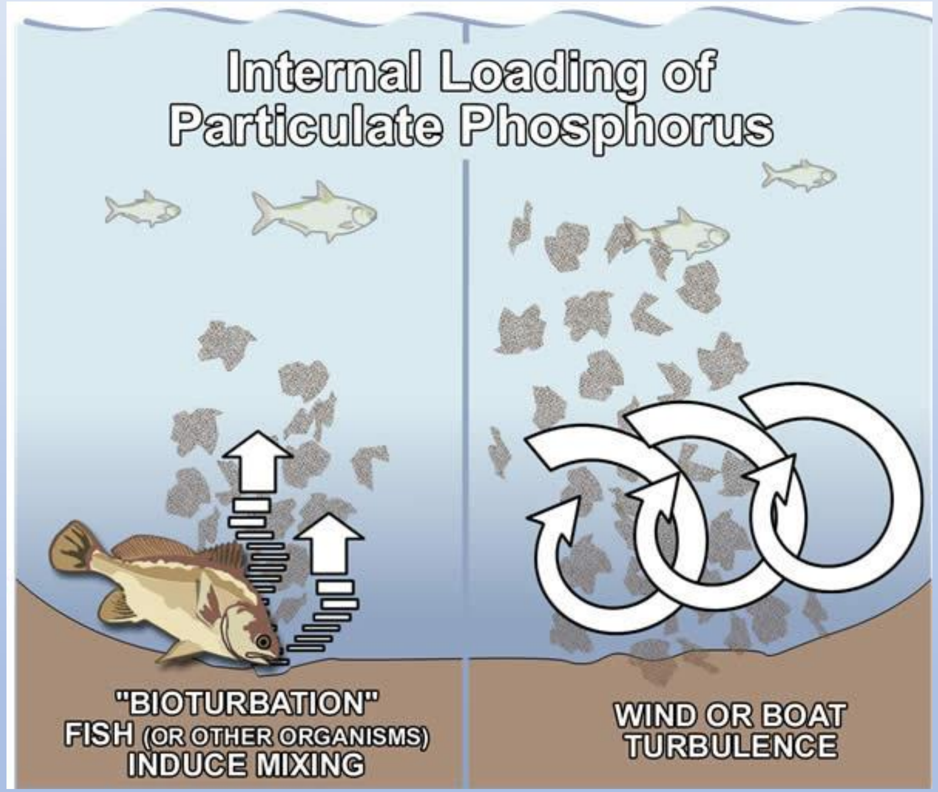


Skaneateles Lake – Benthic Interactions and HABs

- Internal waves & wind driven vertical mixing (Langmuir circulation)

- Importance of benthic disturbance for resuspension of nutrients and entrainment of cyanobacteria into water column

- “A sequence of weather-driven hydrodynamic events stimulates the formation of harmful algal blooms on an oligotrophic lake” (In review)
    - Michael R. Kelly, Vincent W. Moriarty, Harry R. Kolar, Guillaume A. R. Auger, Michael E. Henderson, Campbell D. Watson, Rick A. Relyea, Christopher A. Scholz, Charles T. Driscoll, and Kevin C. Rose



http://www.lmvp.org/Waterline/fall2006/pwithin2.html

Stratification, Cyanobacteria and HABs

Potential impacts of changes in lake stratification strength and duration:

- Warmer epilimnion → Longer growing season → Increased overall productivity
- Stronger stratification → Decreased dissolved oxygen → Increased internal P loading
- Longer stratification periods → Longer periods of anoxia driven internal P loading

- Stronger stratification → Segregation of benthic derived nutrients
    - Stronger stratification and increased periods of stratification may benefit BGA that can control buoyancy

- Increased stratification strength leads to stronger internal wave action, and longer periods of internal wave activity
    - Internal waves interacting with benthos to release (segregated) nutrients & resuspension of akinetes

- Seasonal behavior- Does a warming fall disrupt balance between species that key in on light cues (zooplankton), and species that key on temperature to control fall/winter behavior?
    - 40-year timeseries Lake Washington (Winder & Schindler 2004)
    - Earlier onset of spring stratification (16 days) → Lag between spring phytoplankton and zooplankton peaks

- If turnover is happening later, are there benefits to cold tolerant BGA that benefit from nutrient pulse associated with turnover? (*Dolichospermum)*

November 2020 – HABs in the Adirondacks

- Lake George & Mirror Lake
  - Both oligotrophic lakes
  - Both have first DEC confirmed HABs in 2020
  - Dominant cyanobacteria - *Dolichospermum*

- Lake George – Oct 23, Nov 1, **Nov 7 & 9**
- Mirror Lake – Nov 9

- Other reported blooms *
  - Loon Lake in late October.
  - Friends Lake in September
  - Paradox Lake on Sept. 13.
  - Raquette Lake on Oct. 12.
  - Silver Lake on Oct. 5.

FRIDAY, NOVEMBER 13, 2020

Harmful algal blooms found on Lake George, Mirror Lake

by Ry Rivard

No Comments

In an unfortunate coincidence that may be no coincidence at all given the warm temperatures, two of the region's famed lakes have been partly covered by harmful algal blooms in the past several days.

The first is Lake George, which hadn't had a confirmed algal bloom on its surface.

The second is Mirror Lake, the lake at the center of the Village of Lake Placid. This algal bloom could also be a first for that lake.

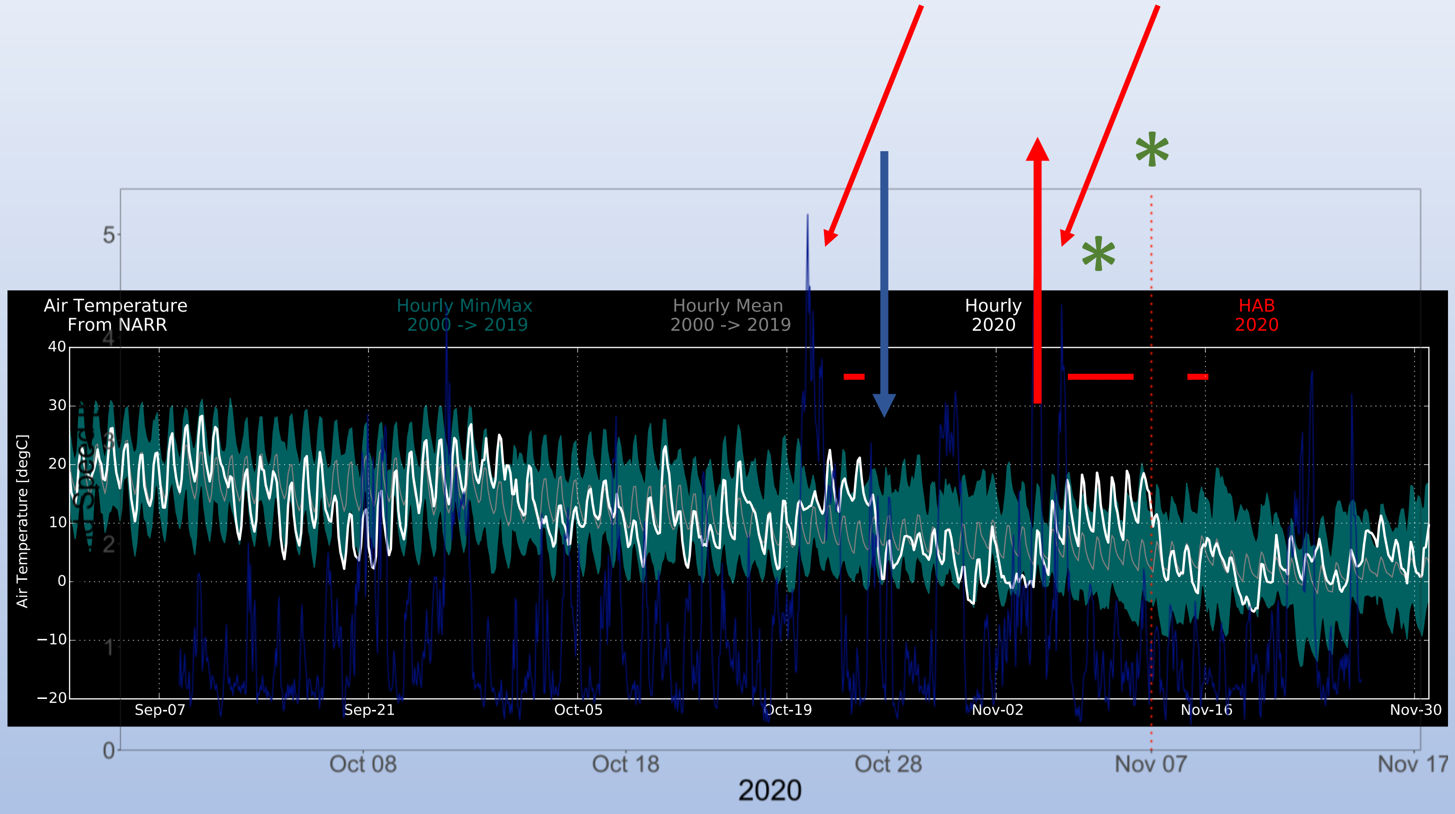
https://www.adirondackalmanack.com/2020/11/harmful-algal-blooms-found-on-lake-george-mirror-lake.html

