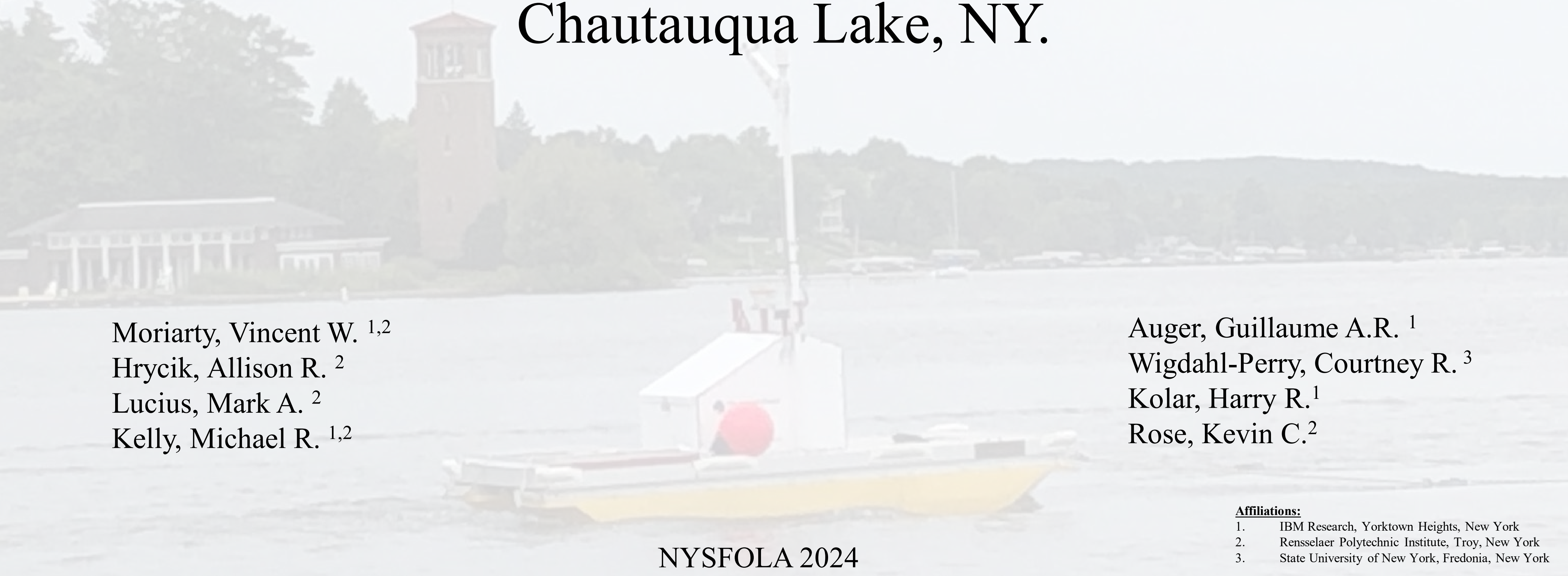
Episodic internal loading in a eutrophic lake: characterizing short-term nutrient fluxes using high-frequency sensor data in Chautauqua Lake, NY.



Moriarty, Vincent W. [1,2]
Hrycik, Allison R. [2]
Lucius, Mark A. [2]
Kelly, Michael R. [1,2]

Auger, Guillaume A.R. [1]
Wigdahl-Perry, Courtney R. [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. State University of New York, Fredonia, New York

NYSFOLA 2024

The Jefferson Project at Lake George

Rensselaer Polytechnic Institute · Knowledge and Thoroughness · 1824

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IBM Research

Internal Loading in Chautauqua Lake

- What are the important time scales associated with internal loading processes?
  - Chronic steady-state release (seasonal)
  - Acute pulses (hourly)

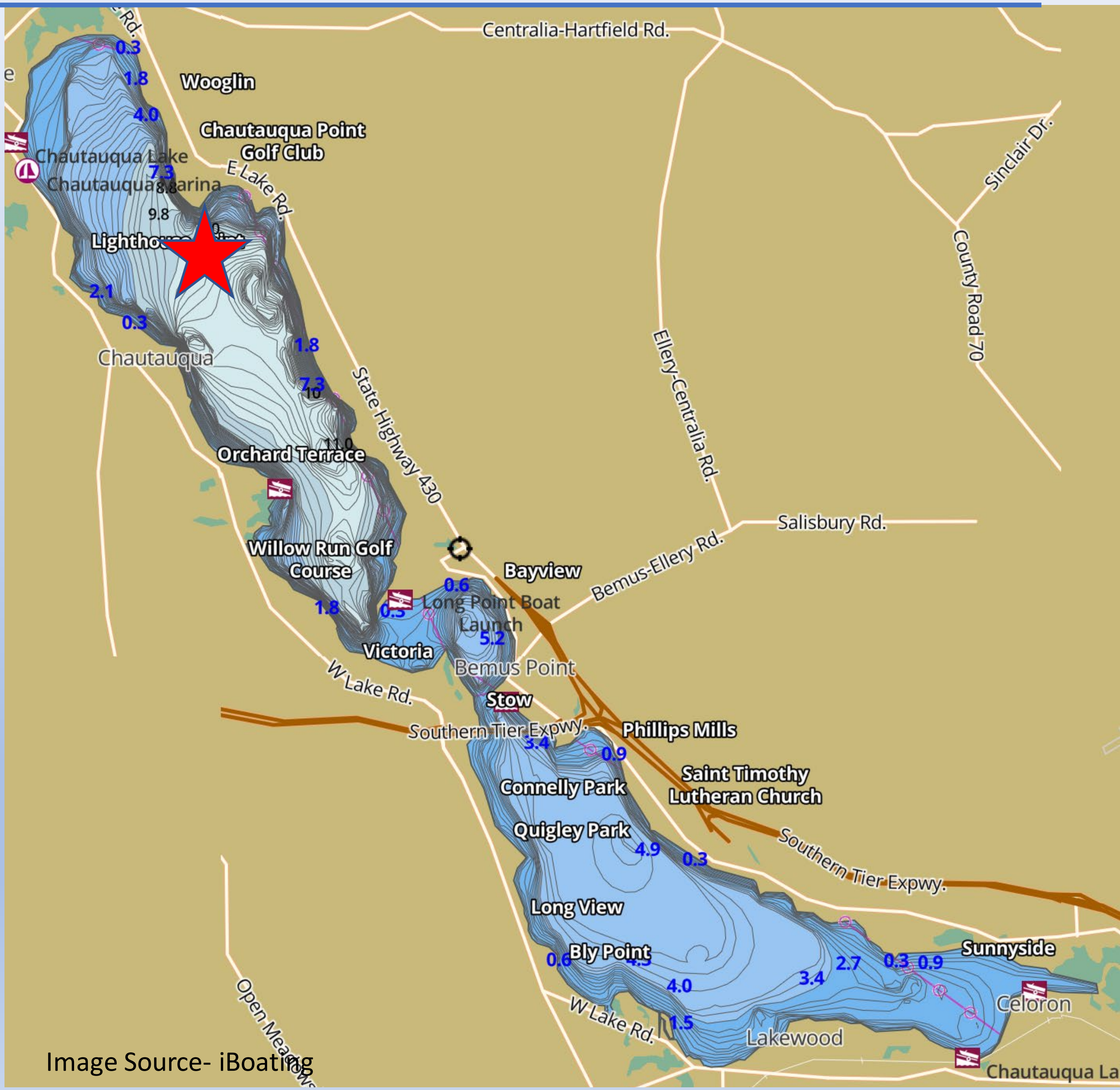
- Why does it matter?
  - How does the timing of nutrient release effect uptake by phytoplankton and other primary producers?

Chautauqua Lake

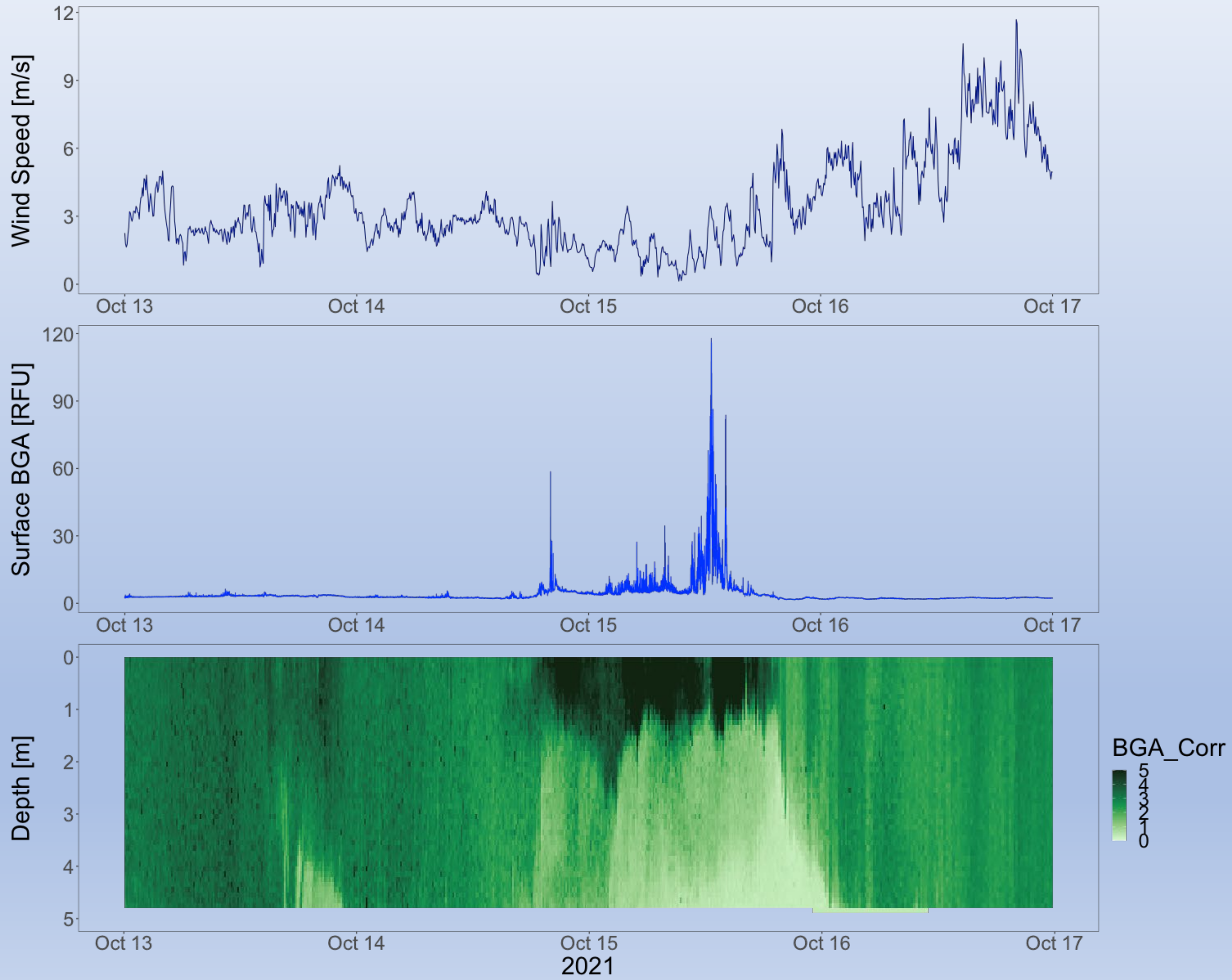
Image Source- NYDEC Harmful Algal Bloom Action Plan

Chautauqua Lake

- North Basin
  - Mean = 7.9m
  - Max = 22.9 m
  - Long-term seasonal stratification and anoxia
- South Basin
  - Mean = 3.3m
  - Max = 5.8m
  - Episodic stratification and anoxia
    - Mark Lucius previous talk

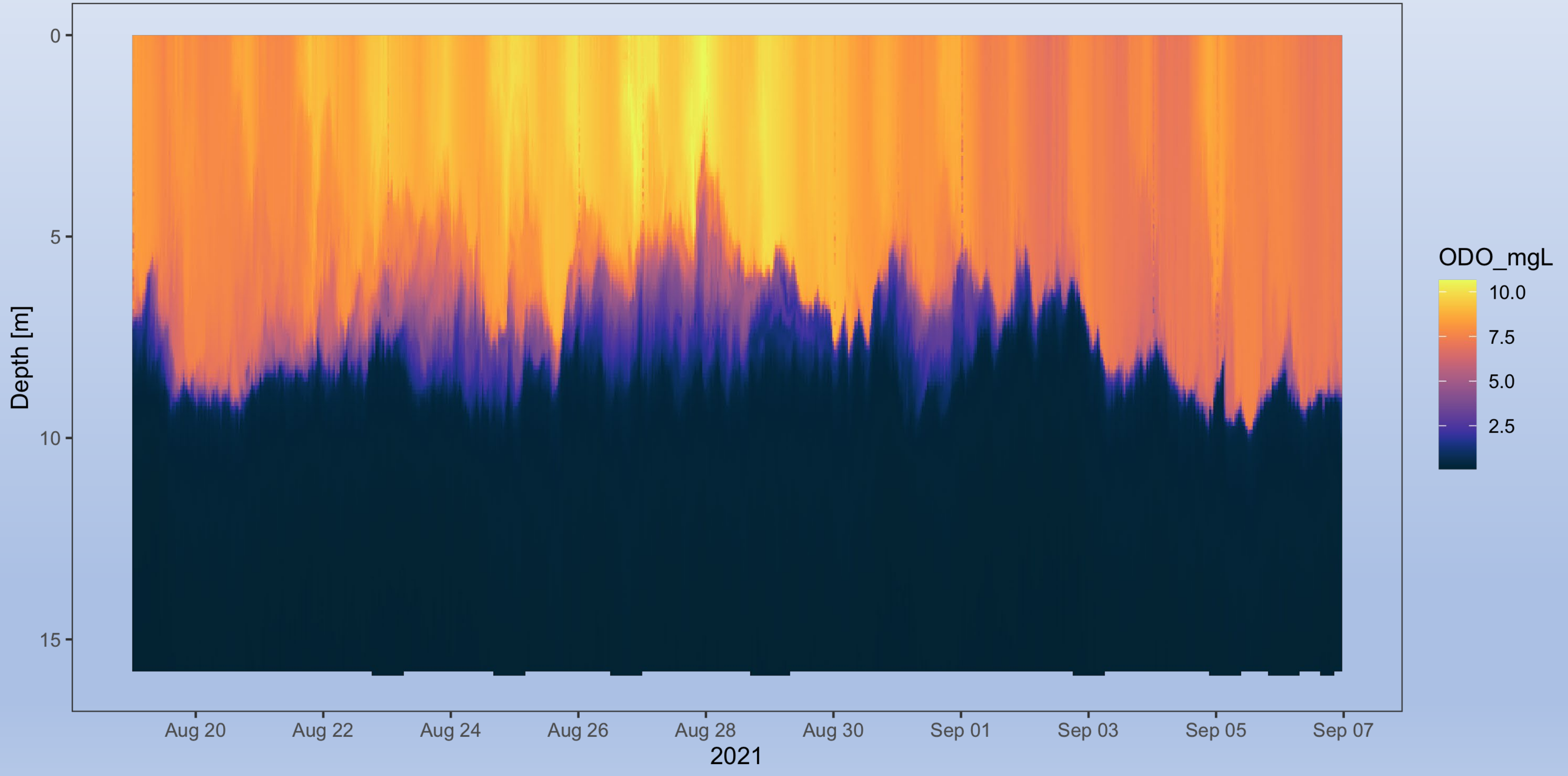


Data Collection



Internal Loading in the North Basin

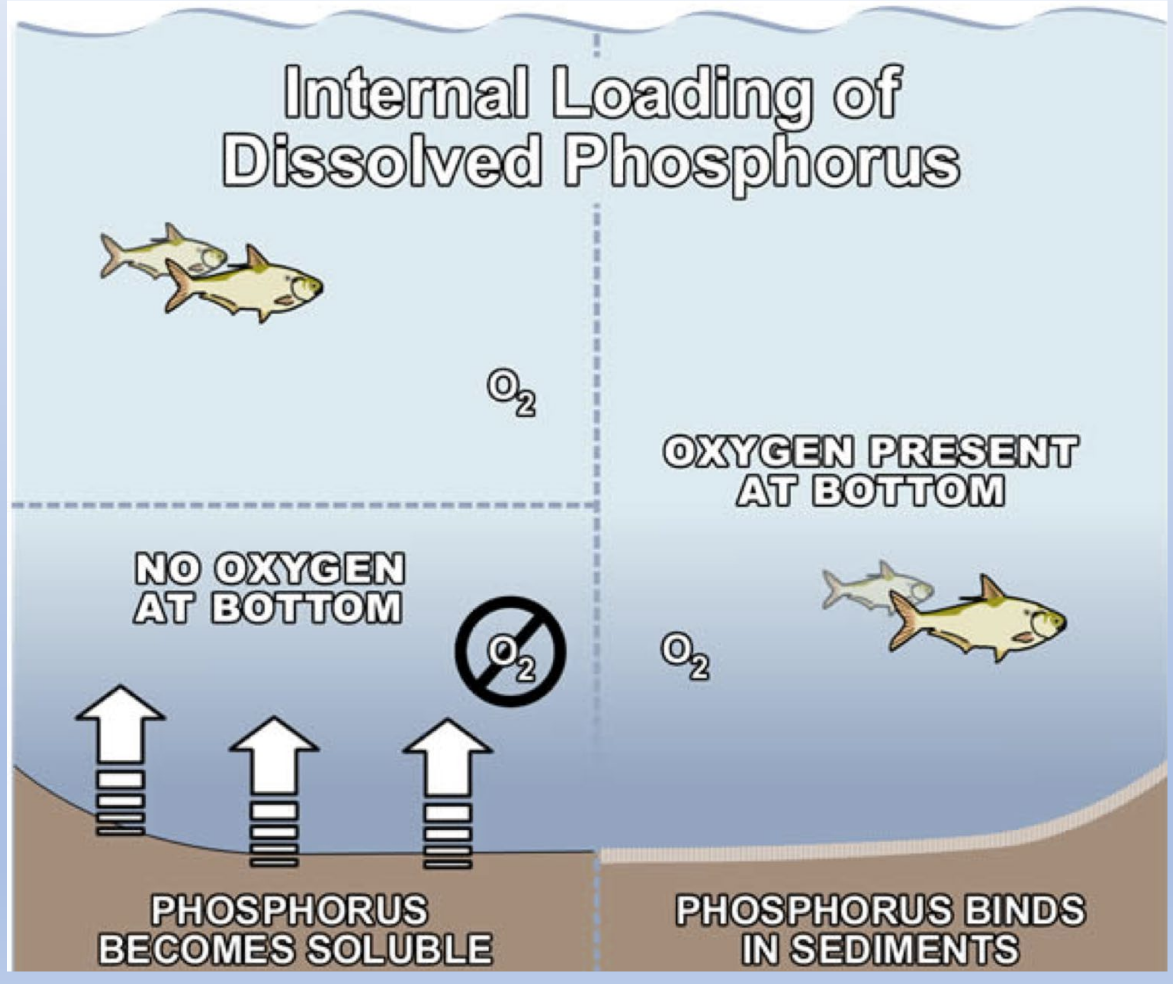
- Chronic anoxia at depth in North Basin