* https://www.adirondackalmanack.com/2021/11/still-blooming.html

Antecedent Weather Leading to 2020 LG HAB Event

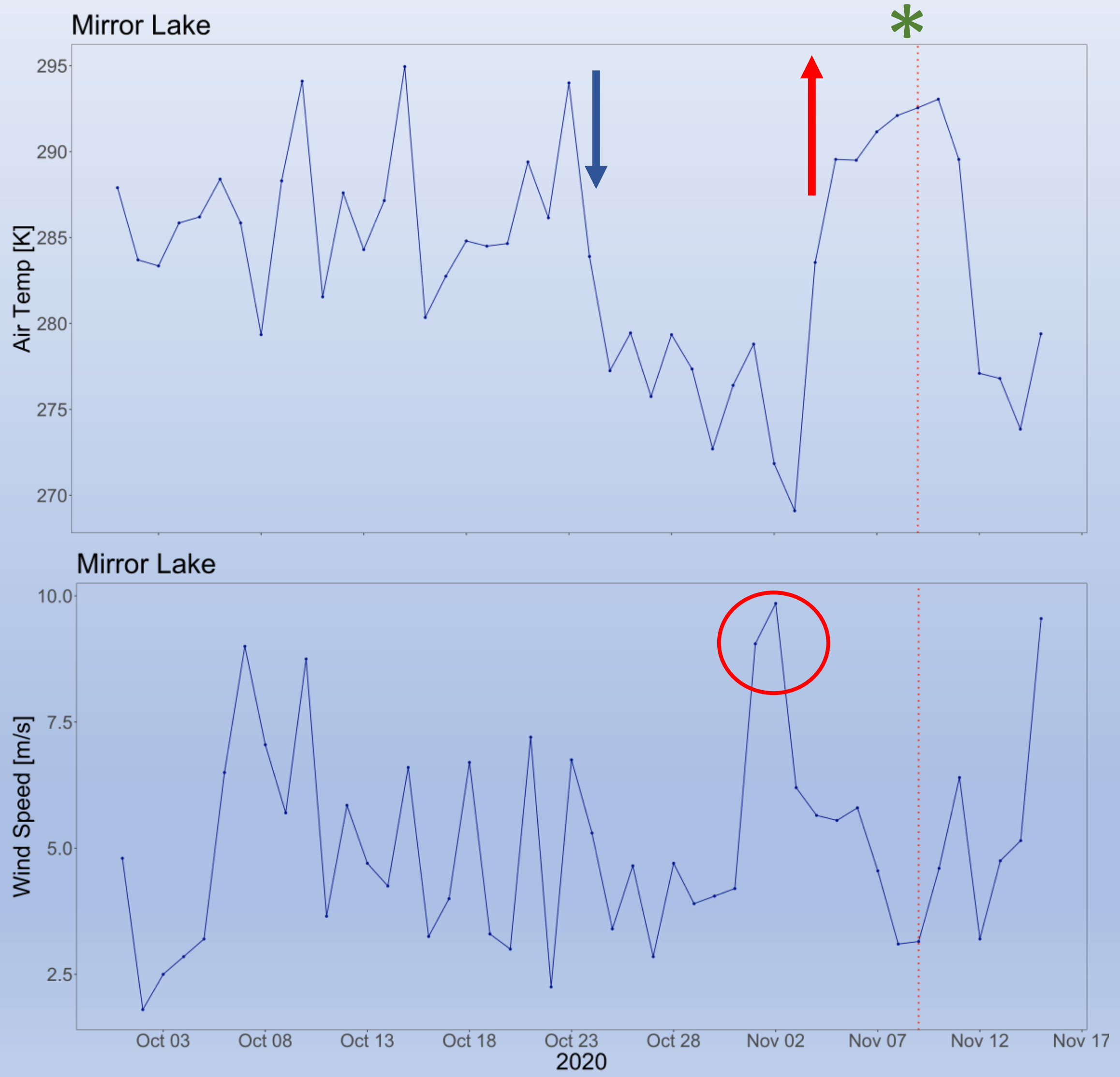
- Was air temperature anomalously warm leading up to November HAB event?
  - Air temperature was warm, but within normal seasonal range

- Were wind speeds anomalously low?
  - Wind speeds were low for a prolonged period associated with HAB event
  - Spike in wind speed leading up to HAB



Mirror Lake Antecedent Weather

- Cold period, followed by warm weather
- Low wind during period of HAB
  - Spike in wind speed leading up to HAB
- Breakdown of stratification

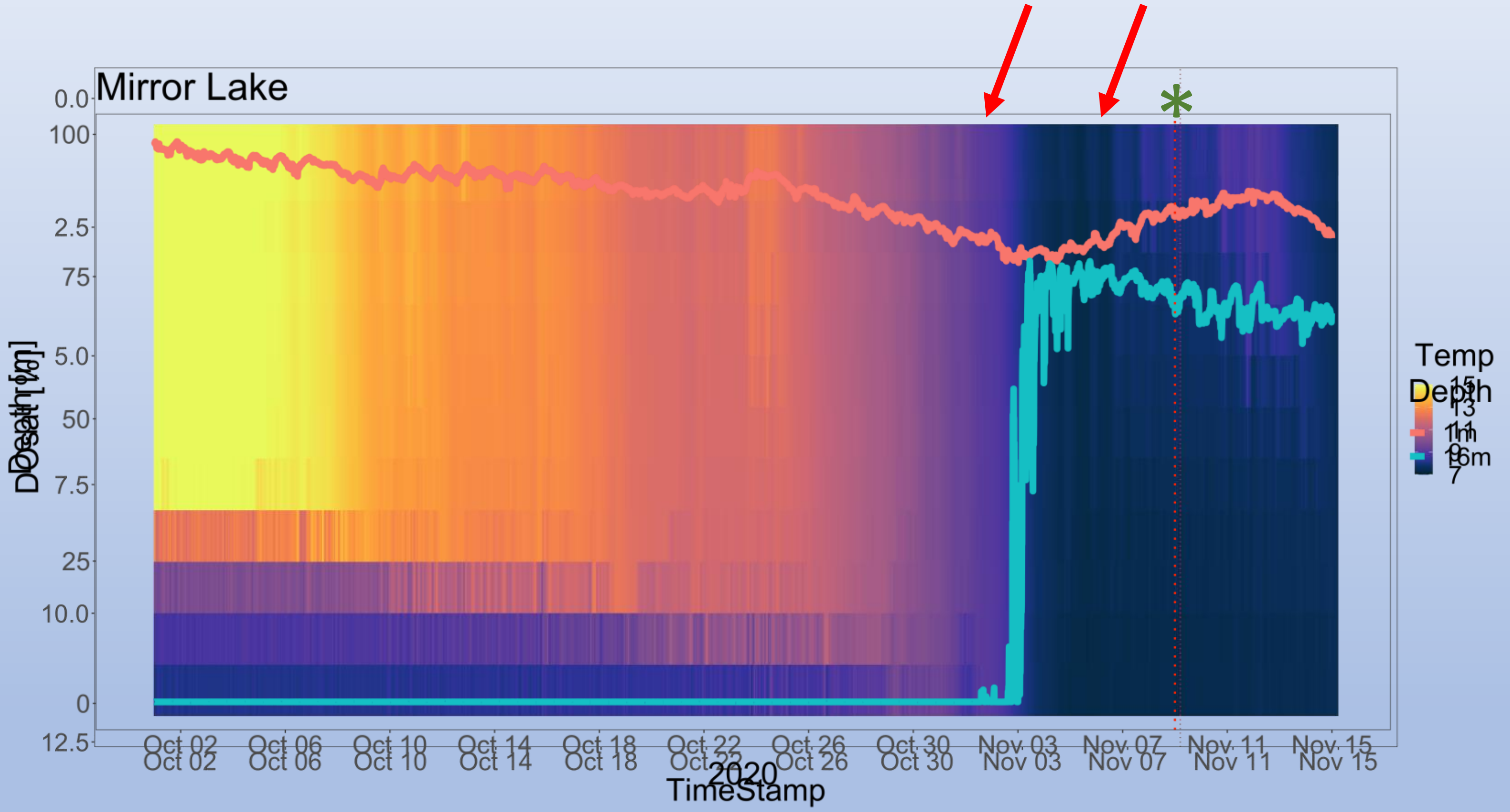


Mirror Lake HAB –Turnover & Restratification

- Mirror Lake fully mixed November 3rd
  - Low air temp & high winds leads to weak stratification
  - Release of nutrients
  - Entrainment of dormant cyanobacteria cells