mob = meters off bottom

Internal Loading

- Phosphorus bound in sediments is released under anoxic conditions

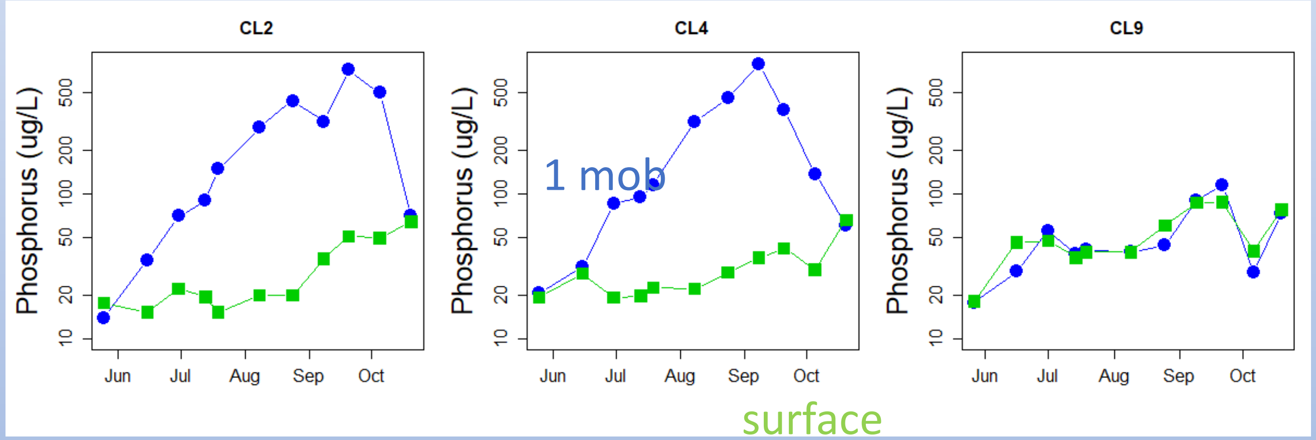


https://assets.ccaps.umn.edu/

Internal Loading in the North Basin

- Chronic anoxia at depth in North Basin
- Phosphorus bonded to iron oxyhydroxides in sediments
- Reductive dissolution in anoxic sediments → Release biologically available ortho-phosphate

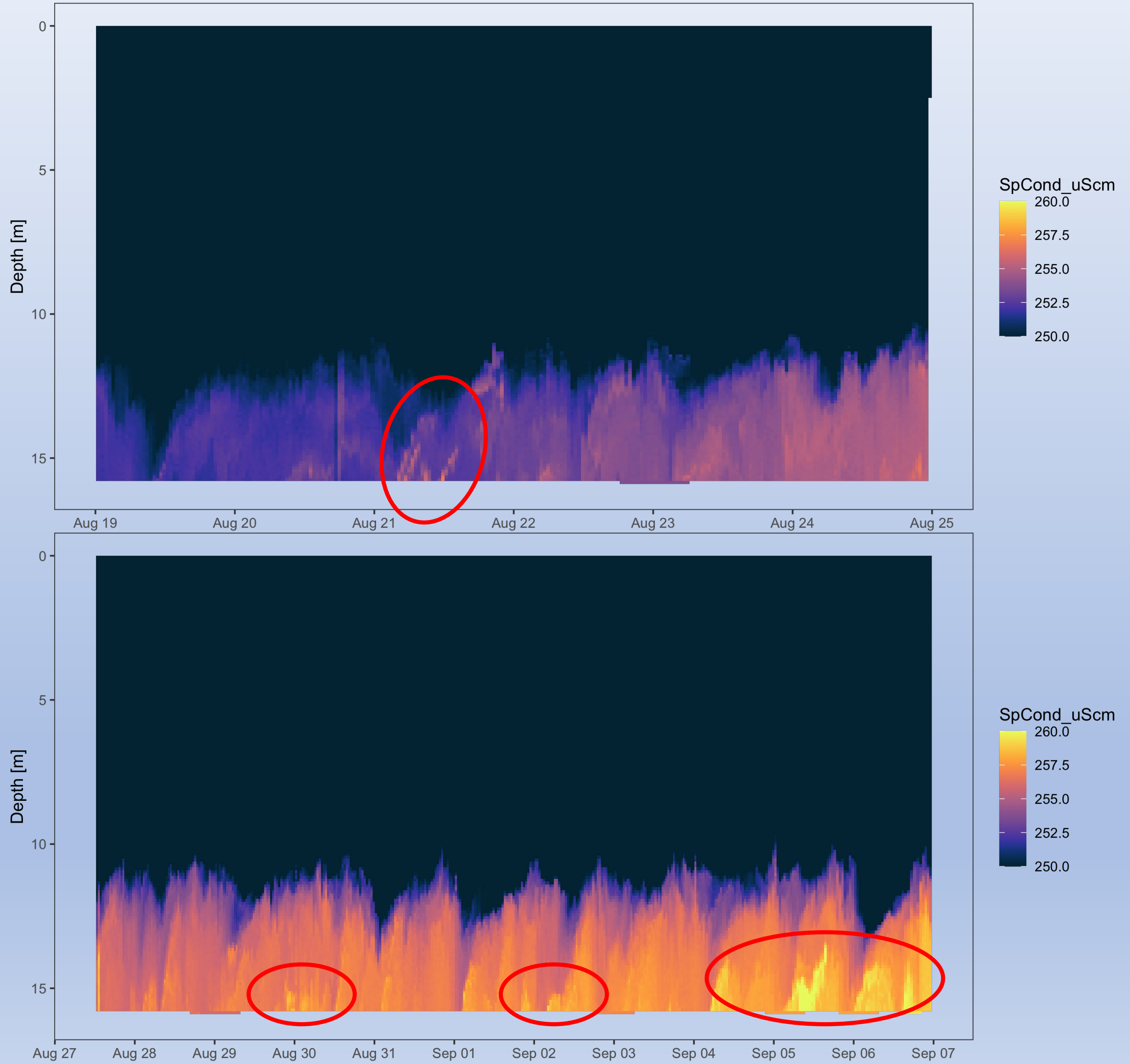
North Basin | Big Bar | South Basin



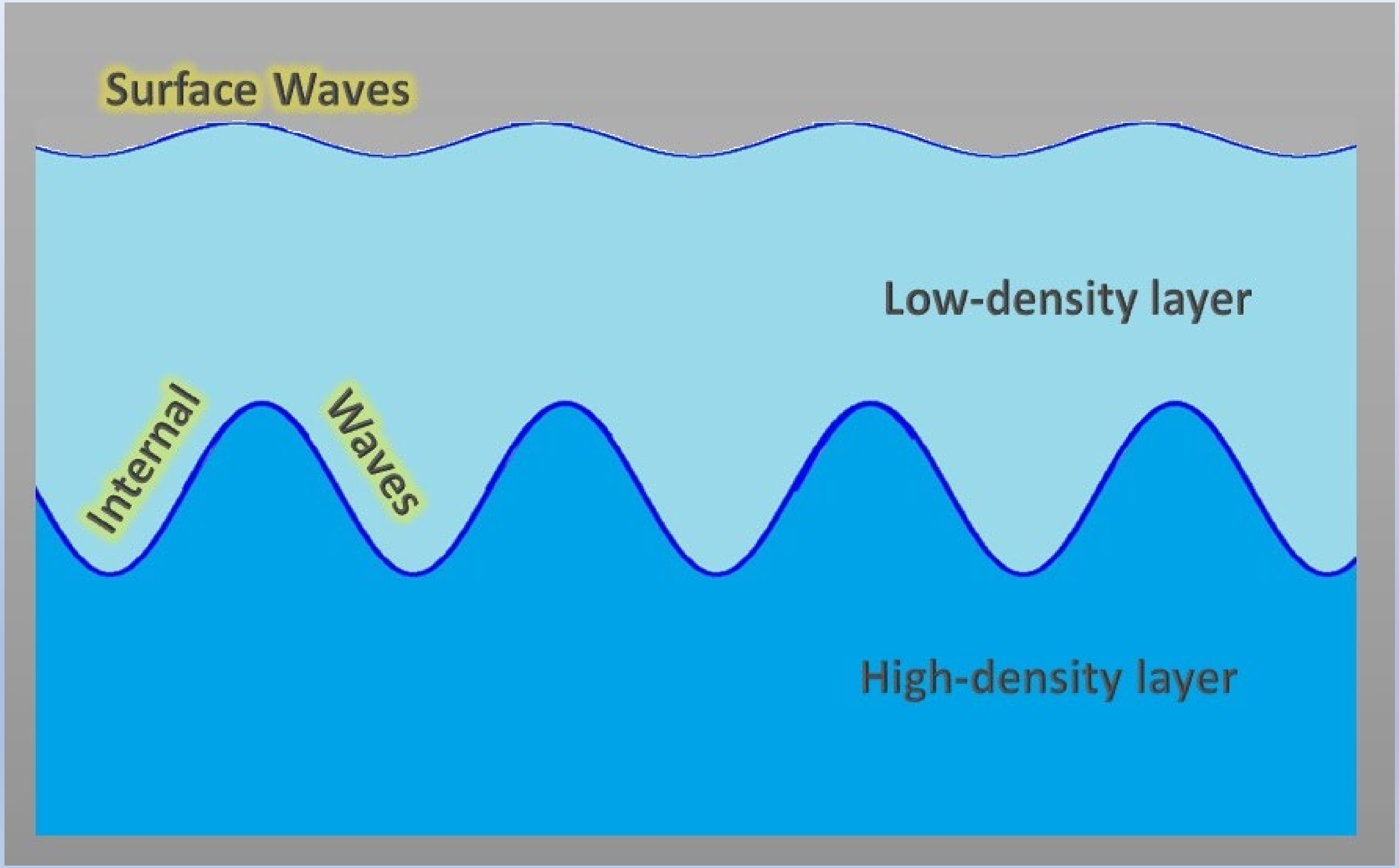
mob = meters off bottom

Internal Loading- pulse events vs chronic release

- Observed episodic increases in conductivity within hypolimnion
- Potential source of increased conductivity
  - ↑ P + ↓ O_2 + reduced products
  - Ferrous iron
  - Internal loading in "real-time"
- *Can we use specific conductance as a tracer to characterize episodic loading?*
- Conductivity is a generalized measure
  - Ability of water to pass an electrical current
  - Not just iron- any dissolved cation/ anion
- Sediment disturbance driving conductivity pulses



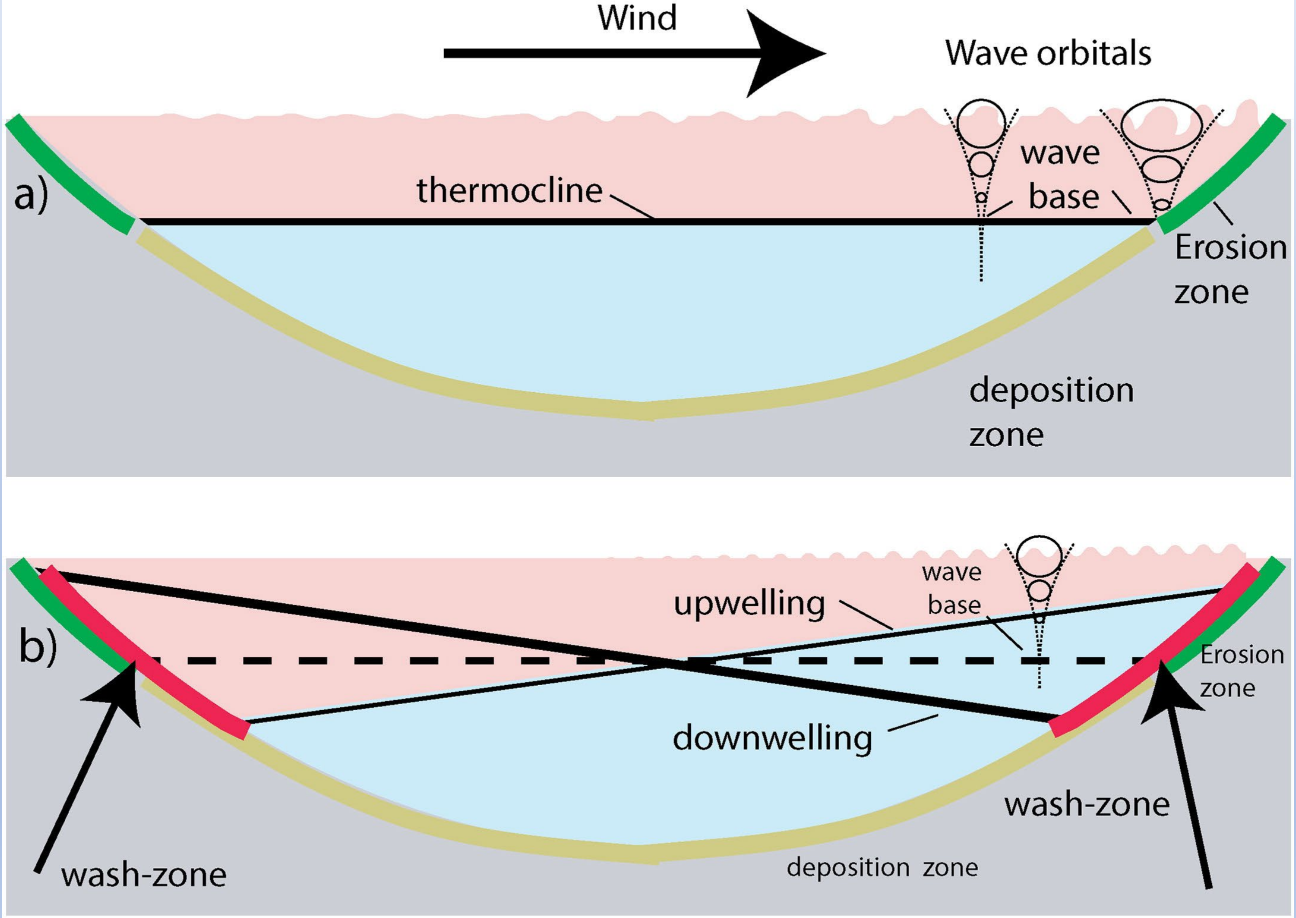
Internal Waves



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

Potential hydrodynamic drivers of pulsed internal loading

- Wash zone
    - Internal wave "crashing" as thermocline interacts with sediments
    - Mike Kelly
        - Skaneateles



Cossu et al. 2017

Potential hydrodynamic drivers of pulsed internal loading

- Wash zone
  - Internal wave “crashing” as thermocline interacts with sediments
  - Mike Kelly
    - Skaneateles
  - Wash zones interact with bathymetry (holes)
  - Migrate with thermocline depth

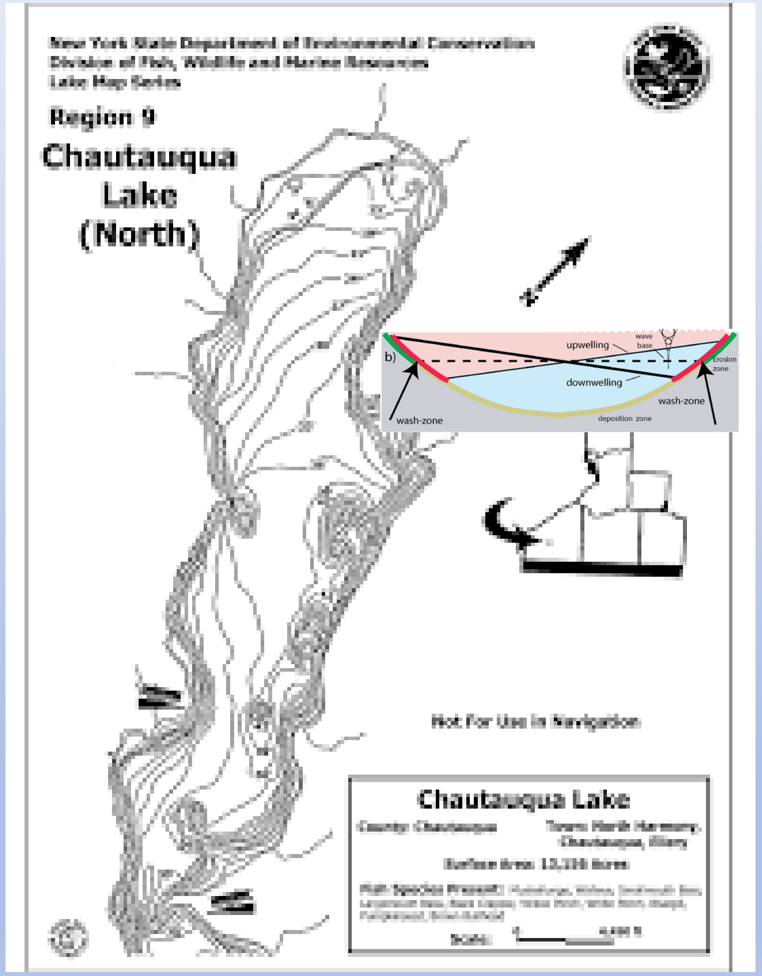


Image Source - NYDEC

Potential hydrodynamic drivers of pulsed internal loading

What might be driving increases in conductivity associated with bottom sediments?