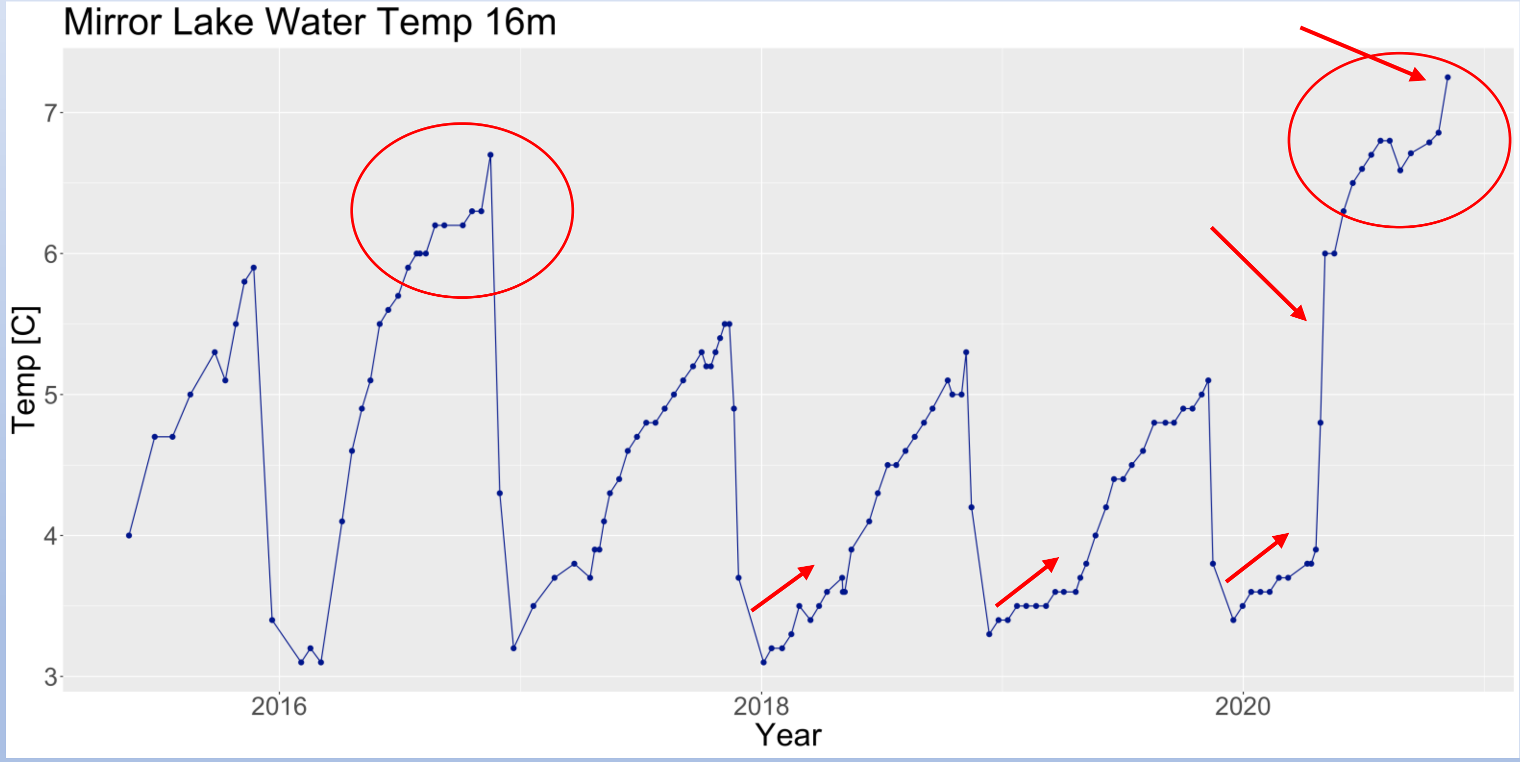
- Warm temperatures (Nov 6th) may increase growth rates in *newly* pelagic & well-fed colonies

- Increased stratification associated with warming is impediment to non-motile species
  - Favors cyanobacteria



Mirror Lake HAB– Changing Hypolimnion

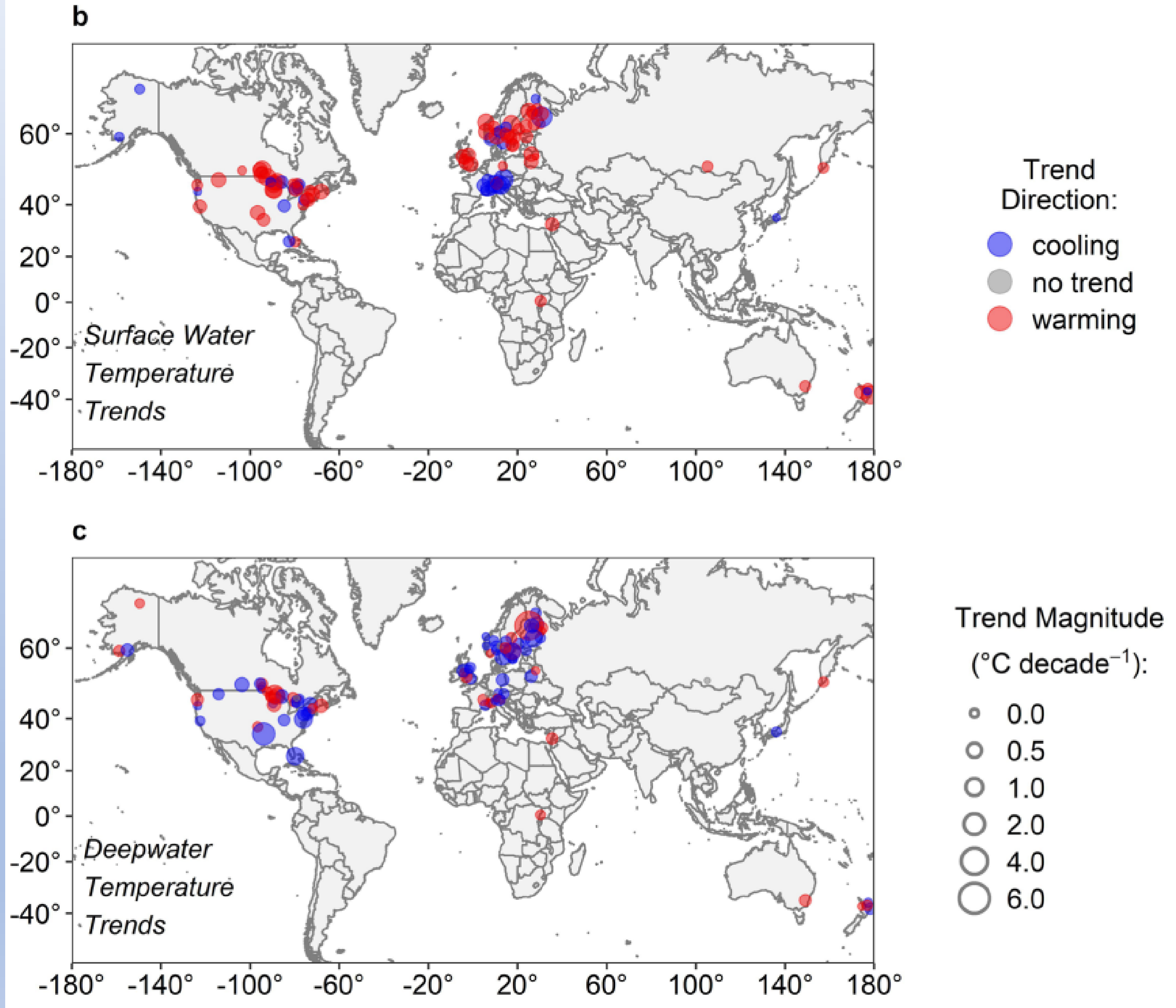
- Incomplete spring mixing 2017-19
  - Road salt runoff (Wiltse et al. 2020)
  - 2016 & 2020- full spring mixing
  - More heat transferred to hypolimnion
- Decrease in cooling
- HAB 2020
  - min temp = 3.5 C
  - ↑ Warming Apr & May
  - Fall temp > 7.2 C
- Multiple stressors



Brendan Wiltse
https://www.ausableriver.org

Lakes as Sentinels of Climate Change

- First appearance of HABs in lakes
  - Lake George – July & Oct 2021
- Changes in ice cover
- Changes in thermal structure
  - Temperature
  - Stratification strength
- Integration of of multiple stressors (direct & indirect)
  - Common to deep lakes in NY
  - Cumulative impacts favor HABs

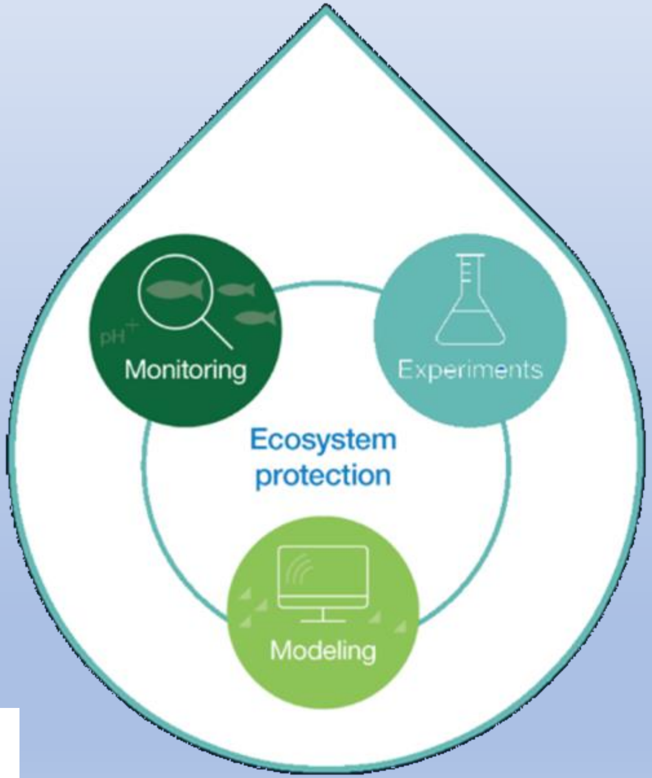


Pilla et al., 2020, Nature Scientific Reports

https://www.kurtgardnerphotography.com/print-store/art_print_products/lake-george-ny

The Jefferson Project at Lake George

Rensselaer



Campbell Watson
Brendan Wiltse
Larry Eichler
Megan Corbiere
Laurie Aherns
Candace Schermerhorn
Rick Relyea
Brian Mattes

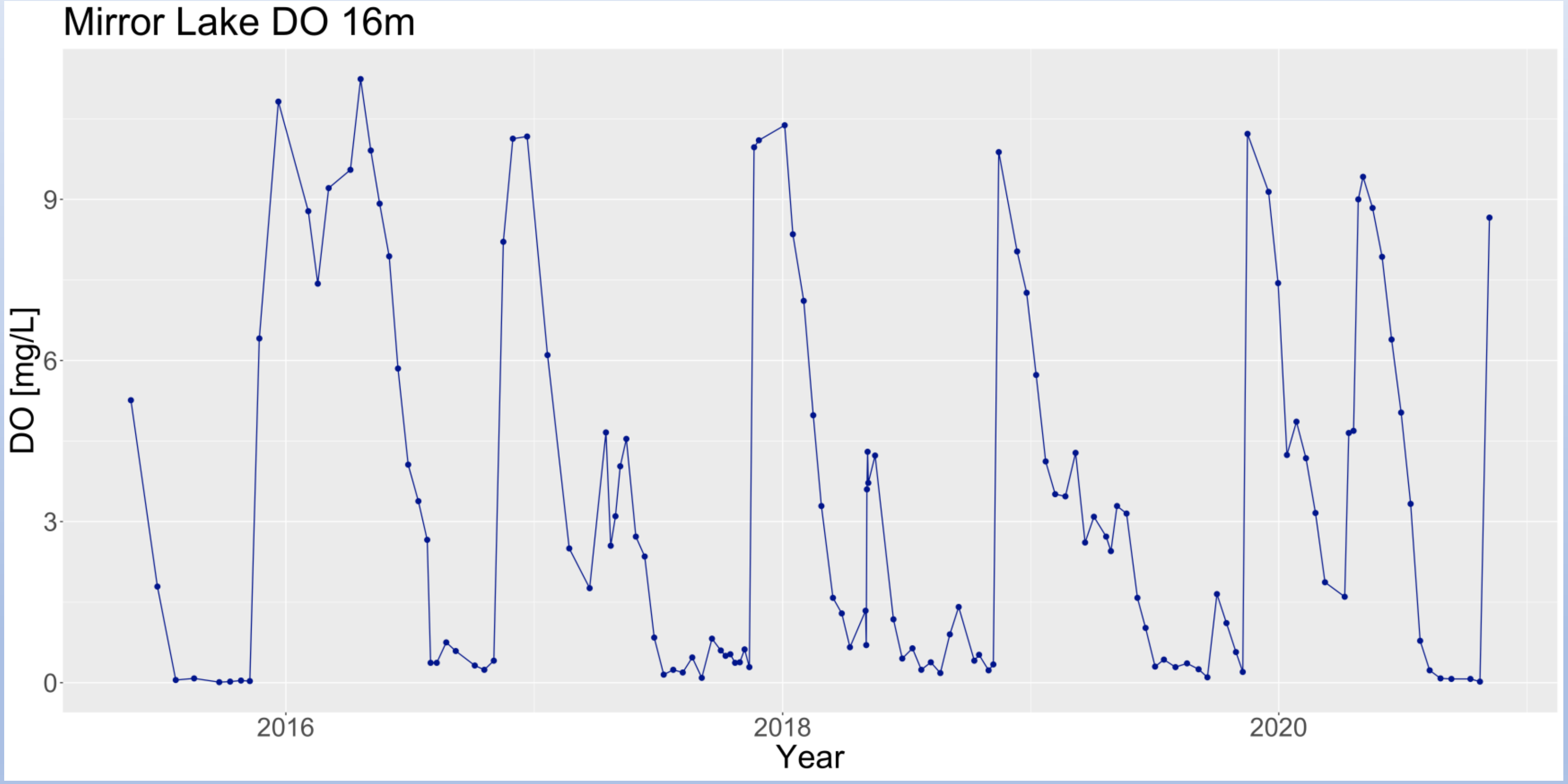
John Stettler
Michael Henderson
Joel Harrison
Mark Lucius
John Ma
Leanna Thalmann
Kelly Tucker
Lija Treibergs
Ausable River Association