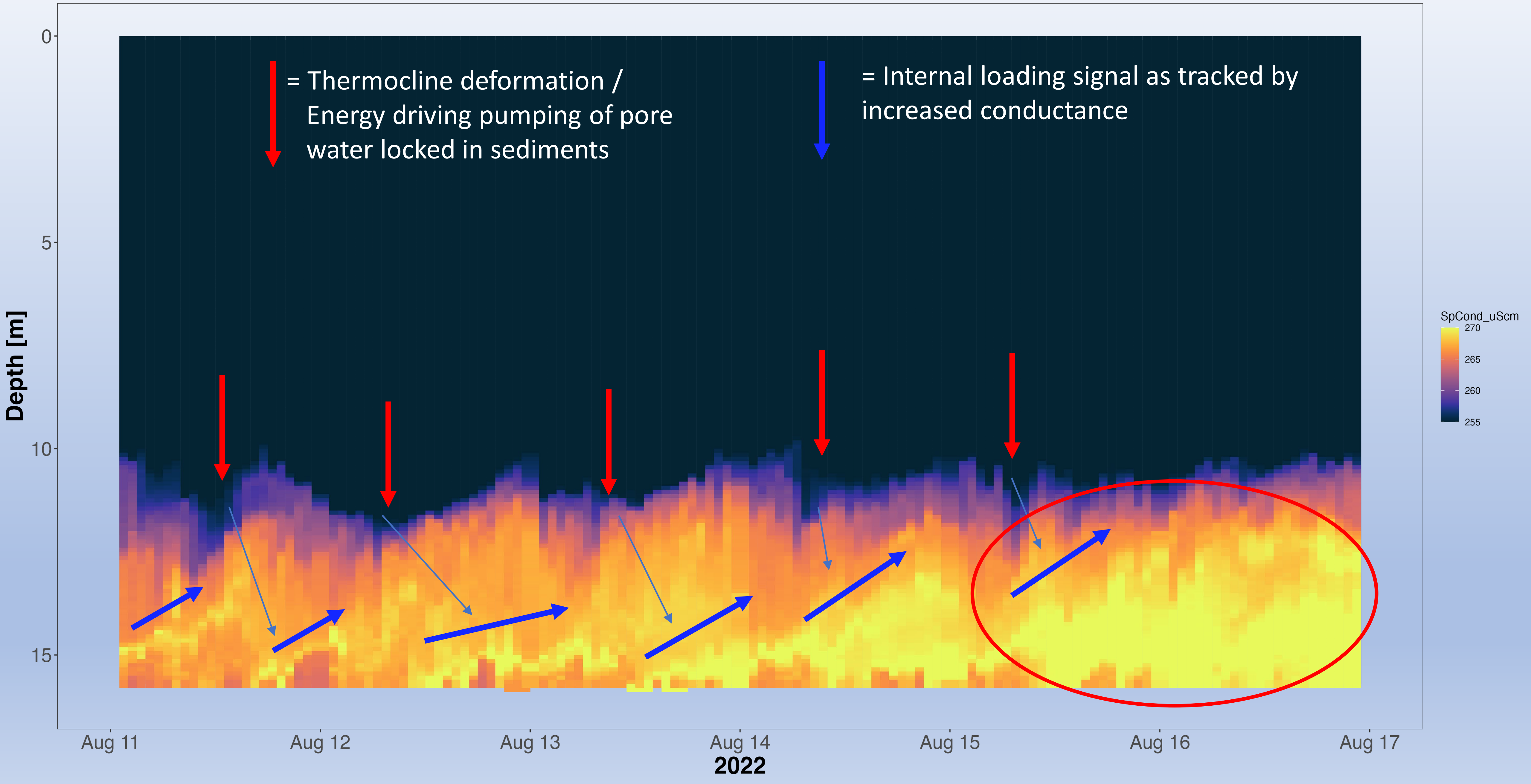
"Advective pore-water exchange driven by surface gravity waves and its ecological implications"
Precht & Huettel 2003

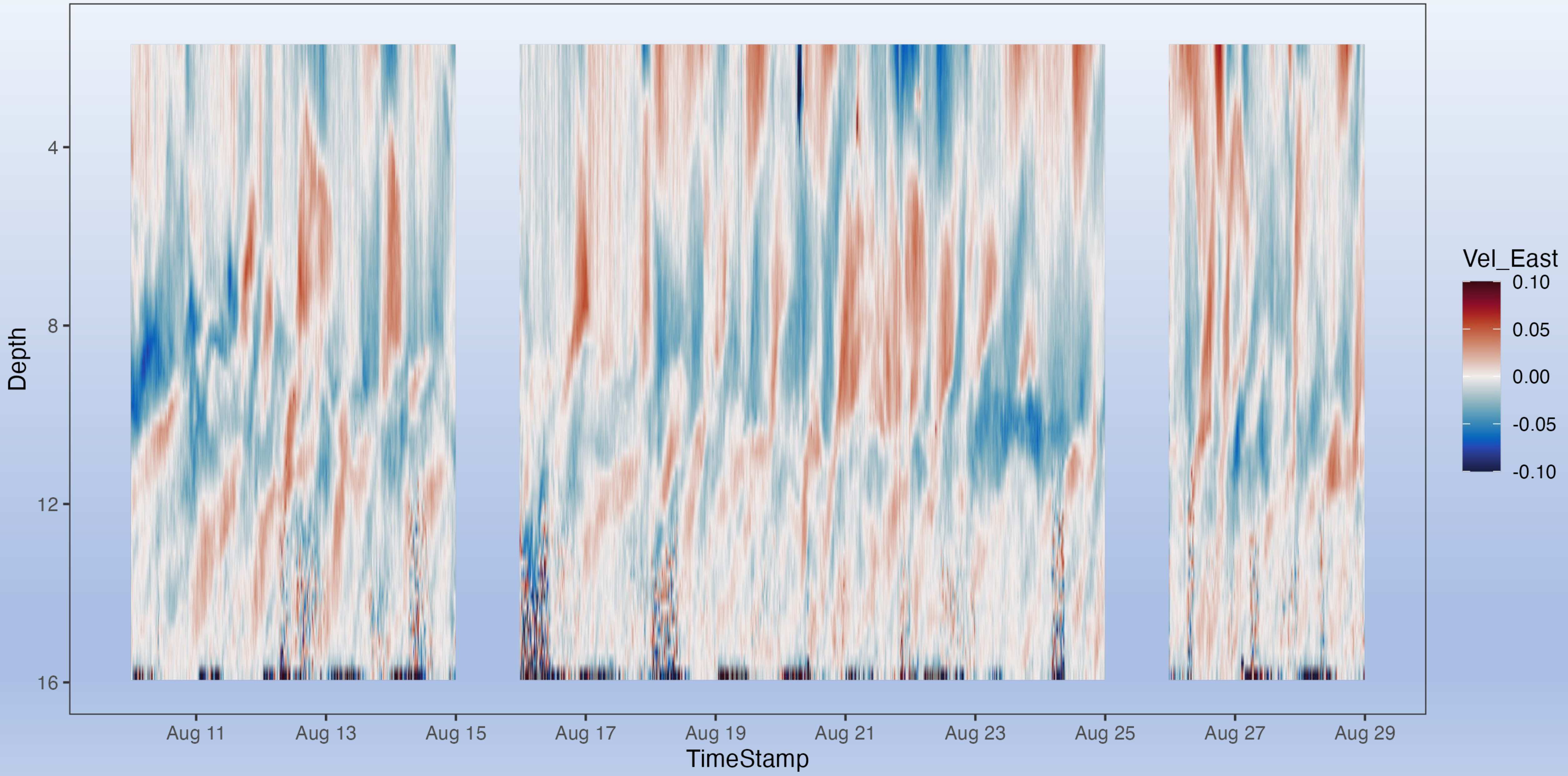
"Our tracer experiments demonstrated that shallow-water waves can *increase fluid exchange between sandy sediment and overlying water 50-fold*, relative to the exchange by molecular diffusion. The main driving force for this increased exchange are the pressure gradients generated by the interaction of oscillating boundary flows and sediment wave ripples."

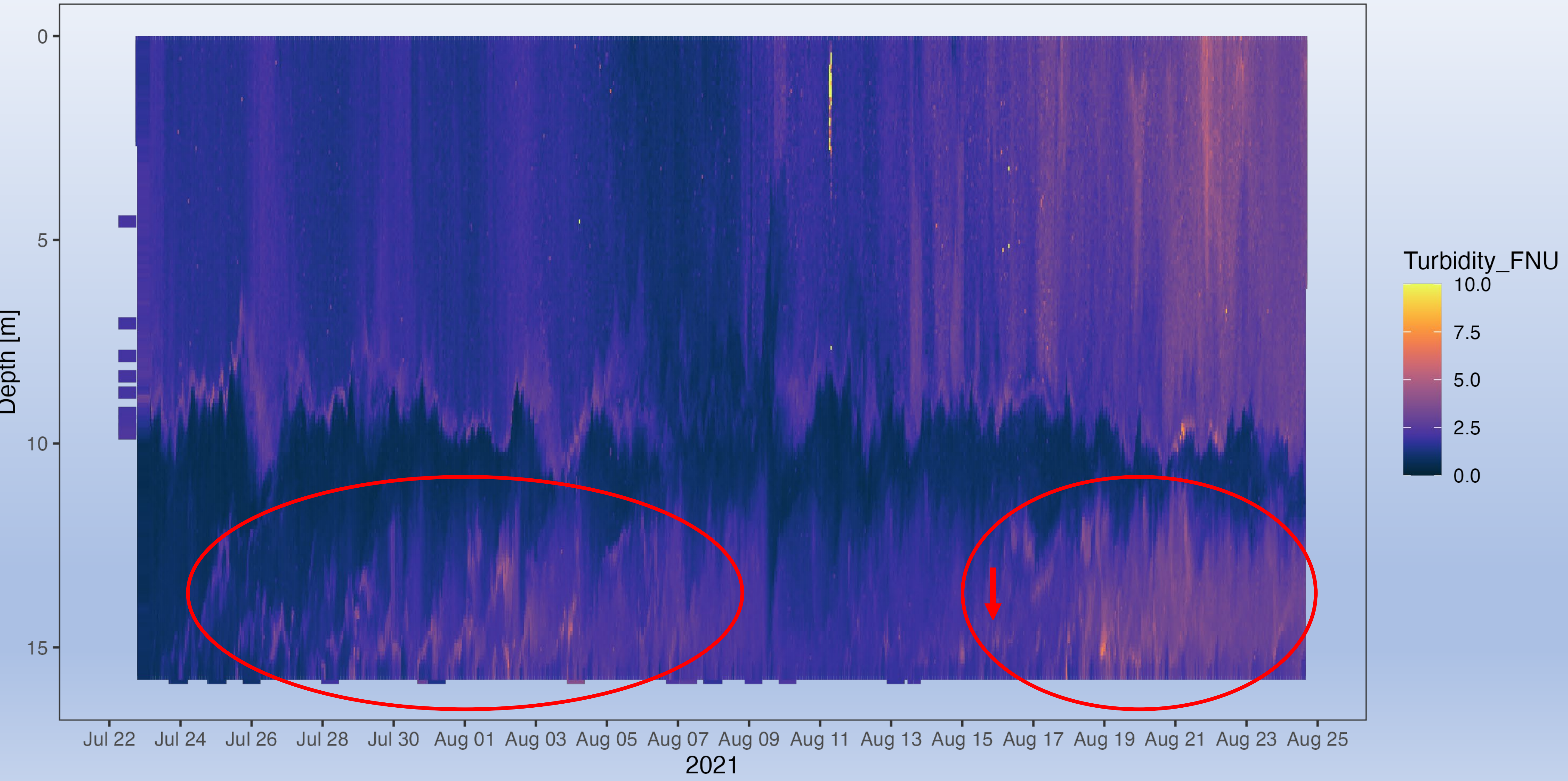
Table 1 Drivers of pore-water exchange in permeable shelves and associated conservative flushing rates for the global shelf, calculated per meter of shoreline (from Santos et al. 2012b)

Driver	Flushing rate ($m^3\ m^{-1}\ d^{-1}$)
Tidal pumping (including pumping through barriers)	4
Wave setup at beach faces	6
Groundwater seepage	10
Density-driven exchange (convection)	10
Shear (Brinkman layer)	100
Bioirrigation (pumping by sedimentary animals)	300
Ripple migration	340
Wave pumping	380
Flow-topography interaction	1,000
Total	2,150

Can we use SpCond as a proxy measurement/ evidence of a *nutrient pump* and internal loading?

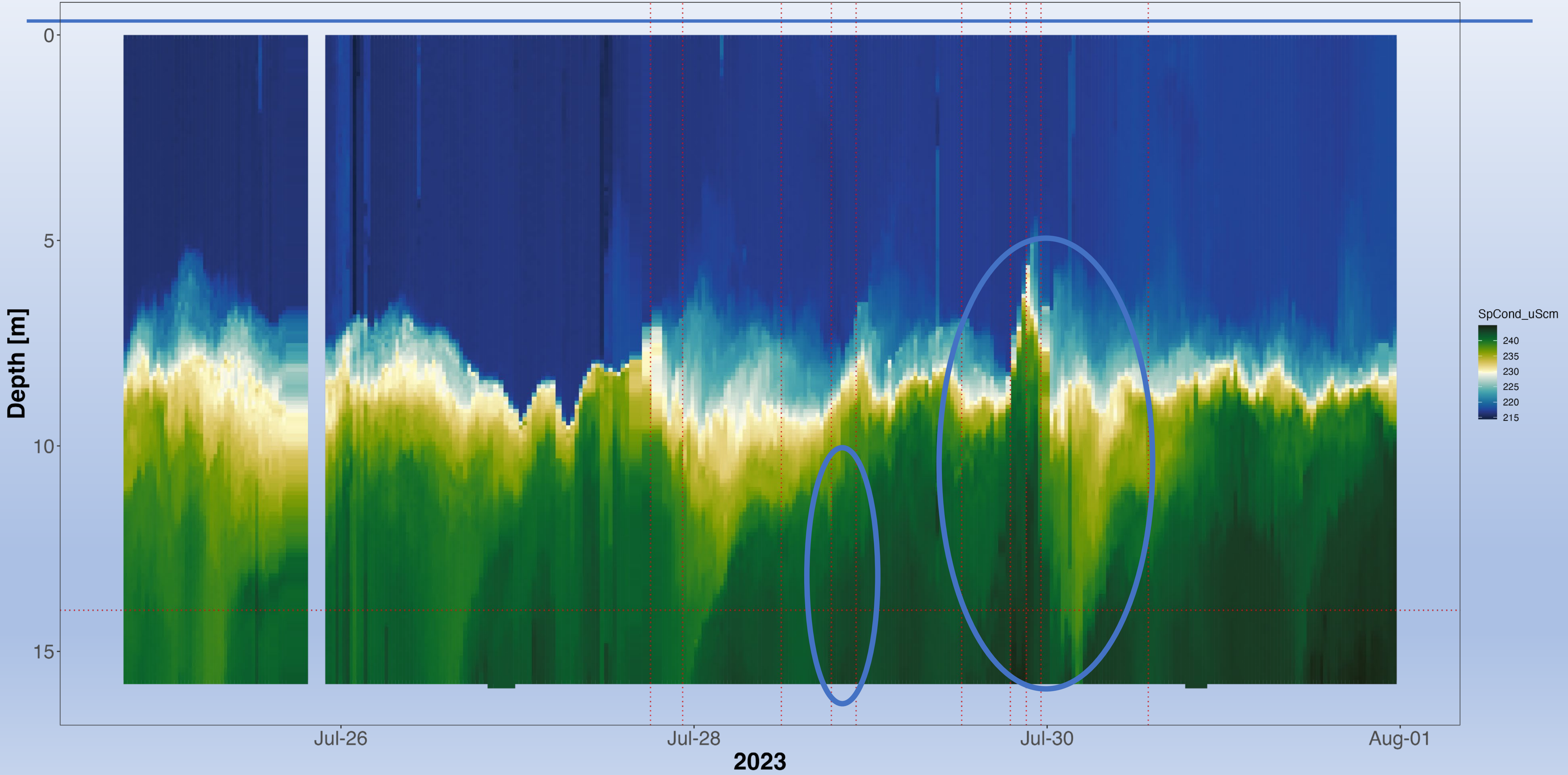



Depth
4
8
12
16
Aug 11
Aug 13
Aug 15
Aug 17
Aug 19
Aug 21
Aug 23
Aug 25
Aug 27
Aug 29
TimeStamp
Vel_East
0.10
0.05
0.00
-0.05
-0.10