LGA Lake George Association

IBM

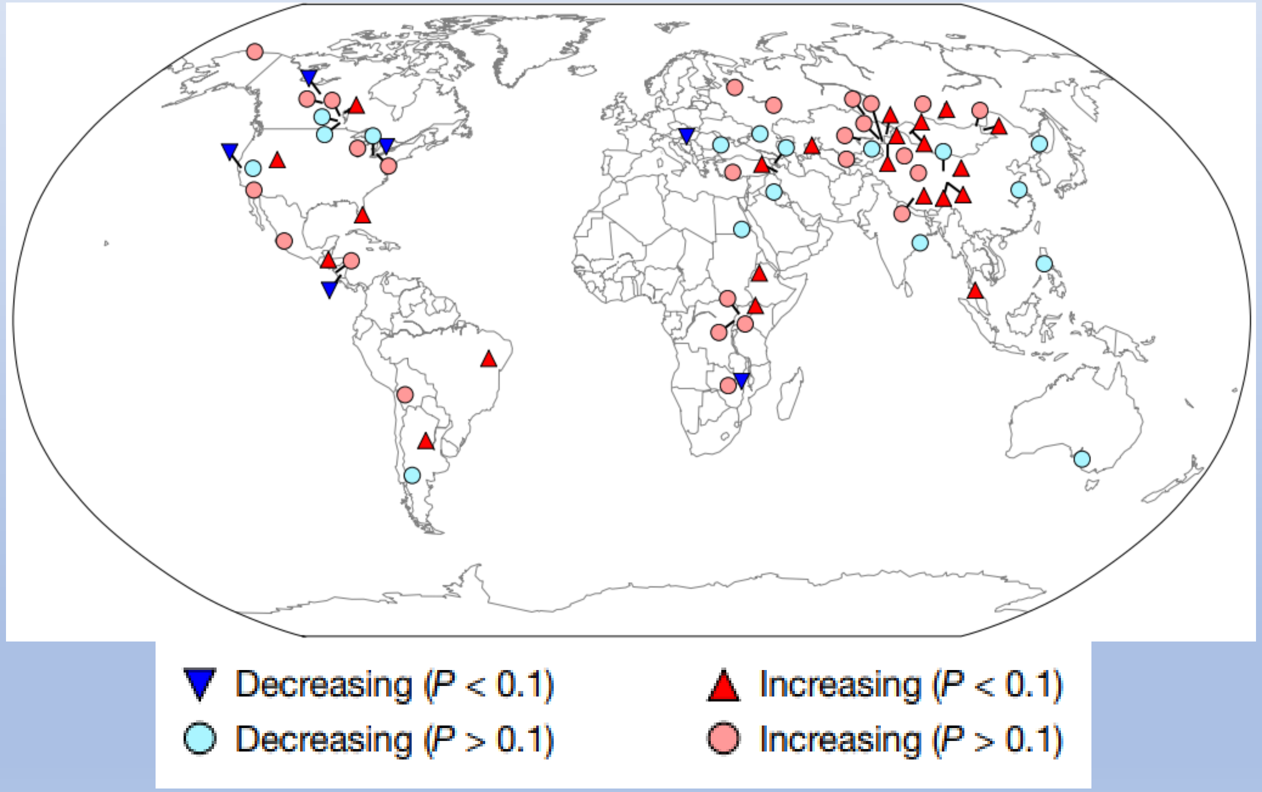
https://jeffersonproject.rpi.edu

Mirror Lake HAB- Changing Hypolimnion



Brendan Wiltse
https://www.ausableriver.org

Remote sensing provides some evidence of increasing algal blooms.



- Peak summertime bloom intensity has increased in 68% of studied lakes.
- The reason behind the increase in bloom intensity remains unclear. Trends do not track consistently with temperature, precipitation, fertilizer-use trends, or other hypothesized drivers.
- Lakes with a decrease in bloom intensity warmed less compared to other lakes, suggesting that lake warming may already be counteracting management efforts to ameliorate eutrophication.

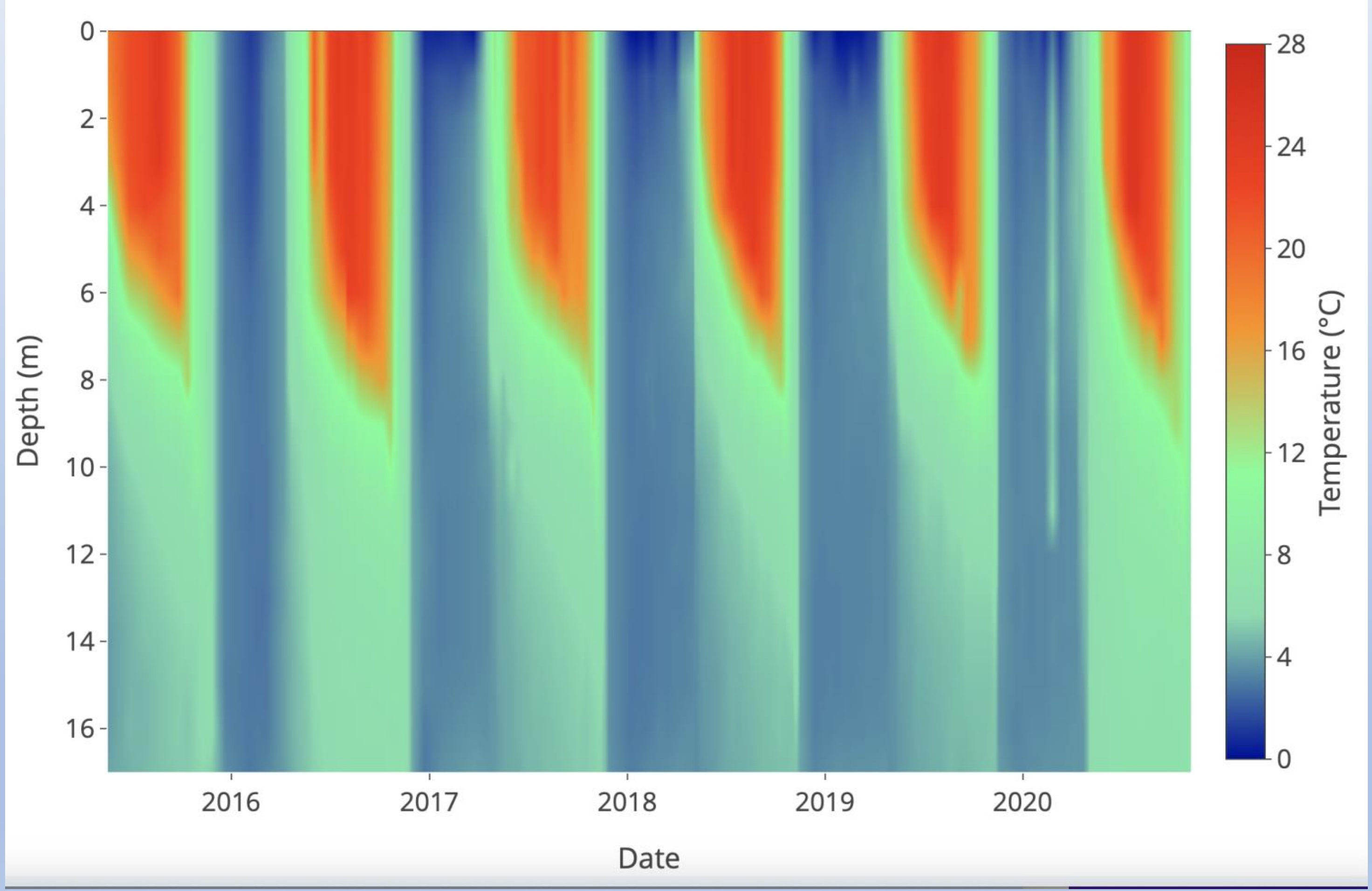
Ho et al., 2019, Nature

Mirror Lake HAB –

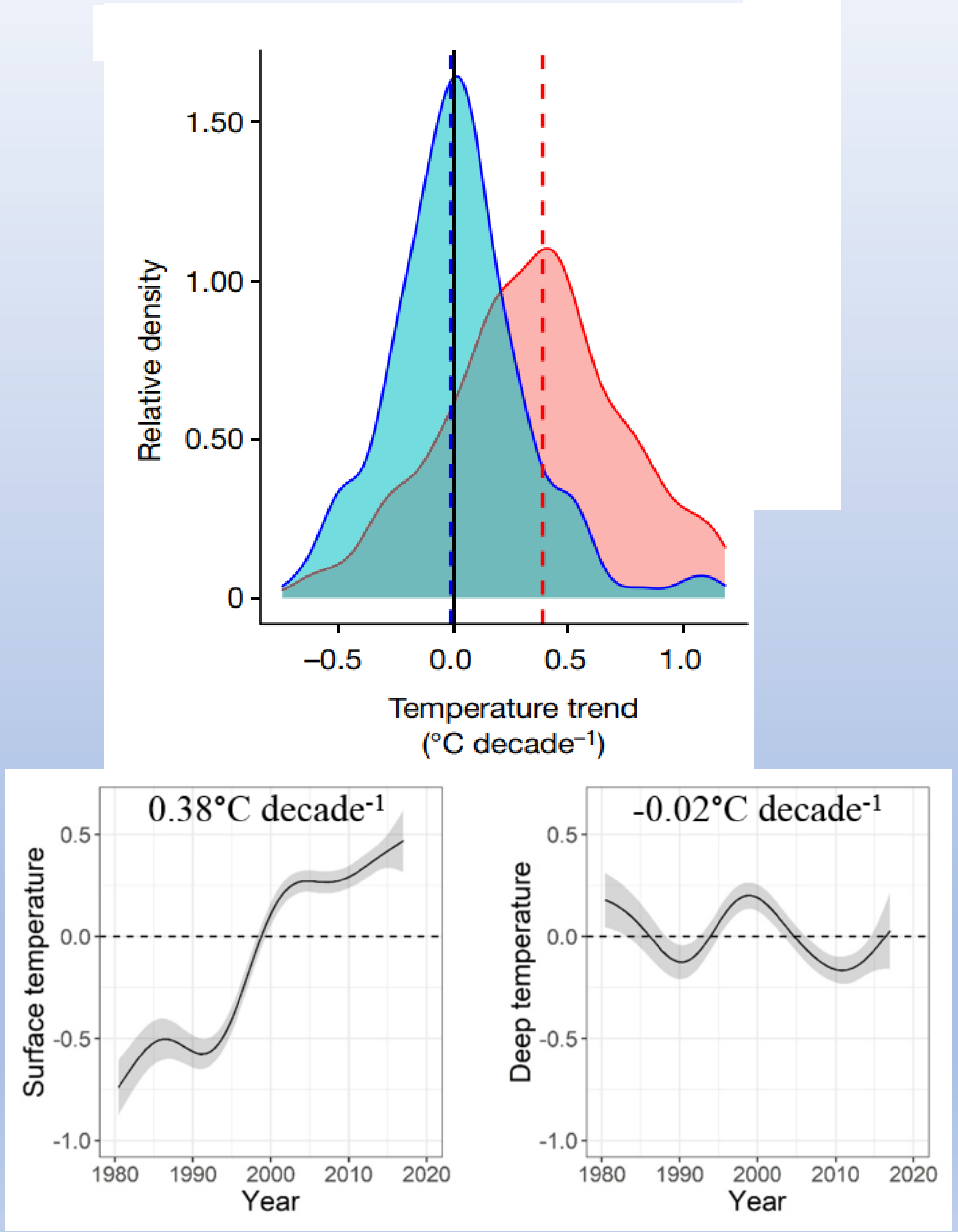
- Mirror Lake fully mixed November 3rd
    - Low air temp & high winds leads to weak stratification
    - Release of nutrients
    - Entrainment of dormant cyanobacteria cells