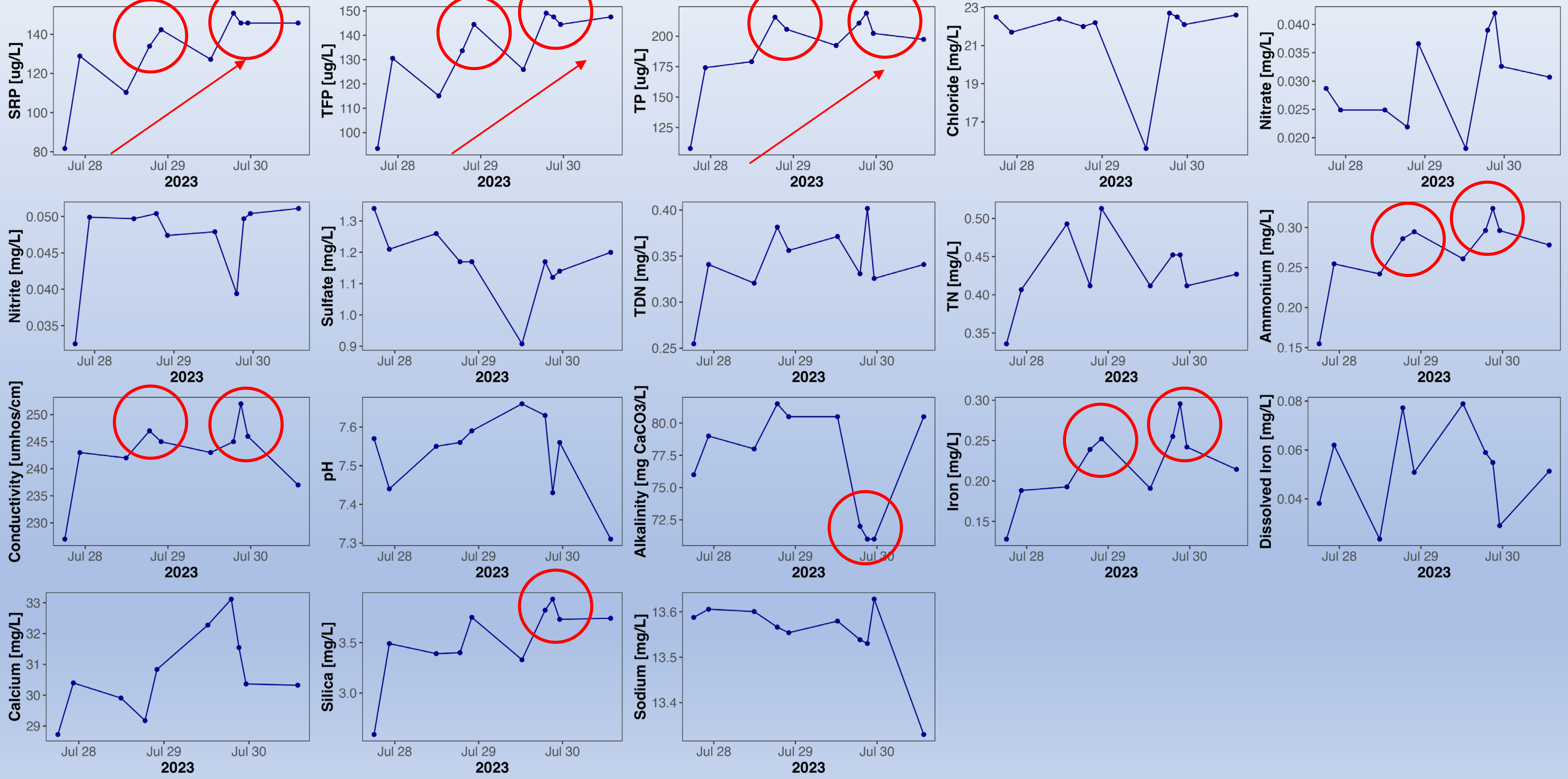
Turbidity_FNU
10.0
7.5
5.0
2.5
0.0
Depth [m]
0
5
10
15
Jul 22
Jul 24
Jul 26
Jul 28
Jul 30
Aug 01
Aug 03
Aug 05
Aug 07
Aug 09
Aug 11
Aug 13
Aug 15
Aug 17
Aug 19
Aug 21
Aug 23
Aug 25
2021

Pulsed Internal Loading



DID NOT collect
Silver
603
602
1
2
3
4
5
7
8
11

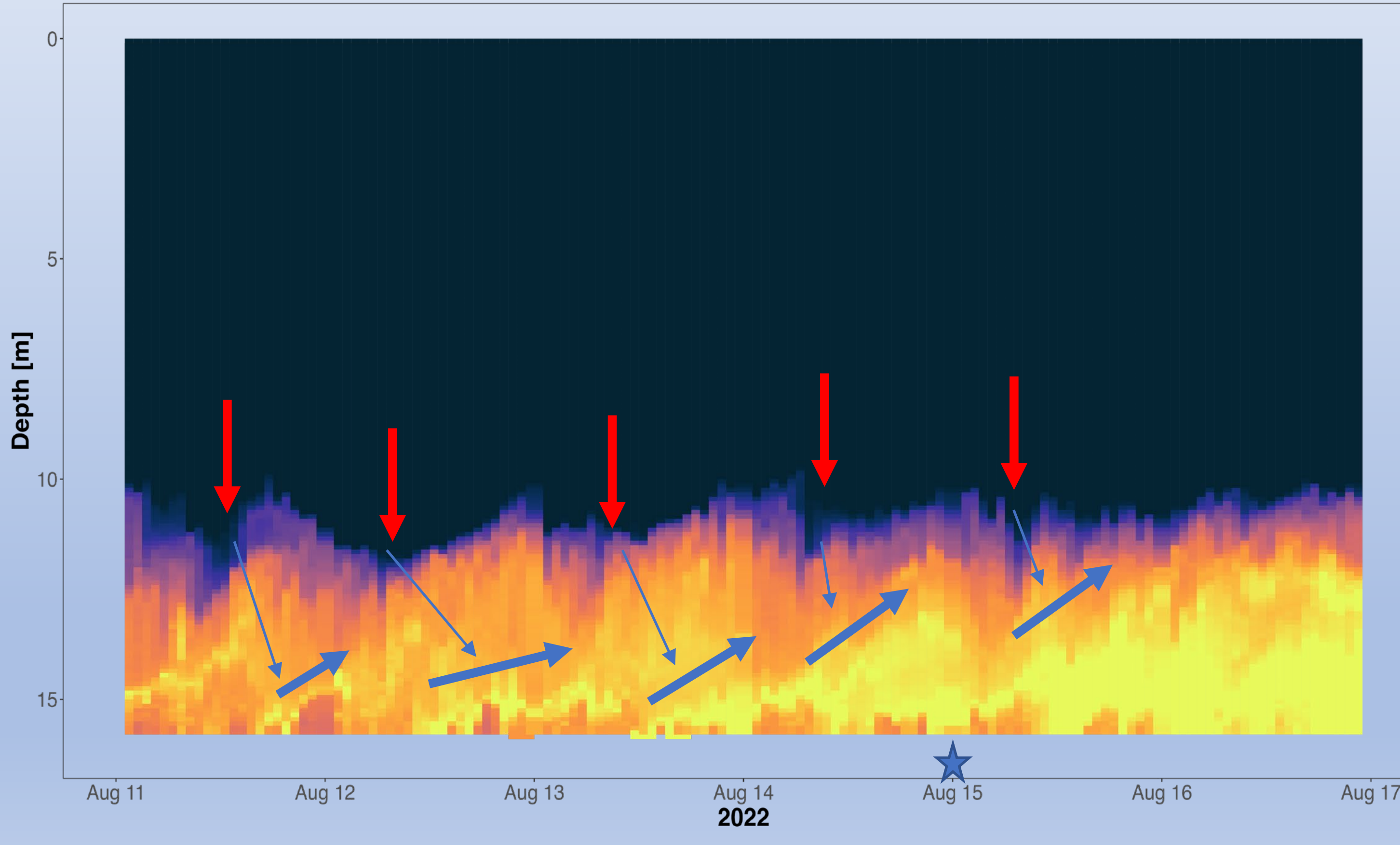
Pulsed Internal Loading



Pulsed Internal Loading

- Timing of conductivity pulses are coincident with observed internal waves

- Timing of conductivity pulses is coincident with increases in multiple analytes, including Iron and different forms of phosphorus



Pulsed Internal Loading

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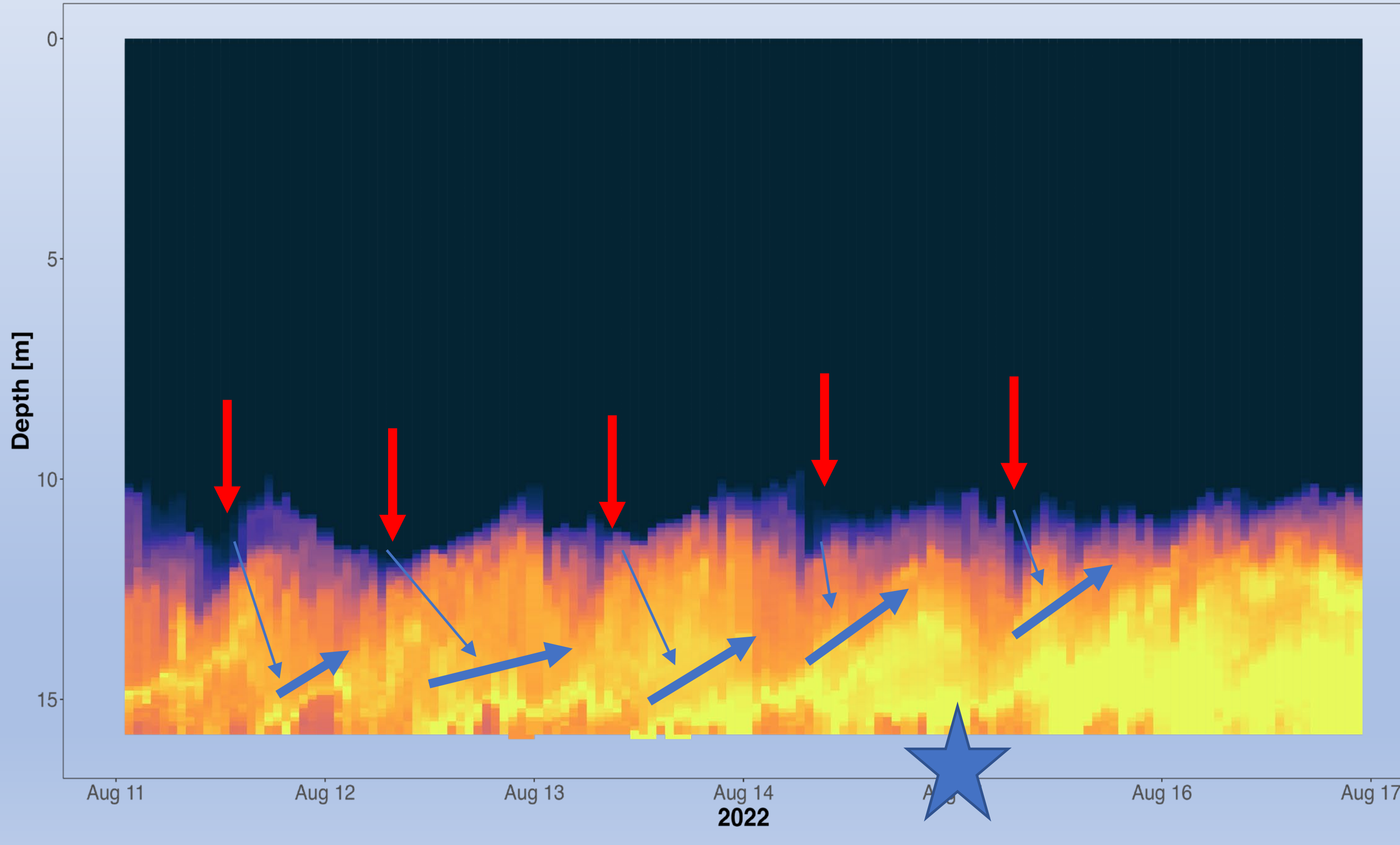
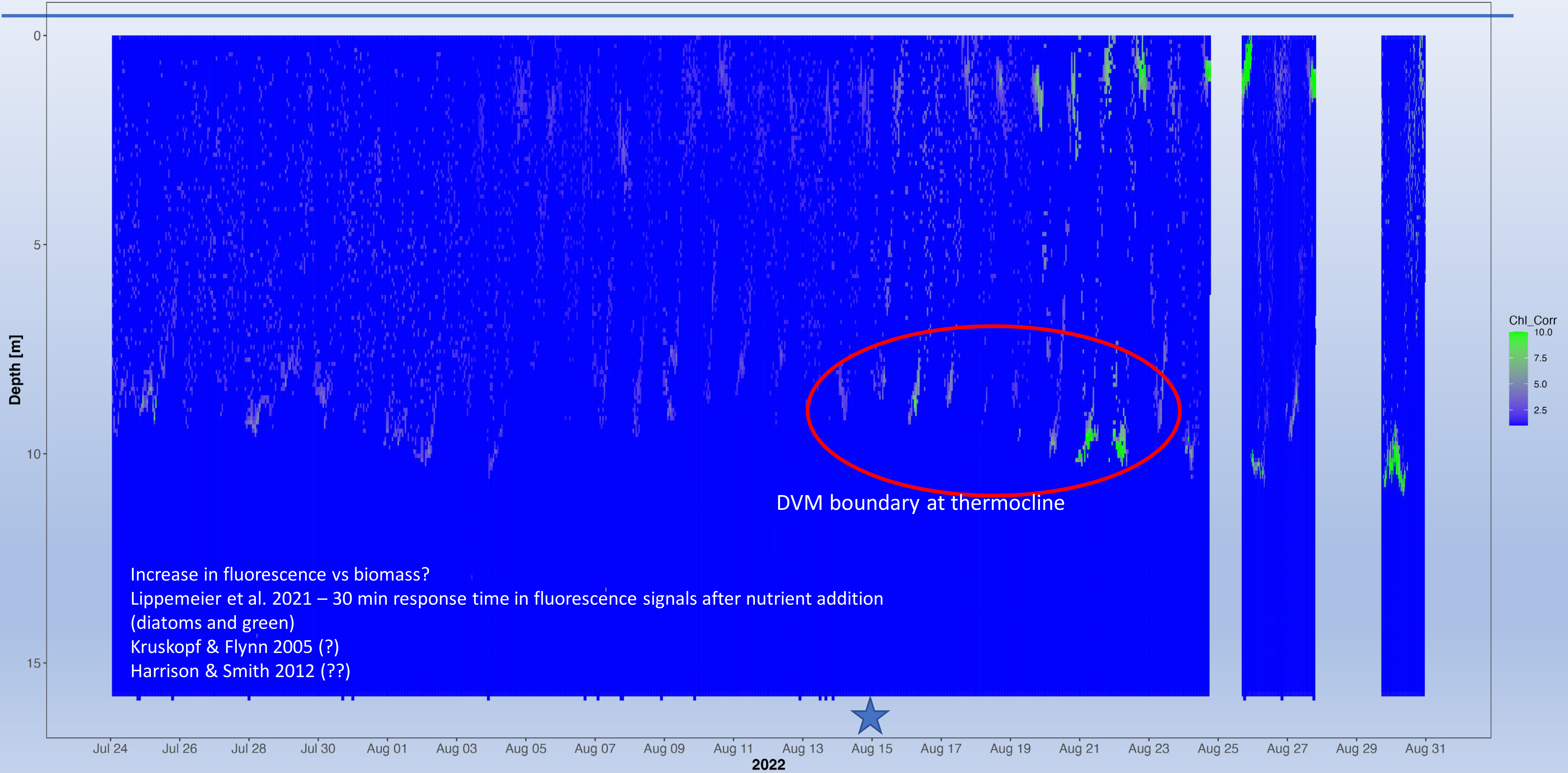
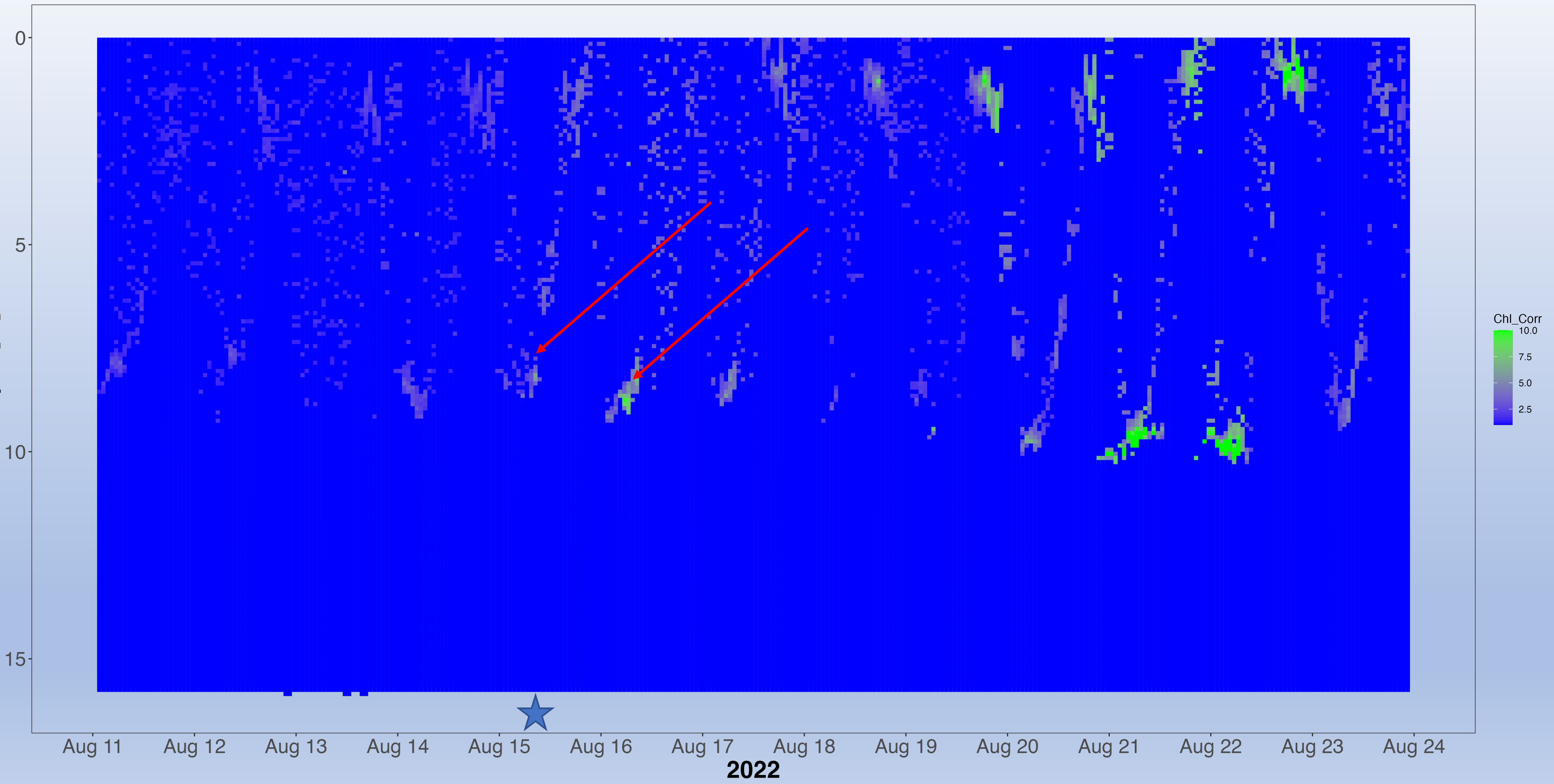
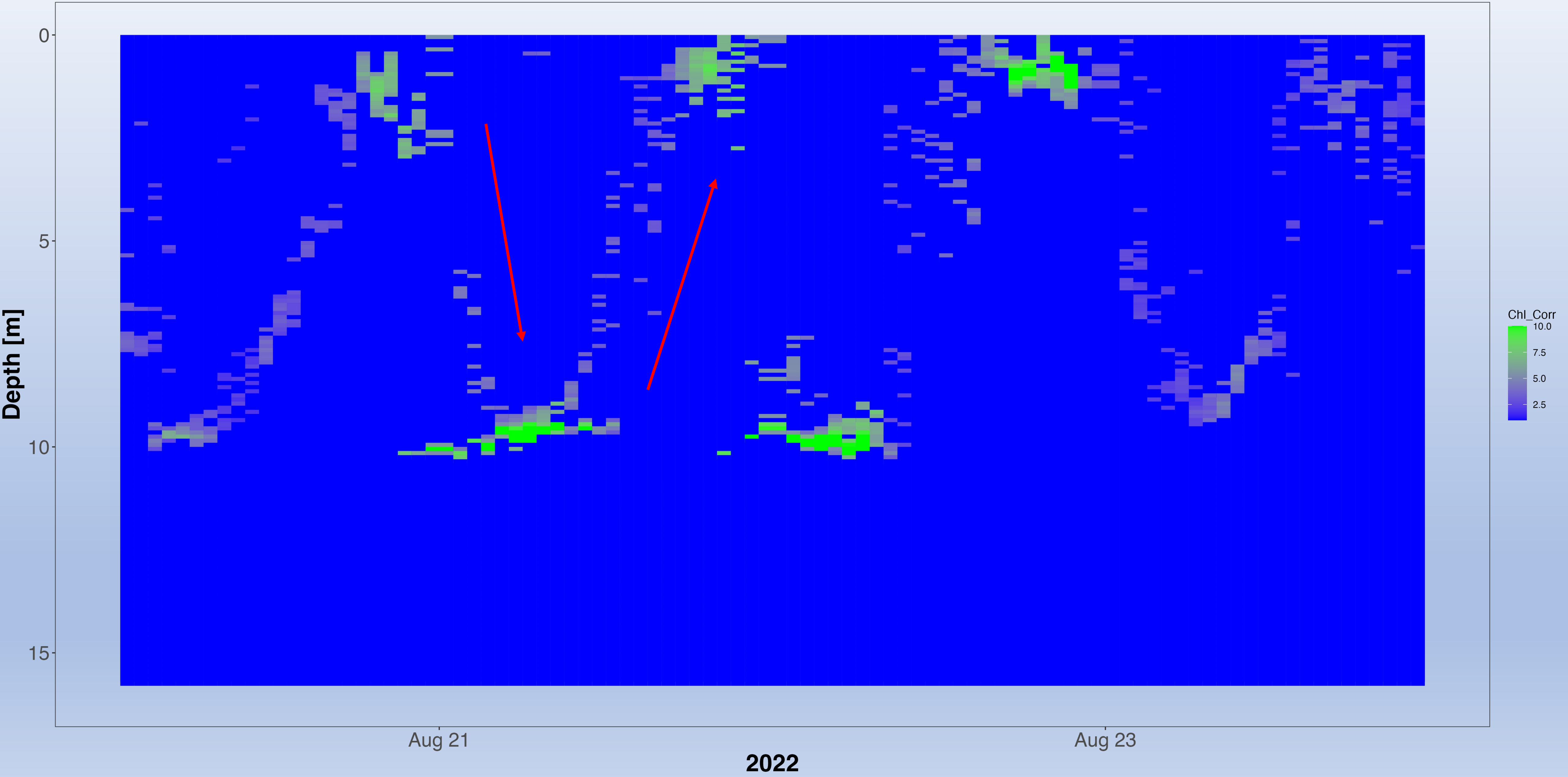