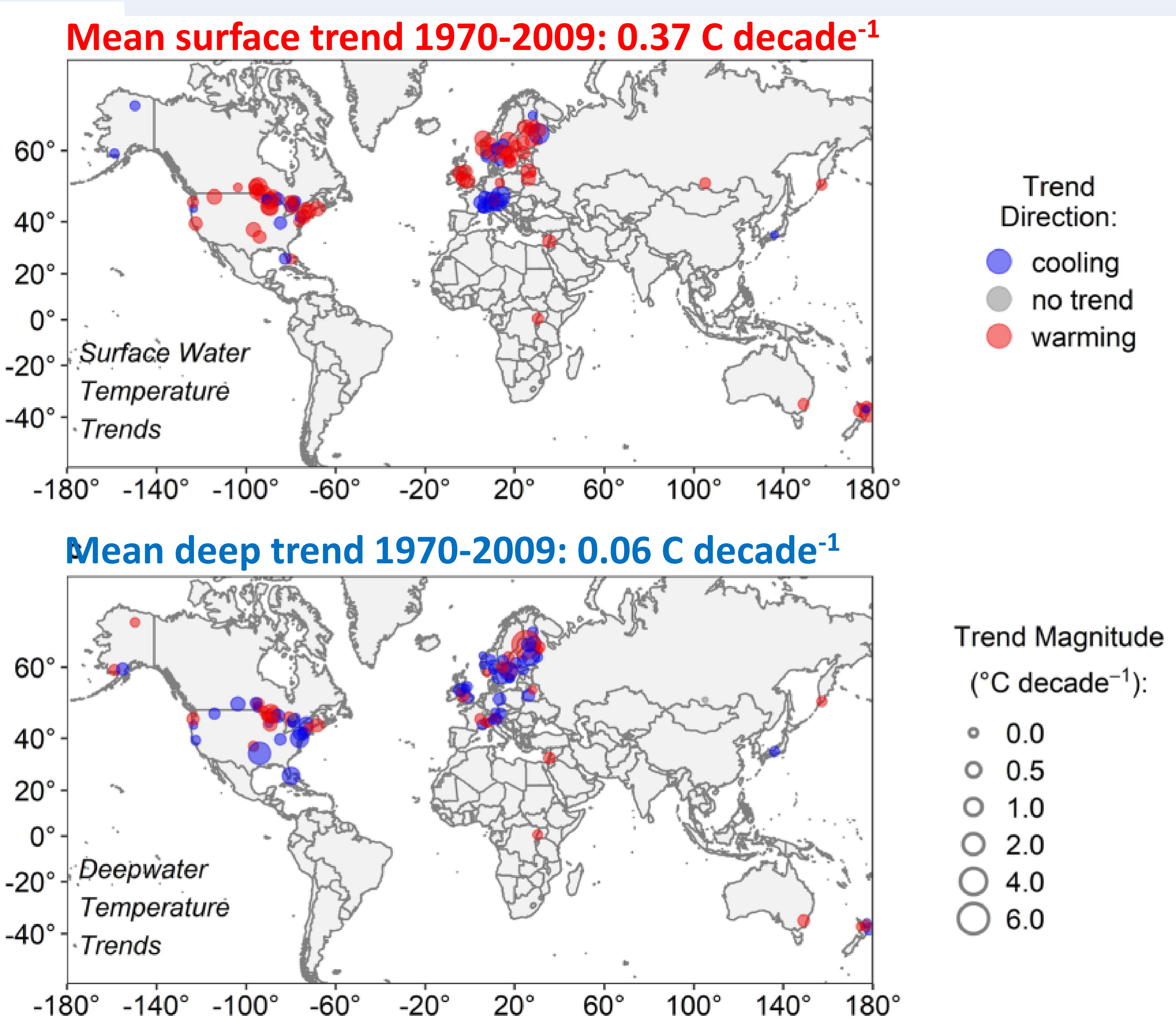
- Warm temperatures (Nov 6th) may increase growth rates in *newly* pelagic & well-fed colonies

- Increased stratification associated with warming is impediment to non-motile species
    - Favors cyanobacteria



Deep-water temperatures are not consistently warming.