Implications for Phytoplankton Ecology

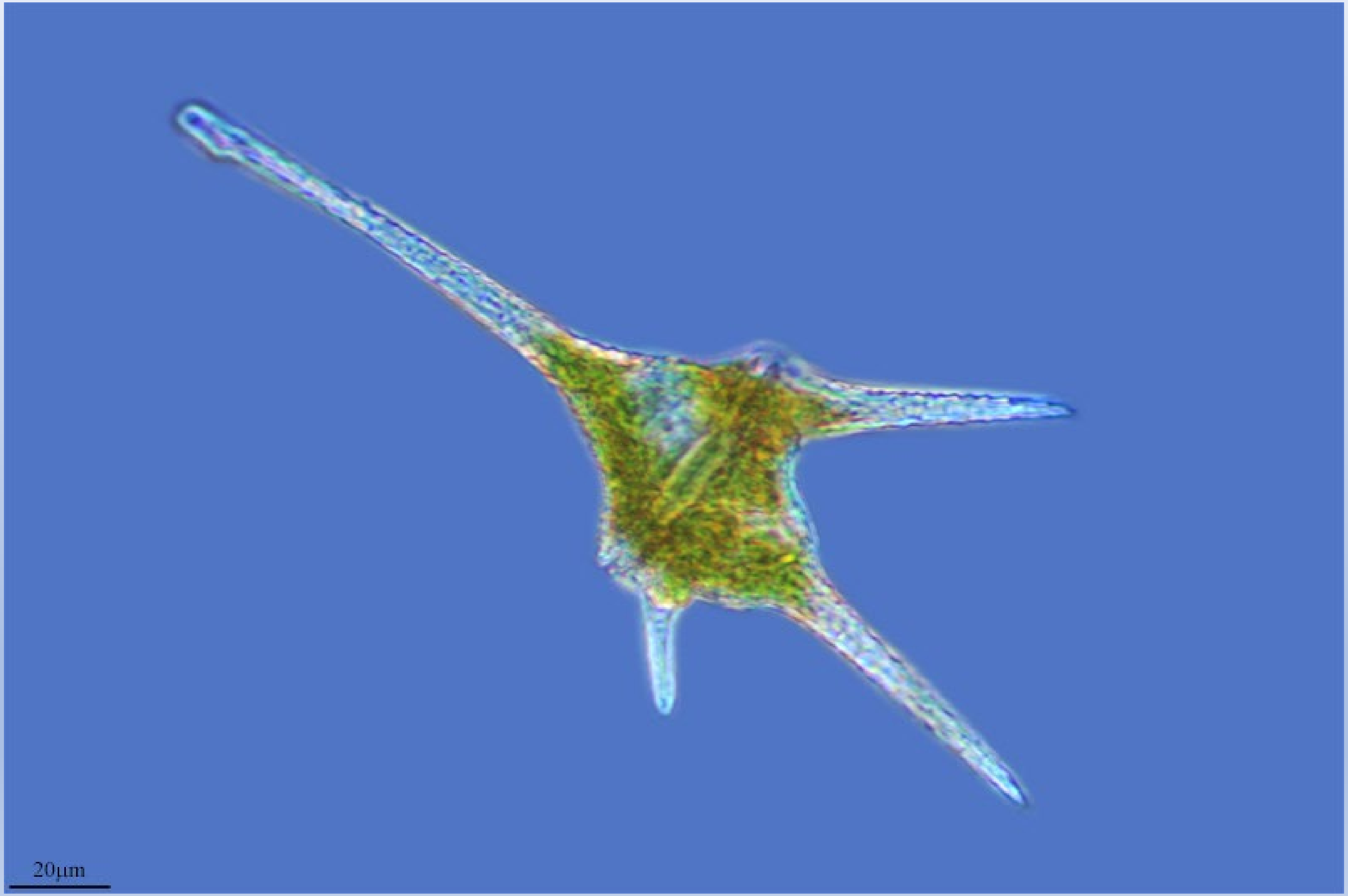



0
5
10
15
Aug 11
Aug 12
Aug 13
Aug 14
Aug 15
Aug 16
Aug 17
Aug 18
Aug 19
Aug 20
Aug 21
Aug 22
Aug 23
Aug 24
2022
Chl_Corr
10.0
7.5
5.0
2.5



0
5
10
15
Depth [m]
Aug 21
Aug 23
2022
Chl_Corr
10.0
7.5
5.0
2.5

Ceratium hirundinella

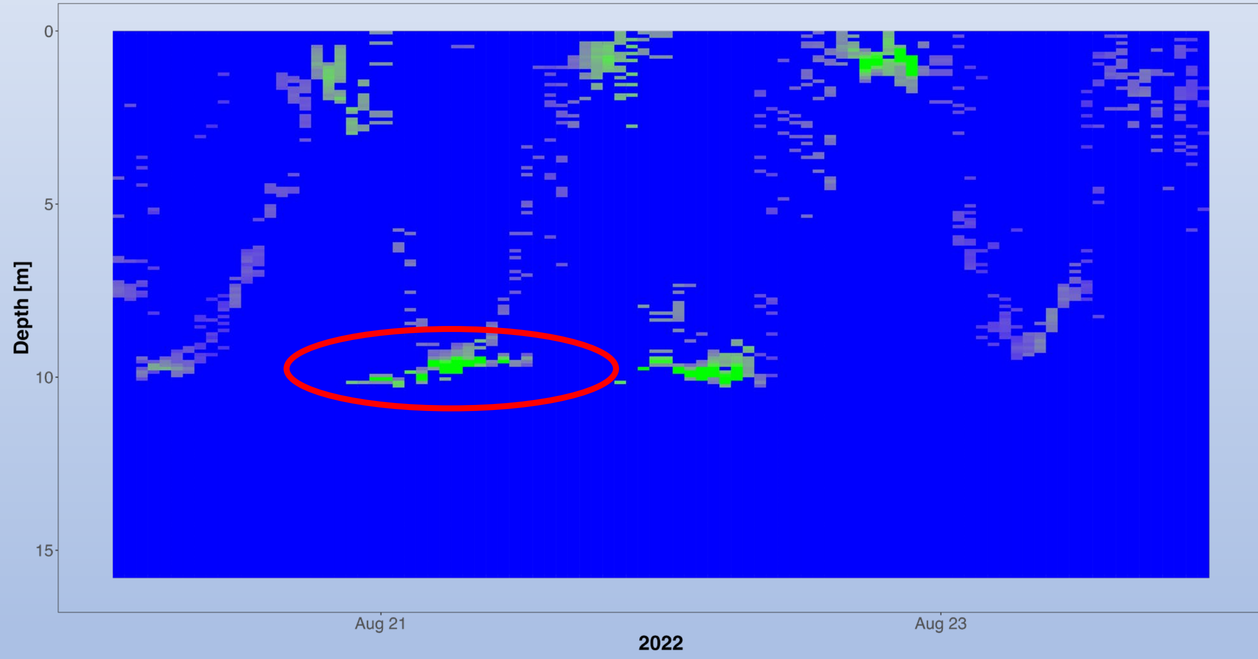


https://www.inaturalist.org/taxa/345252-Ceratium-hirundinella

Ceratium hirundinella

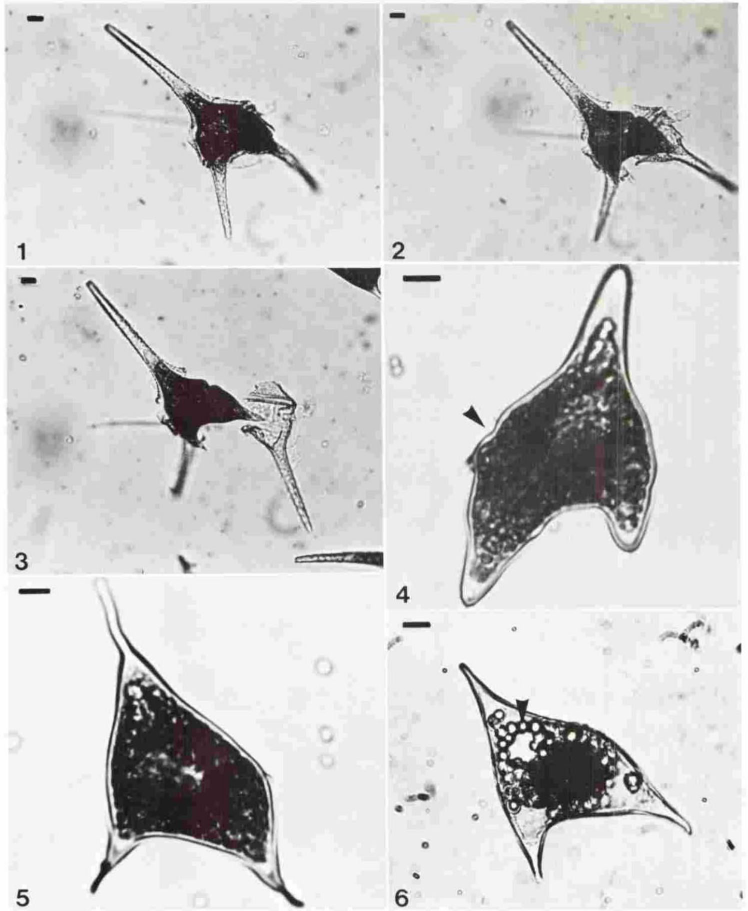
- Dinoflagellate (mixotroph)

- DVM
  - Oxycline is barrier to DVM
  - Diurnal microstratification just above oxycline



Ceratium hirundinella

- Overwinter cysts
  - Mass encystment or sudden lysis late in season
  - Associated with turnover



FIGS. 1–6. Cyst formation in *Ceratium hirundinella*. Scale bars = 10 μm. FIGS. 1–3. The dark cyst within the theca is released by bursting open the wall which then falls away. FIG. 4. The newly released cyst is conspicuous by its rounded horns and an impression left by the girdle around the middle (arrow). FIG. 5. A fully formed smooth-walled cyst from Blelham Tarn. FIG. 6. A dormant, granular-walled cyst from Esthwaite Water. The chloroplasts have migrated to the center of the cyst and are surrounded by lipid globules (arrow).