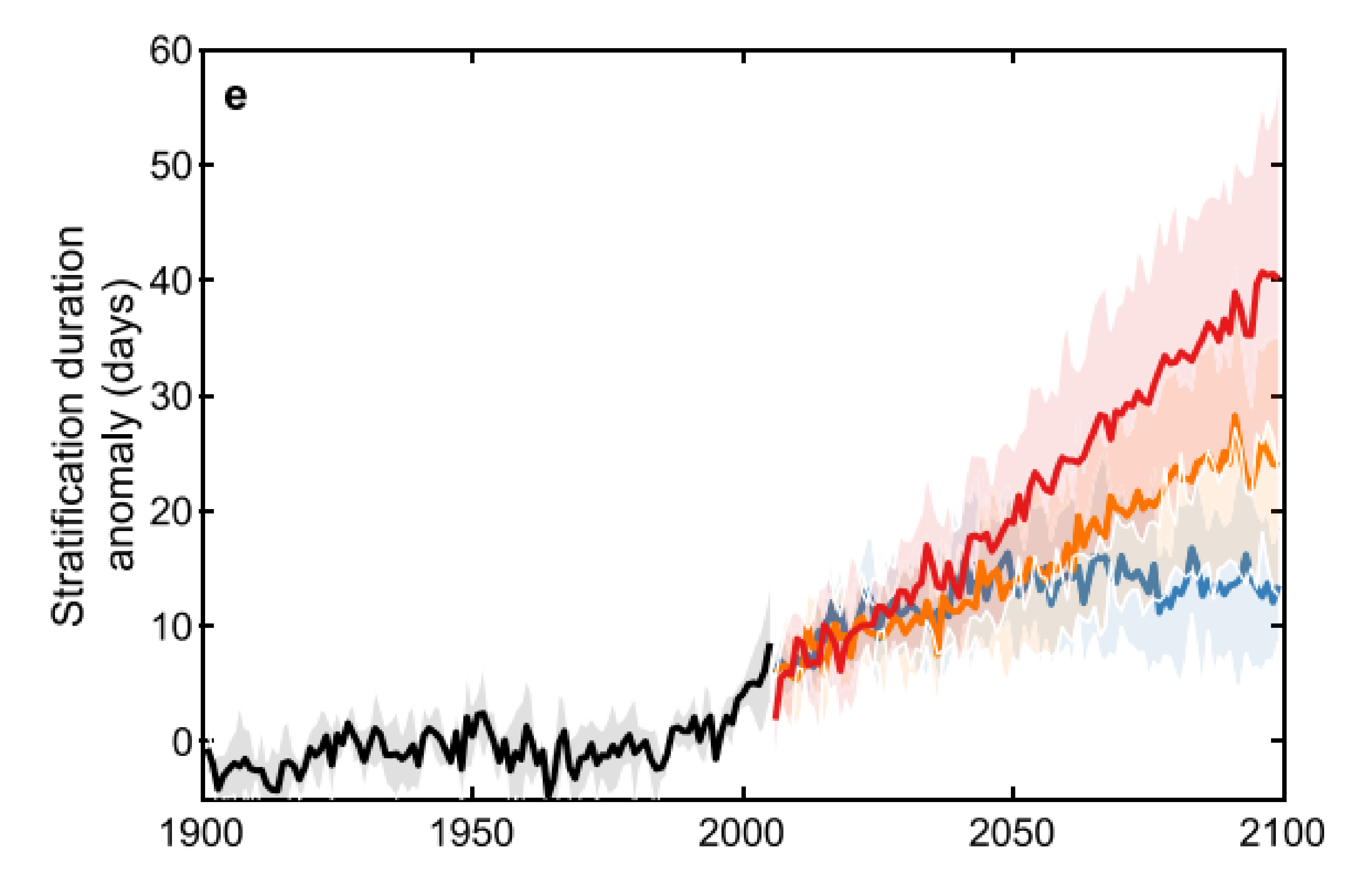


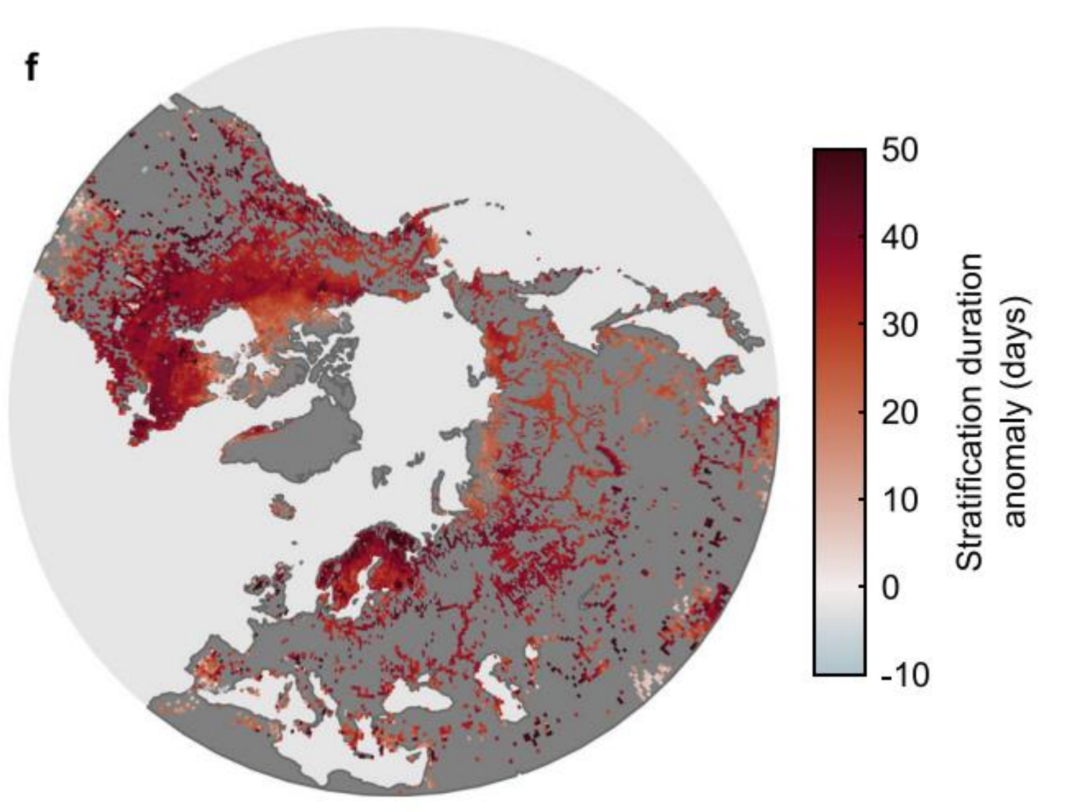


Jane et al., 2021, Nature

Pilla et al., 2020, Nature Scientific Reports

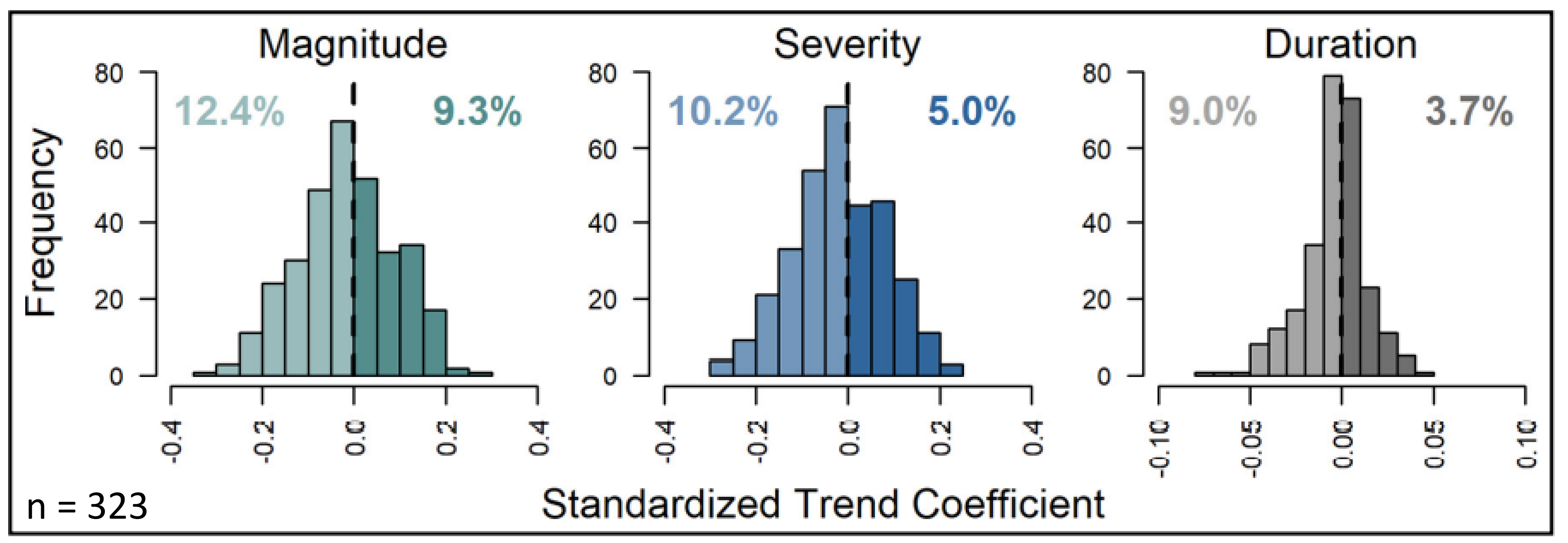
Climate change is increasing the duration of lake stratification, which will likely exacerbate deoxygenation.