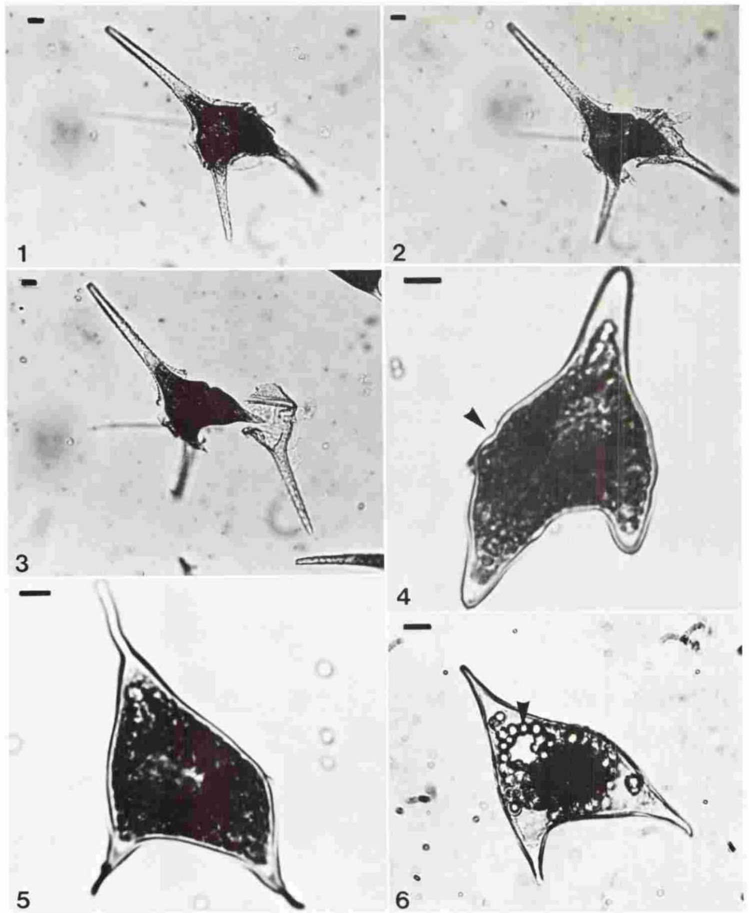
Heaney 1976, Talling 1971, Pollingher 1993

Chapman et al 1982

Ceratium hirundinella

- Ceratium as nutrient pump
  - Seasonal pump
    - Overwinter cysts absorb "luxury" nutrients from sediments and rise to epi
    - 5x increase in P

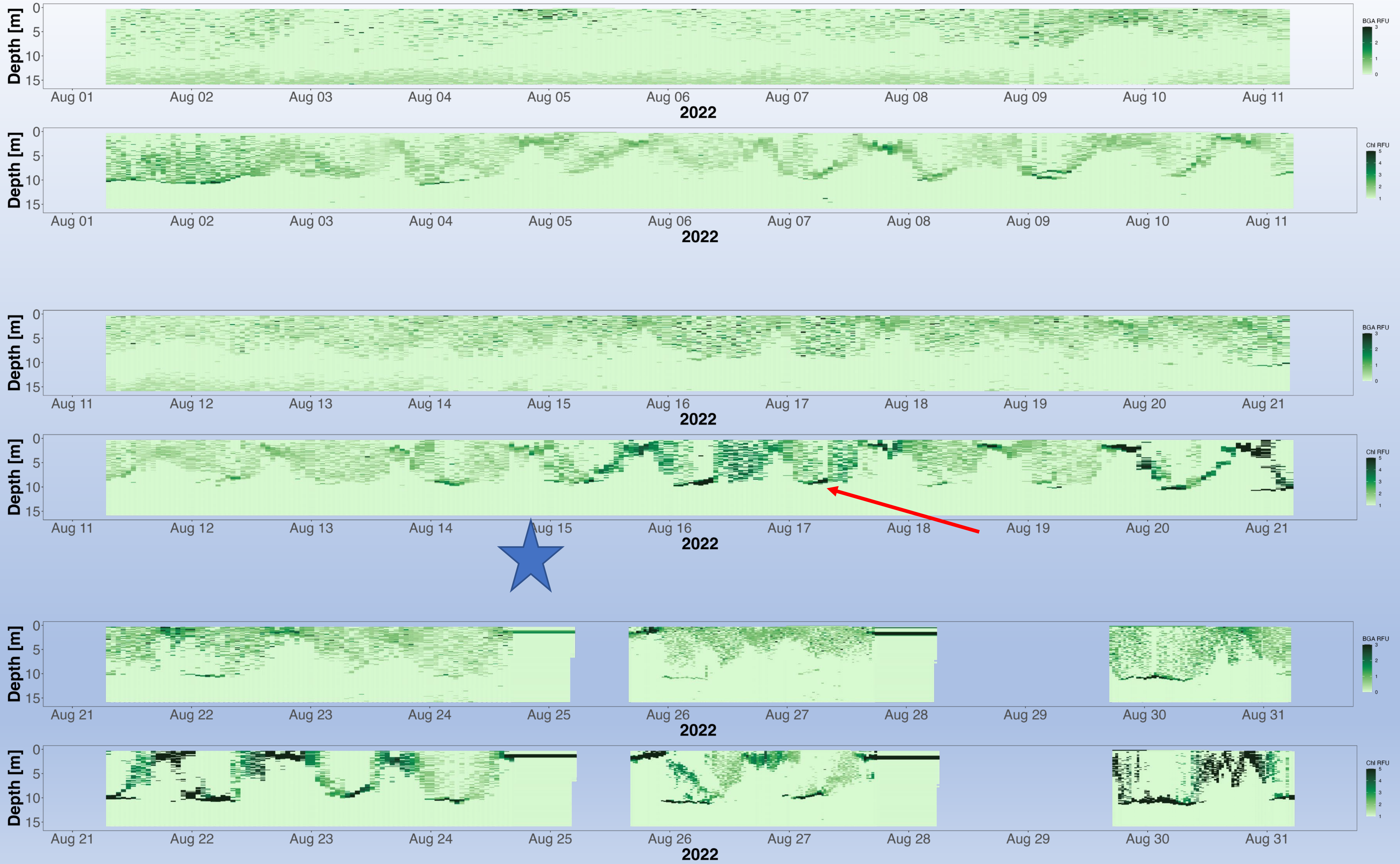
  - Short-term
    - DVM allows Ceratium to "come within reach" of hypolimnetic nutrients – *near thermocline*
    - Pathway to transfer P from hypolimnion to epilimnion



FIGS. 1–6. Cyst formation in *Ceratium hirundinella*. Scale bars = 10 μm. FIGS. 1–3. The dark cyst within the theca is released by bursting open the wall which then falls away. FIG. 4. The newly released cyst is conspicuous by its rounded horns and an impression left by the girdle around the middle (arrow). FIG. 5. A fully formed smooth-walled cyst from Blelham Tarn. FIG. 6. A dormant, granular-walled cyst from Esthwaite Water. The chloroplasts have migrated to the center of the cyst and are surrounded by lipid globules (arrow).

Chapman et al 1982

Heaney 1976, Talling 1971, Pollingher 1993


Depth [m]
0
5
10
15
Aug 01
Aug 02
Aug 03
Aug 04
Aug 05
Aug 06
Aug 07
Aug 08
Aug 09
Aug 10
Aug 11
2022
BGA RFU
Chl RFU
Aug 12
Aug 13
Aug 14
Aug 15
Aug 16
Aug 17
Aug 18
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Aug 22
Aug 23
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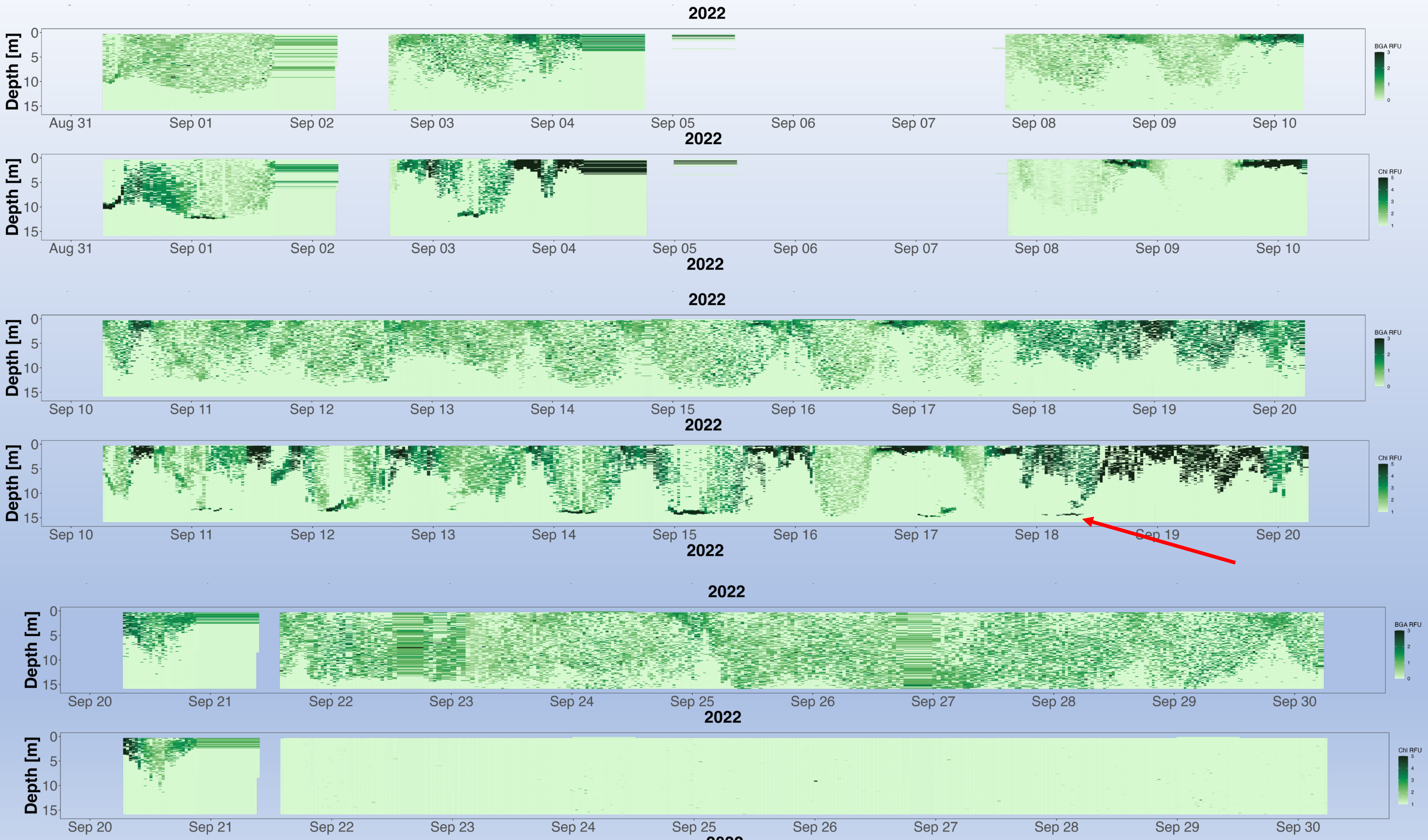
Aug 30
Aug 31


2022
Depth [m]
0
5
10
15
Aug 31
Sep 01
Sep 02
Sep 03
Sep 04
Sep 05
Sep 06
Sep 07
Sep 08
Sep 09
Sep 10
BGA RFU
2022
Depth [m]
Chl RFU
2022
2022
Depth [m]
Sep 10
Sep 11
Sep 12
Sep 13
Sep 14
Sep 15
Sep 16
Sep 17
Sep 18
Sep 19
Sep 20
BGA RFU
2022
Depth [m]
Chl RFU
2022
2022
Depth [m]
Sep 20
Sep 21
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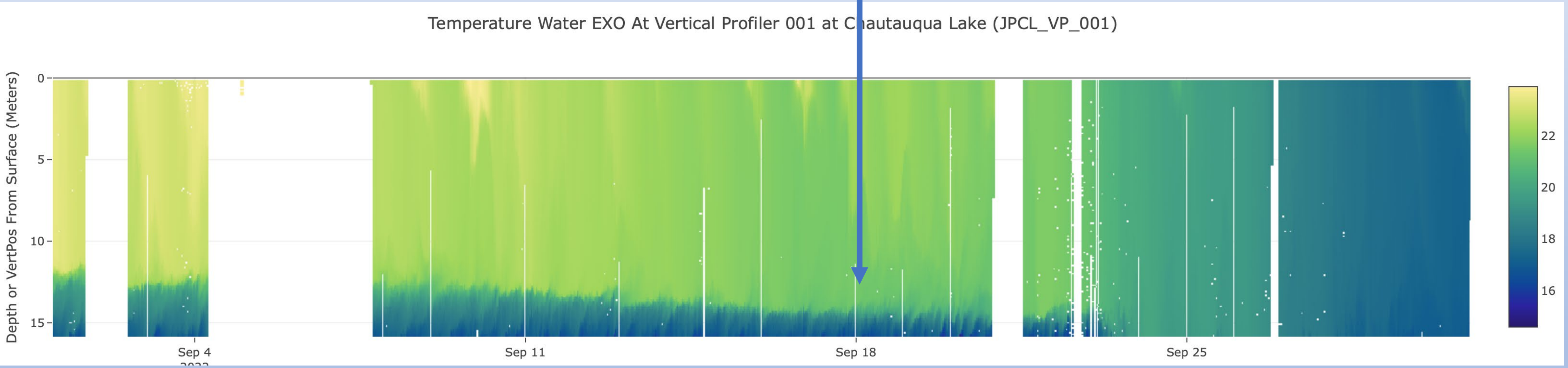
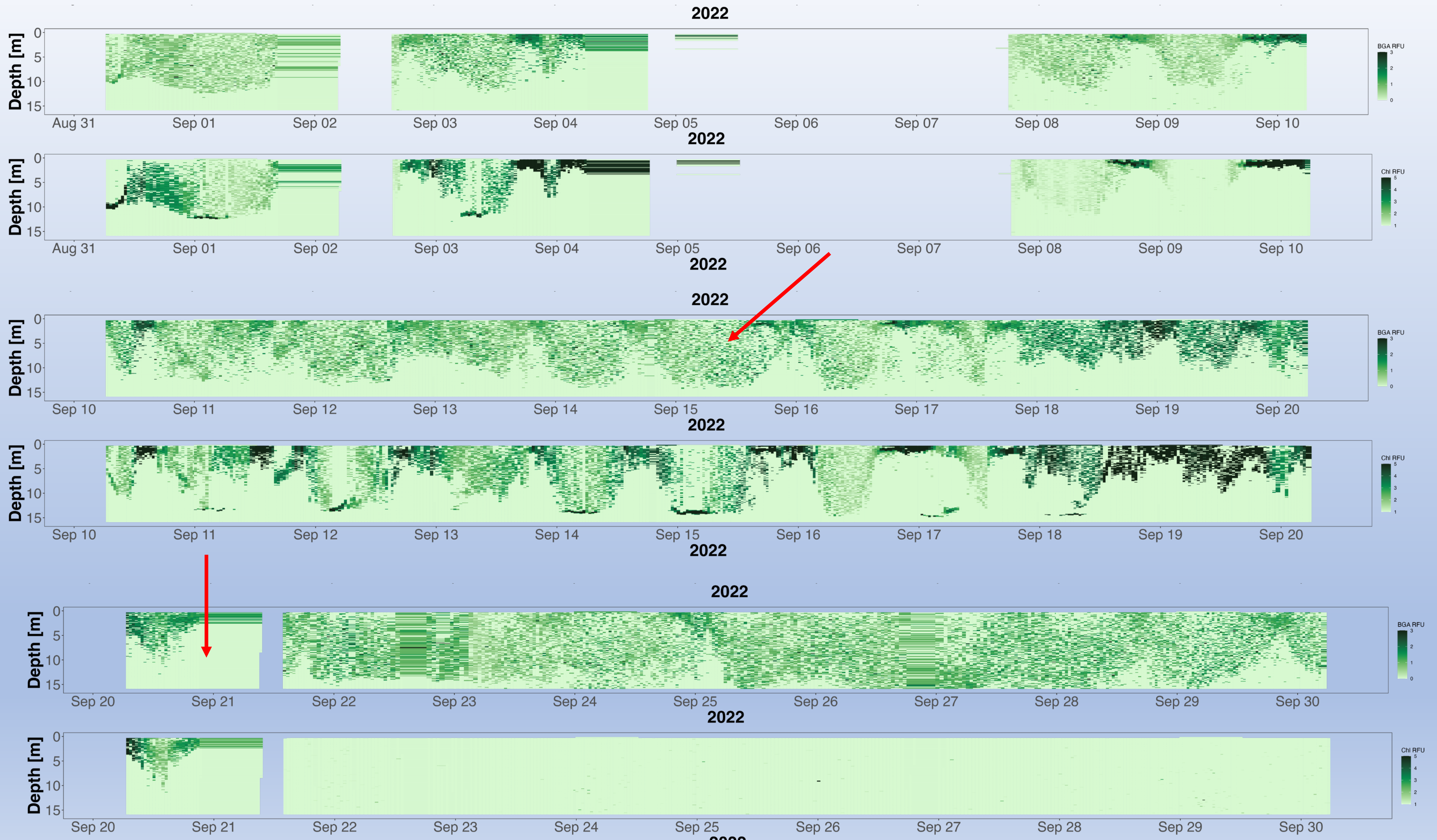
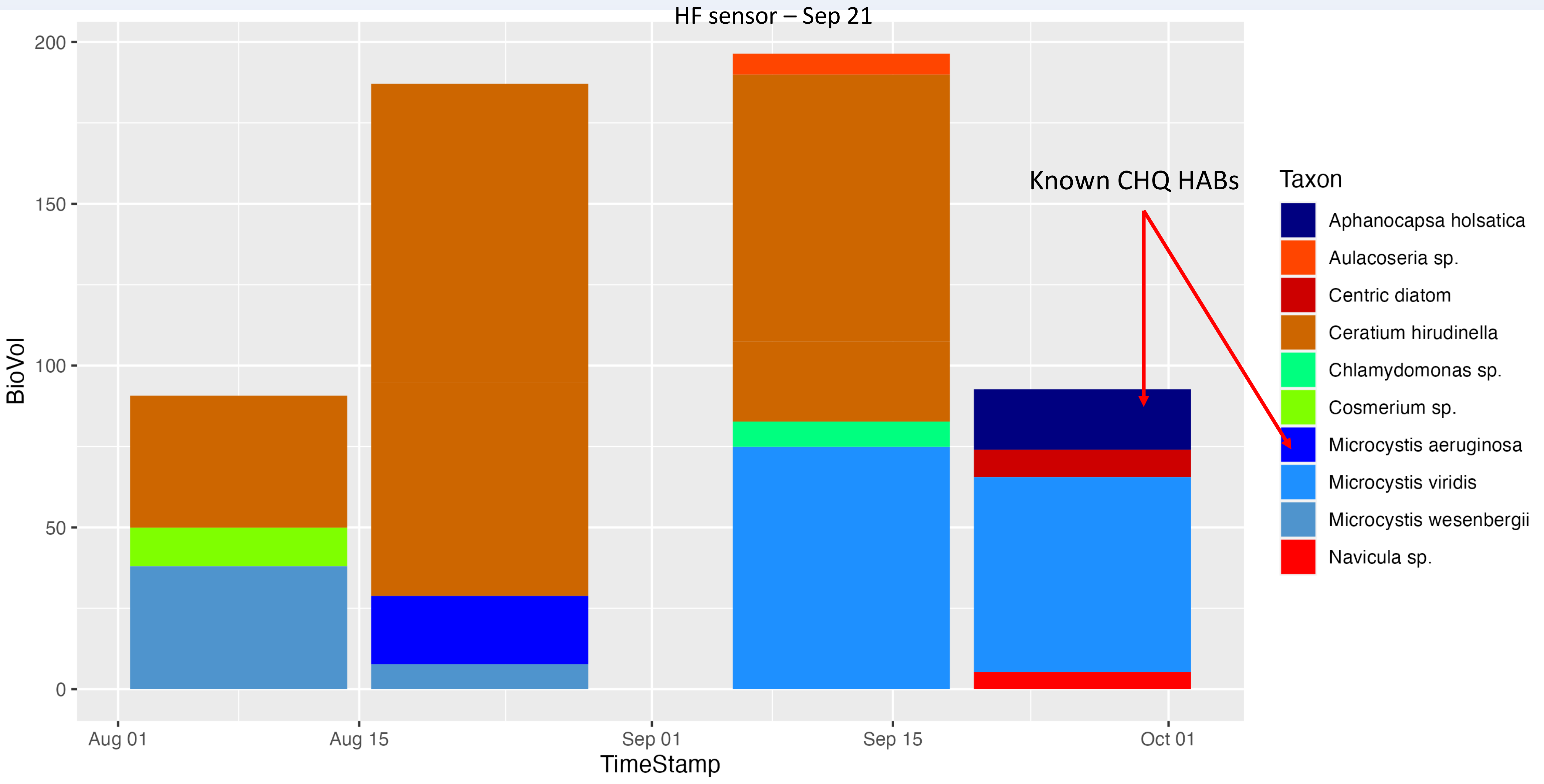
Sep 30
BGA RFU
2022
Depth [m]
Chl RFU


Temperature Water EXO At Vertical Profiler 001 at Chautauqua Lake (JPCL_VP_001)
Depth or VertPos From Surface (Meters)
0
5
10
15
Sep 4
Sep 11
Sep 18
Sep 25
22
20
18
16


2022
Depth [m]
0
5
10
15
Aug 31
Sep 01
Sep 02
Sep 03
Sep 04
Sep 05
Sep 06
Sep 07
Sep 08
Sep 09
Sep 10
BGA RFU
2022
Depth [m]
Chl RFU
2022
2022
Depth [m]
Sep 10
Sep 11
Sep 12
Sep 13
Sep 14
Sep 15
Sep 16
Sep 17
Sep 18
Sep 19
Sep 20
BGA RFU
2022
Depth [m]
Chl RFU
2022
2022
Depth [m]
Sep 20
Sep 21
Sep 22
Sep 23
Sep 24
Sep 25
Sep 26
Sep 27
Sep 28
Sep 29
Sep 30
BGA RFU
2022
Depth [m]
Chl RFU

2022 Biovolume
Aug 8, Aug 22, Sept 12, Sep 26



Hypothesized series of events

1. Deoxygenation of hypolimnion leads to internal loading

2. Pore water pumping/ wash zone drives pulses of nutrient rich water higher into the hypolimnion (conductivity as proxy)

3. By mid season nutrient super-rich water nears upper layers of hypolimnion, enough so that Ceratium can access it

4. Ceratium DVM acts as daily nutrient pump, bringing nutrients to epilimnion (leaky bodies), driving growth of other phytoplankton groups

5. Ceratium maintains dominance until turnover
    1. Cold water drives encystment -OR-
    2. Competition with other cyanobacteria (toxins) drives them into encystment

6. Void left by Ceratium allows cyano HABs in North Basin

Why does it matter?

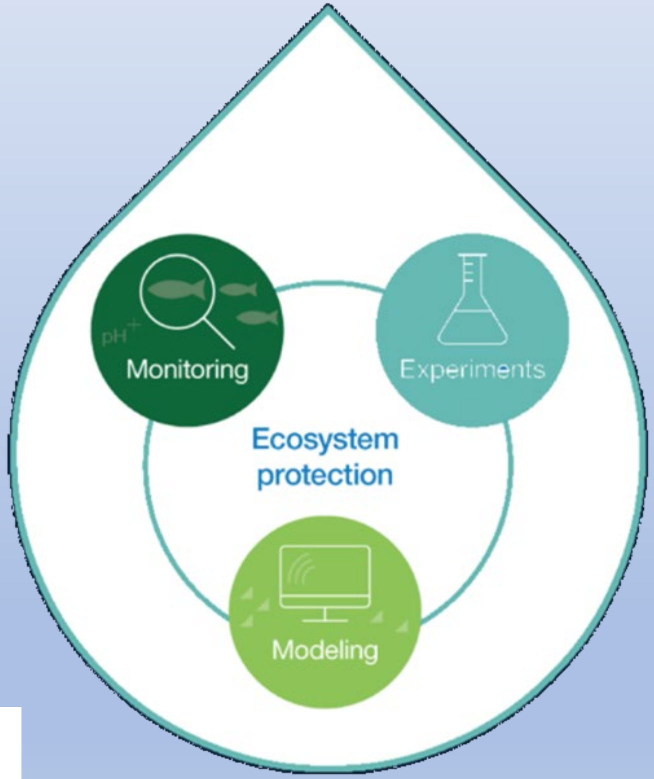
- Help explain timing of late season CHABs in North Basin of Chautauqua Lake

- Provides predicative capability for HABs in other lakes
  - Monitor for episodic internal loading events

The Jefferson Project at Lake George

Rensselaer

- Brian Mattes
- Michael Henderson
- Chautauqua Institution
- Chautauqua Lake and Watershed Management Alliance



- Lloyd Treinish
- Anthony Praino
- John Ma
- Jon Borrelli
- Maria Pelusi

LGA Lake George Association

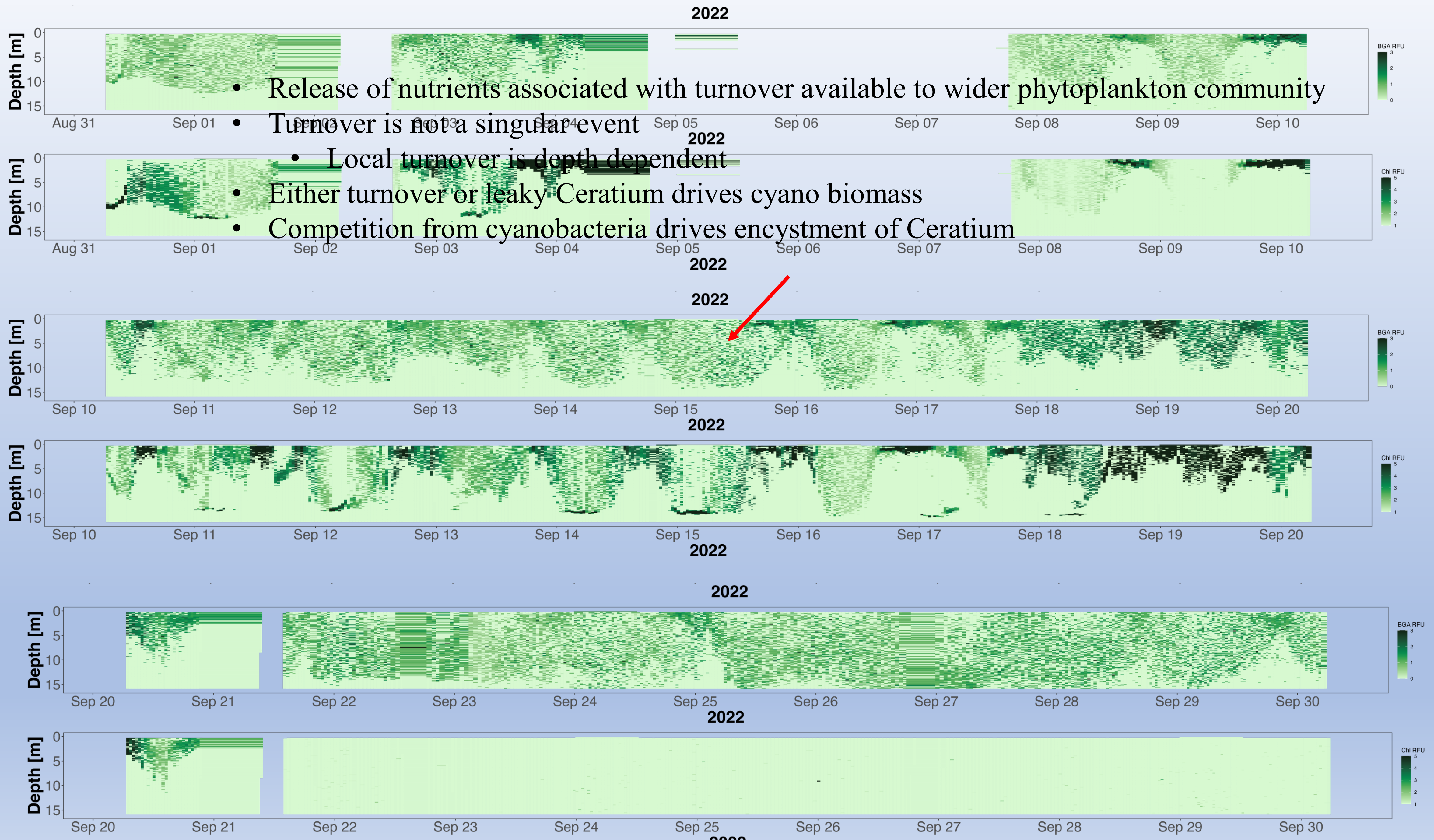
IBM®

https://jeffersonproject.rpi.edu

Hypothesized series of events

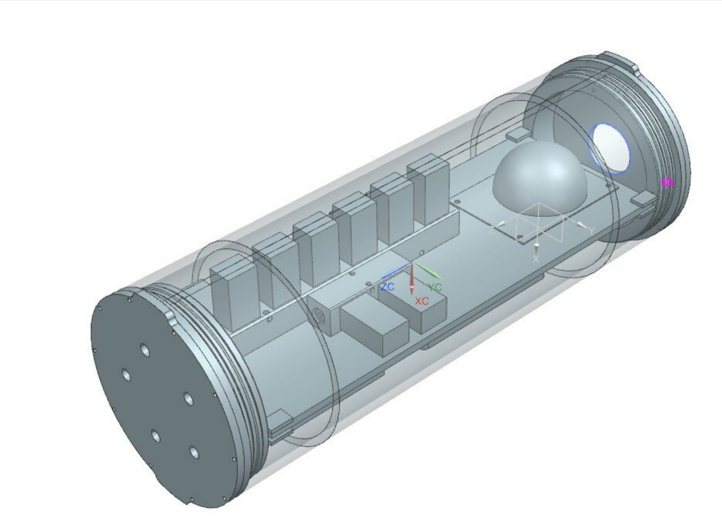
1. Deoxygenation of hypolimnion leads to internal loading
2. Pore water pumping (or mix of hydrodynamic drivers) pulses nutrient rich water higher into the hypolimnion (conductivity as proxy)
3. By mid season nutrient super-rich water nears upper layers of hypolimnion, enough so that Ceratium can access it
4. Ceratium DVM acts as daily nutrient pump, bringing nutrients to epilimnion (leaky bodies), driving growth of other phytoplankton groups
5. Ceratium maintains dominance until turnover
    1. Cold water drives encystment -OR-
    2. Competition with other cyanobacteria (toxins) drives them into encystment
6. Void left by Ceratium allows cyano HABs in North Basin

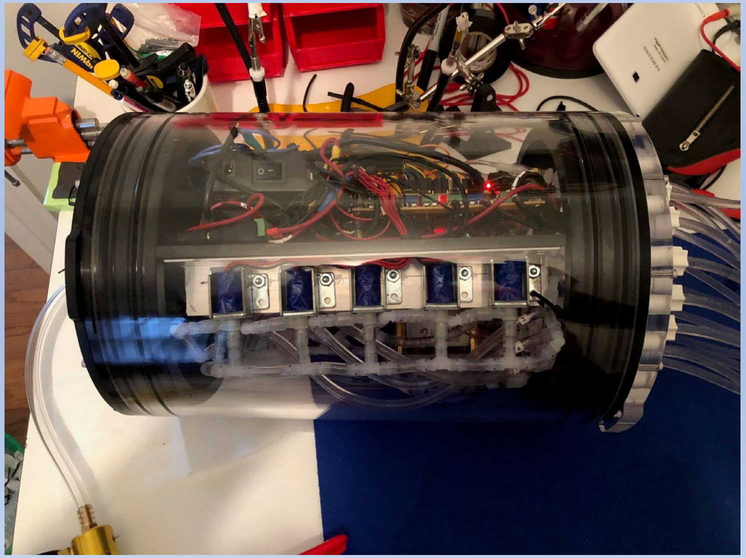
- Release of nutrients associated with turnover available to wider phytoplankton community
- Turnover is not a singular event
  - Local turnover is depth dependent
- Either turnover or leaky Ceratium drives cyano biomass
- Competition from cyanobacteria drives encystment of Ceratium



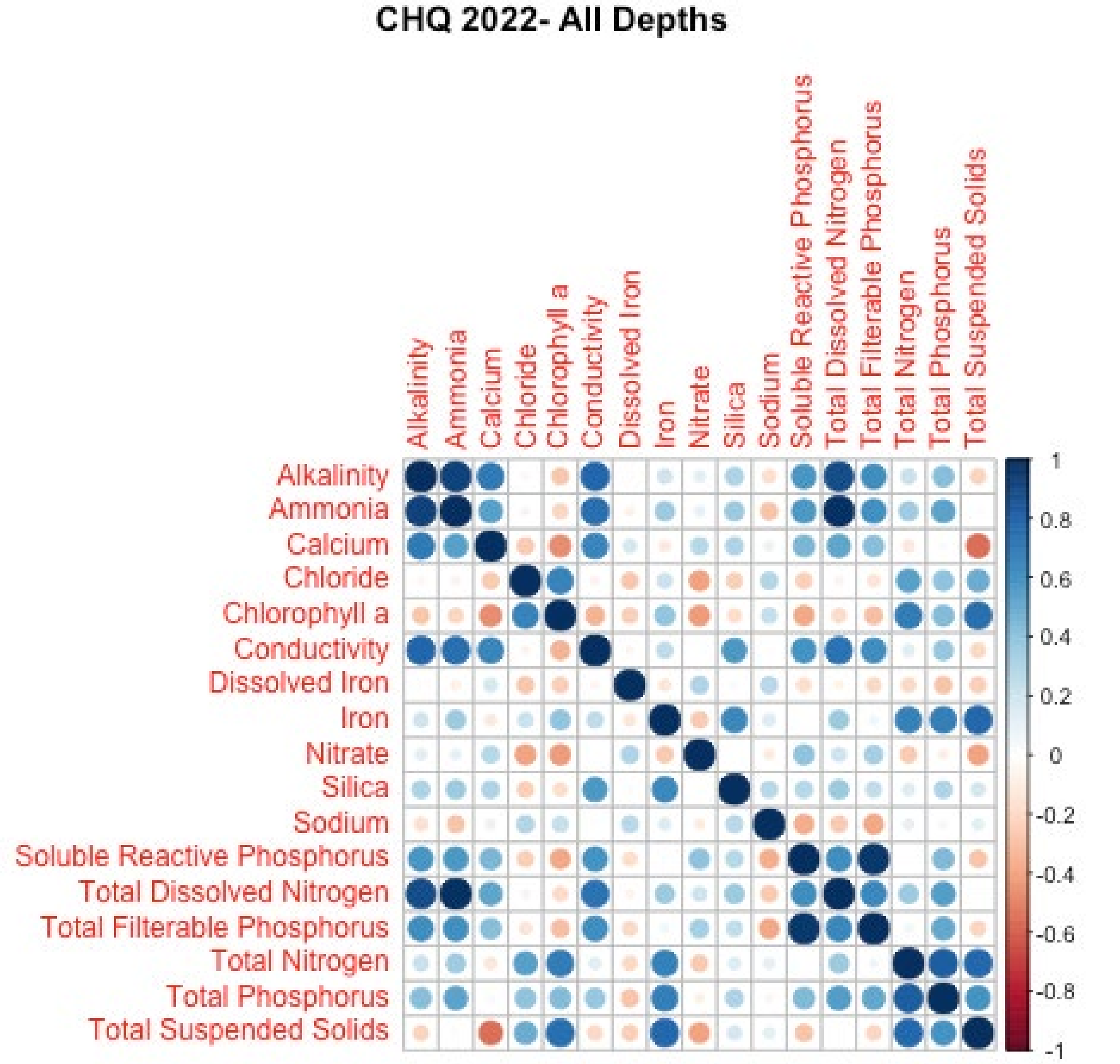
S.P.A.T.S.