Woolway et al., 2020, Nature Communications

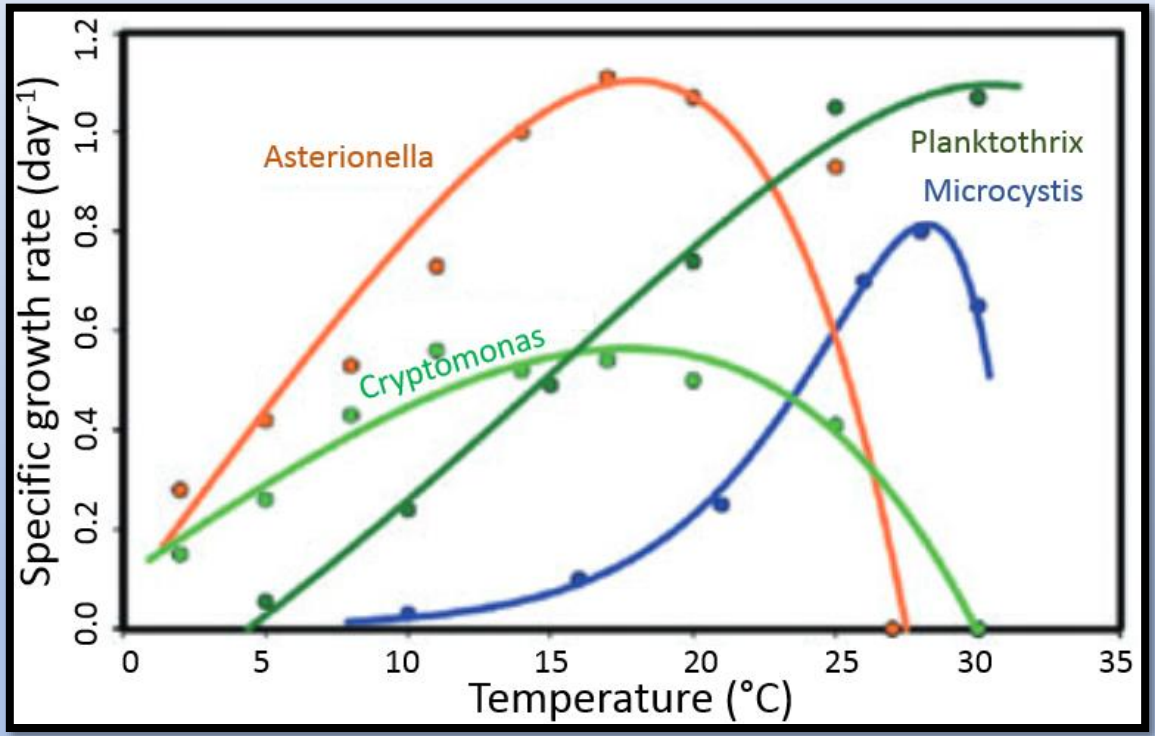
However, other in situ studies do not indicate algal blooms are intensifying.



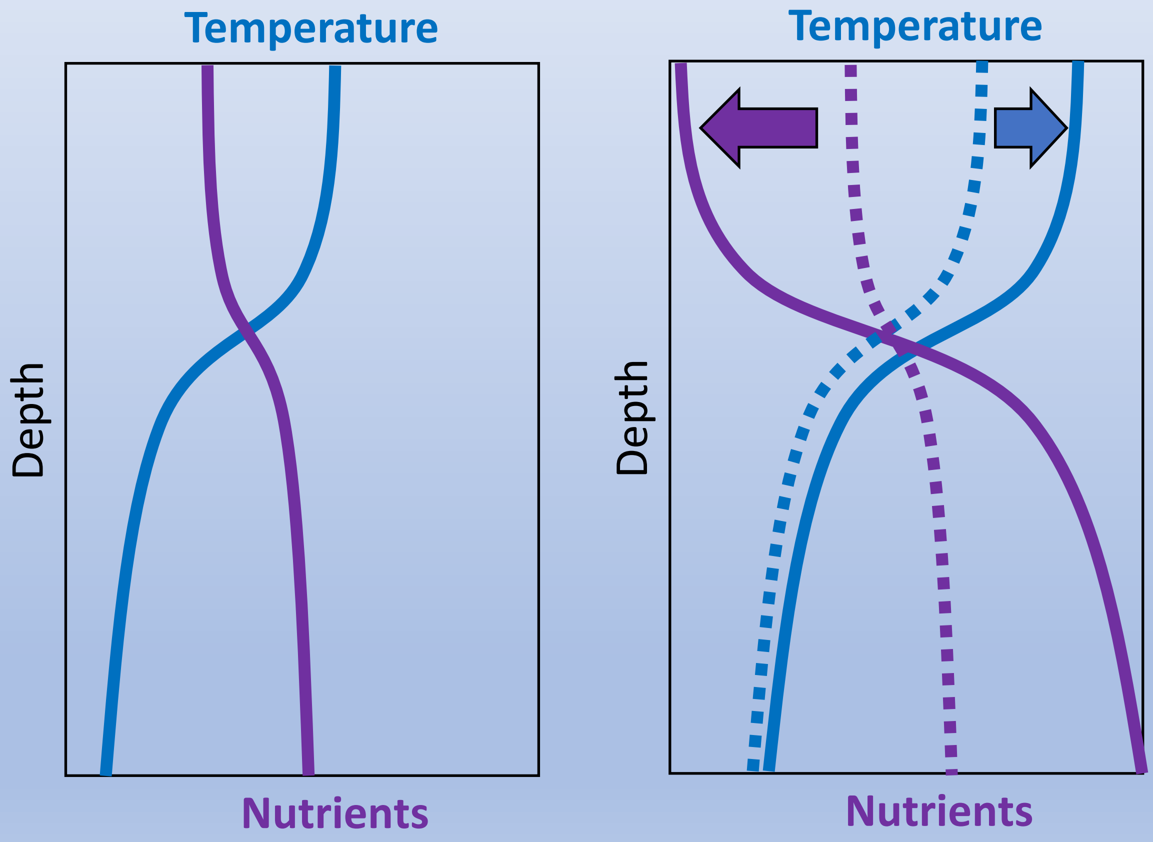
Distributions of standardized trend coefficients for bloom **magnitude** (annual mean chlorophyll-a concentration), **severity** (annual 95th percentile of chlorophyll-a concentrations), and **duration** (proportion of chlorophyll-a observations exceeding a region-specific impairment threshold).

Wilkinson et al., 2020, Frontiers in Ecology & the Env.

- **Hypothesis 1: Climate warming will increase lake productivity**



- **Hypothesis 2: Climate warming will decrease lake productivity**



Paerl and Huisman 2009, Environmental microbiology reports

E.g., Cohen et al., 2016, PNAS

How will climate warming* influence lake productivity?

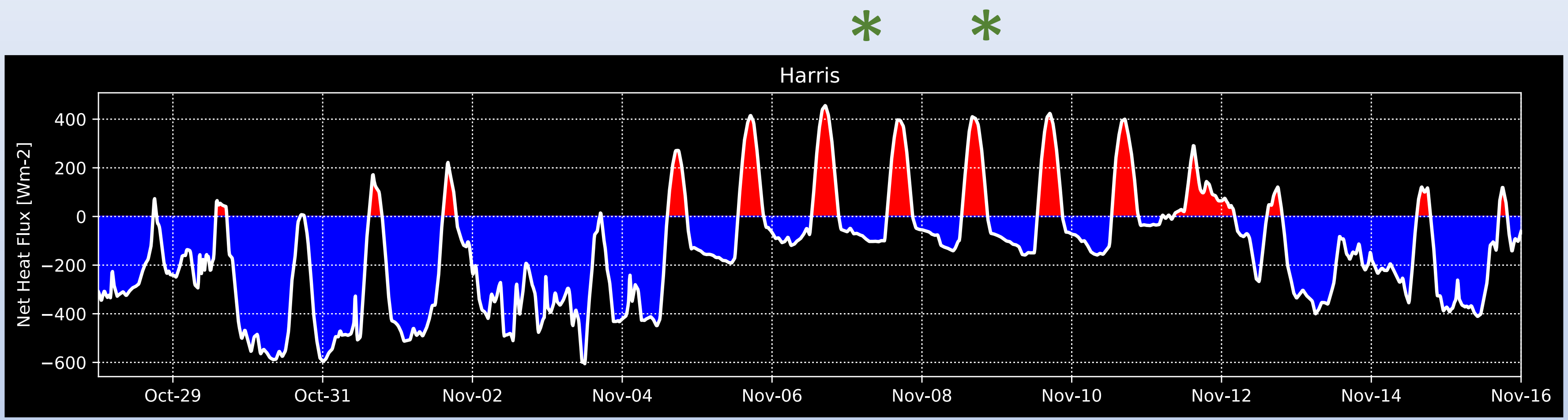
- **Hypothesis 1: Climate warming will increase lake productivity**
- Metabolic theory argues production will go up; all enzymatic processes are temperature dependent.
- Harmful algal blooms will become more prevalent due to stronger stratification, greater anoxia, and temperatures closer to thermal optima.

- **Hypothesis 2: Climate warming will decrease lake productivity**
- Hydrodynamics indicates that factors other than temperature will suppress primary production.
- Overall, productivity will decline due to increasing nutrient limitation associated with reduced mixing.

*Here, I focus just on warming. Other climate changes, such as in the amount, timing, or intensity of precipitation also matter a great deal. This gets complicated quickly!

Lake George HAB– November 7 & 9

- Net Heat Flux
  - Blue = lake is cooling
  - Red = lake is warming



- Turbulent Diffusion
  - ↑ Diffusion = Ease of mixing + entrainment leading up to HAB
  - ↓ Diffusion = restricted migration during HAB period