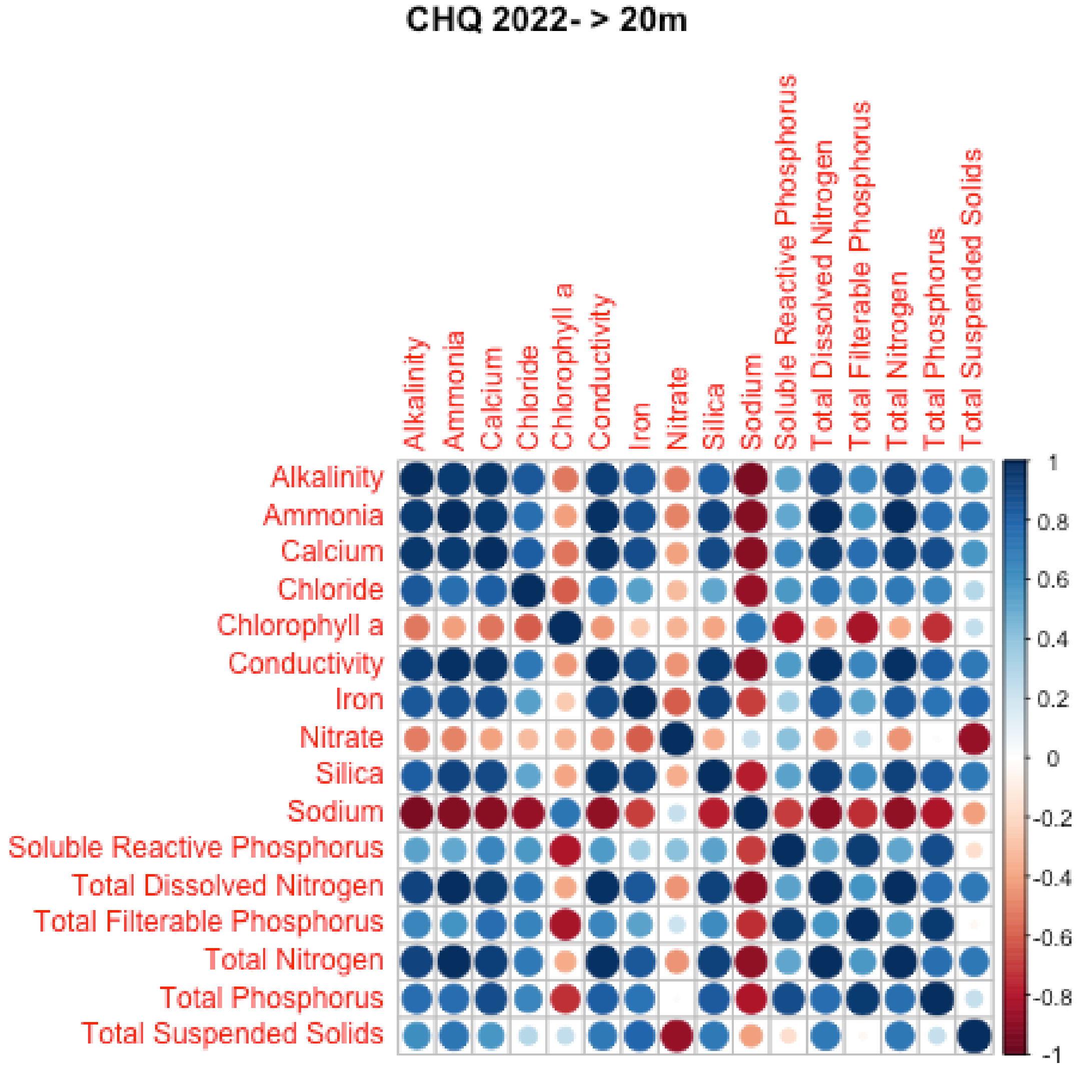
- Submersible Platform for Automated Timeseries Sampling
  - Julia Levan (RPI Arch Student)
- 2023 North Basin and South Basin VP deployments
  - Near-Sediment interface sampling
- Other Research Questions?



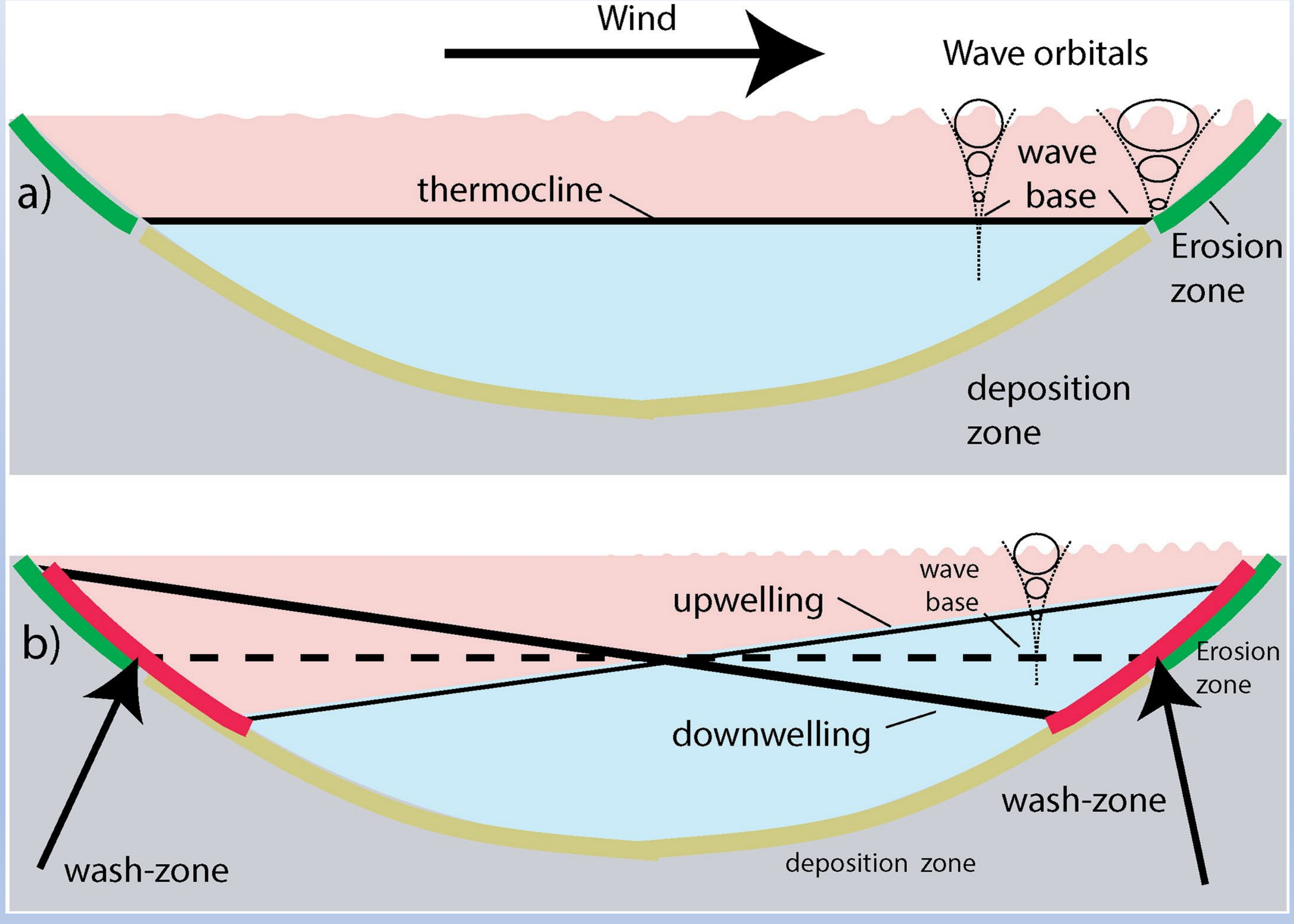


Pulsed Internal Loading

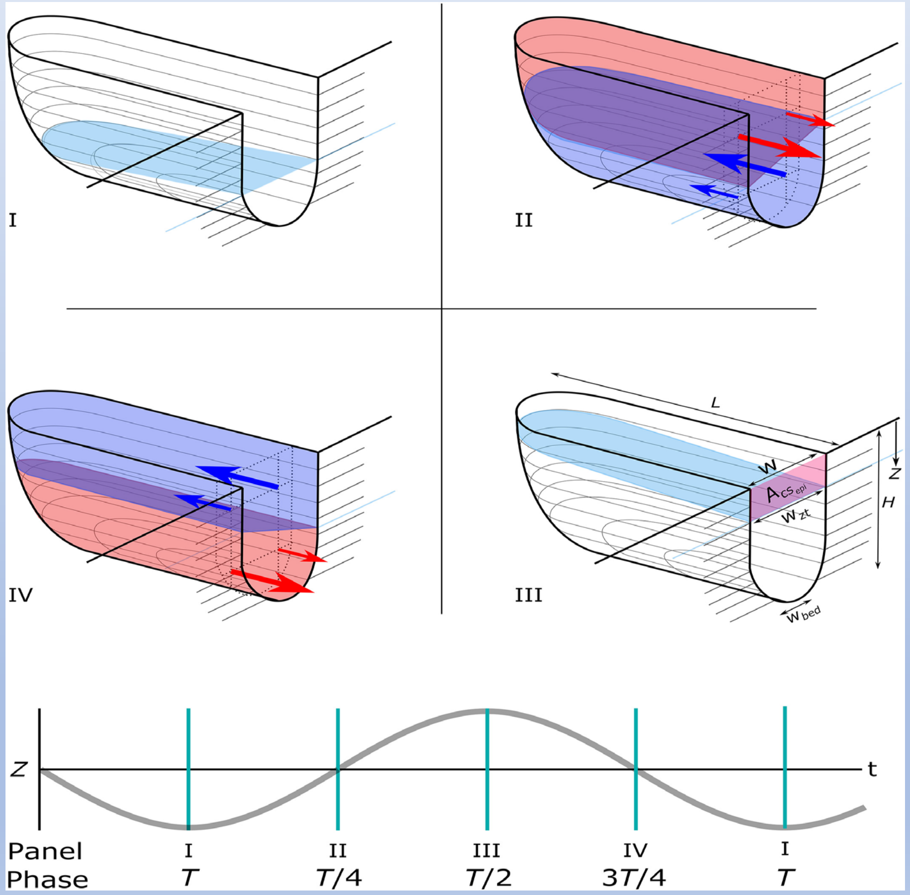




Potential hydrodynamic drivers of pulsed internal loading

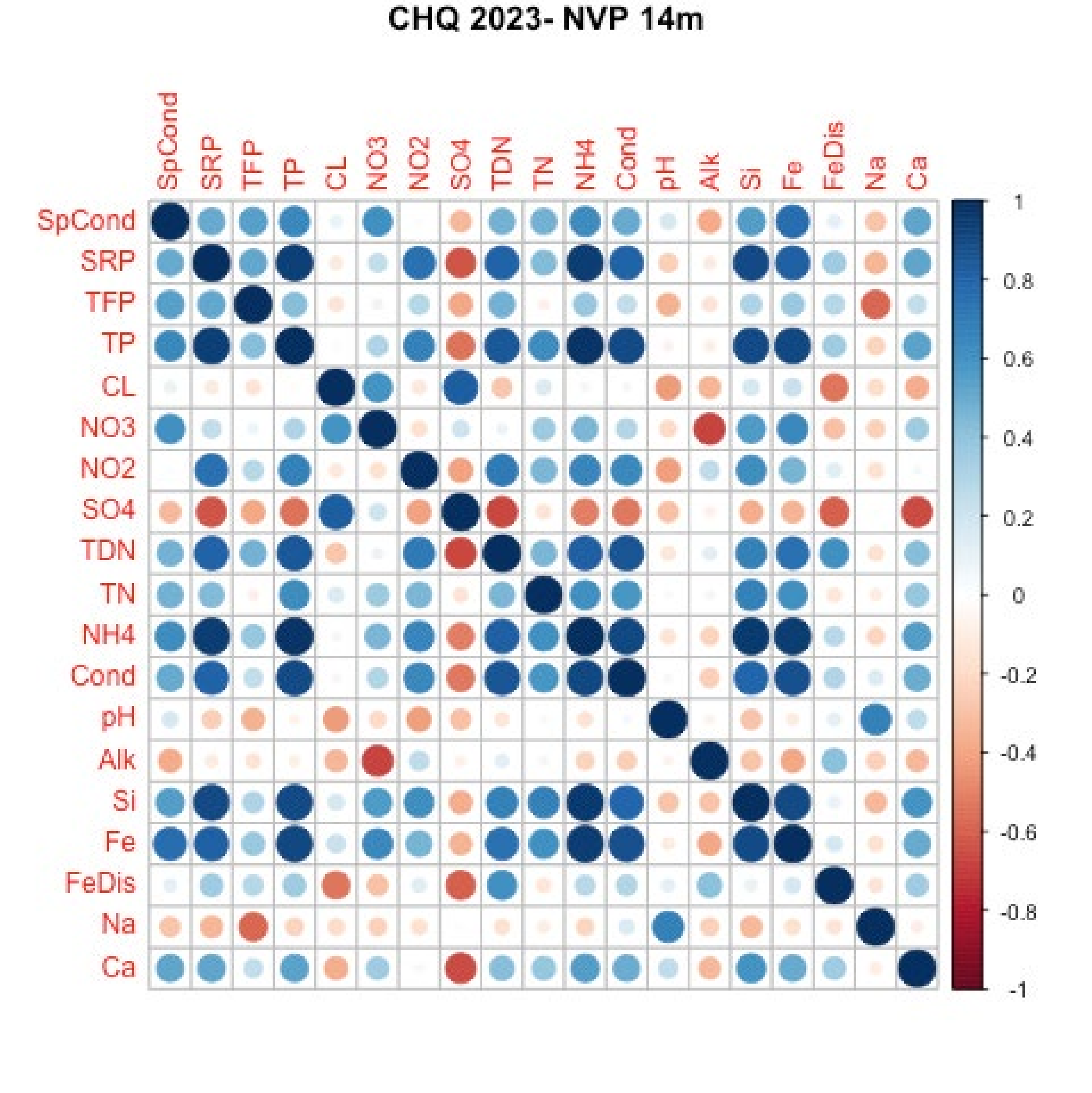


Cossu et al. 2017

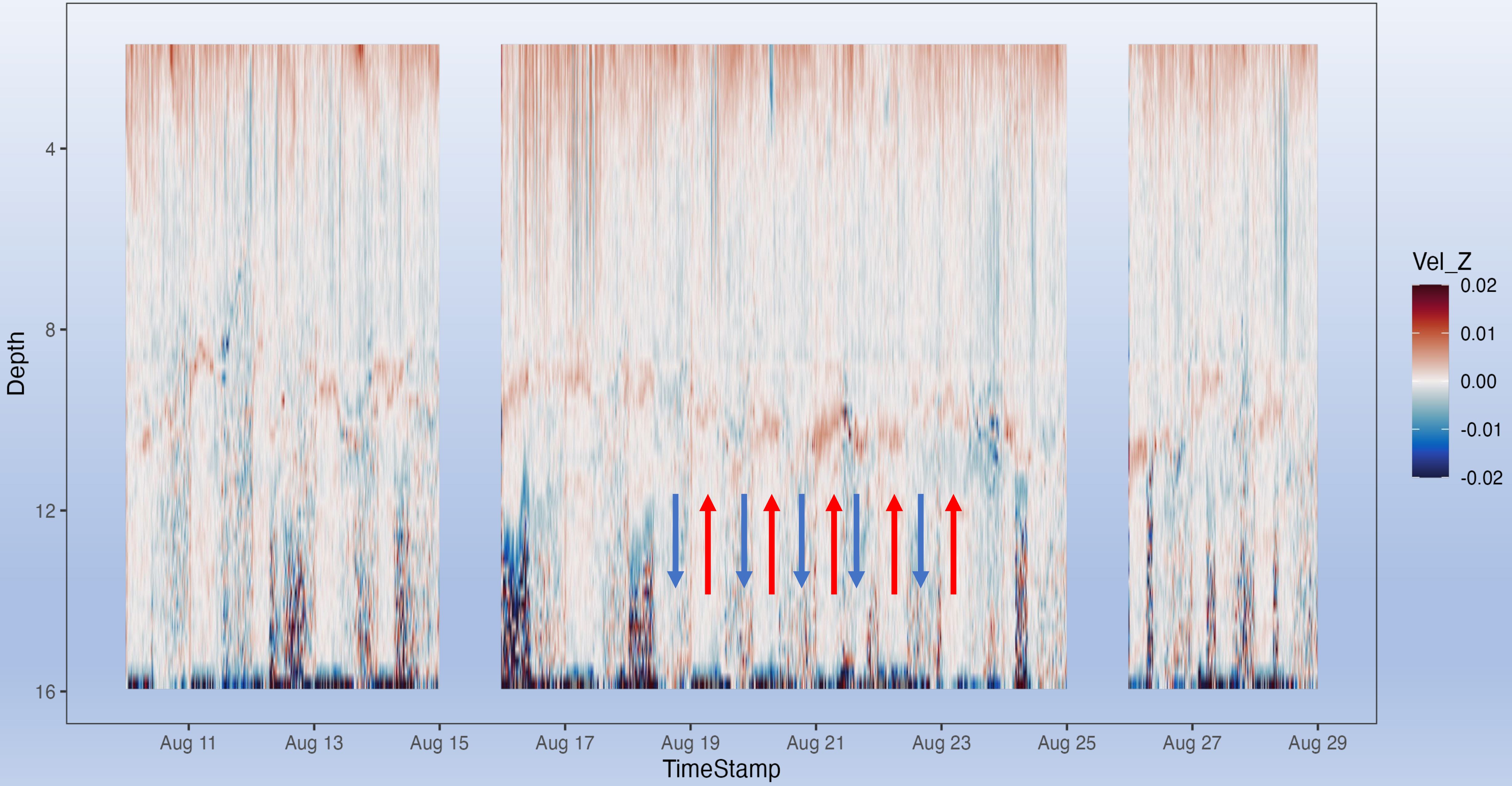


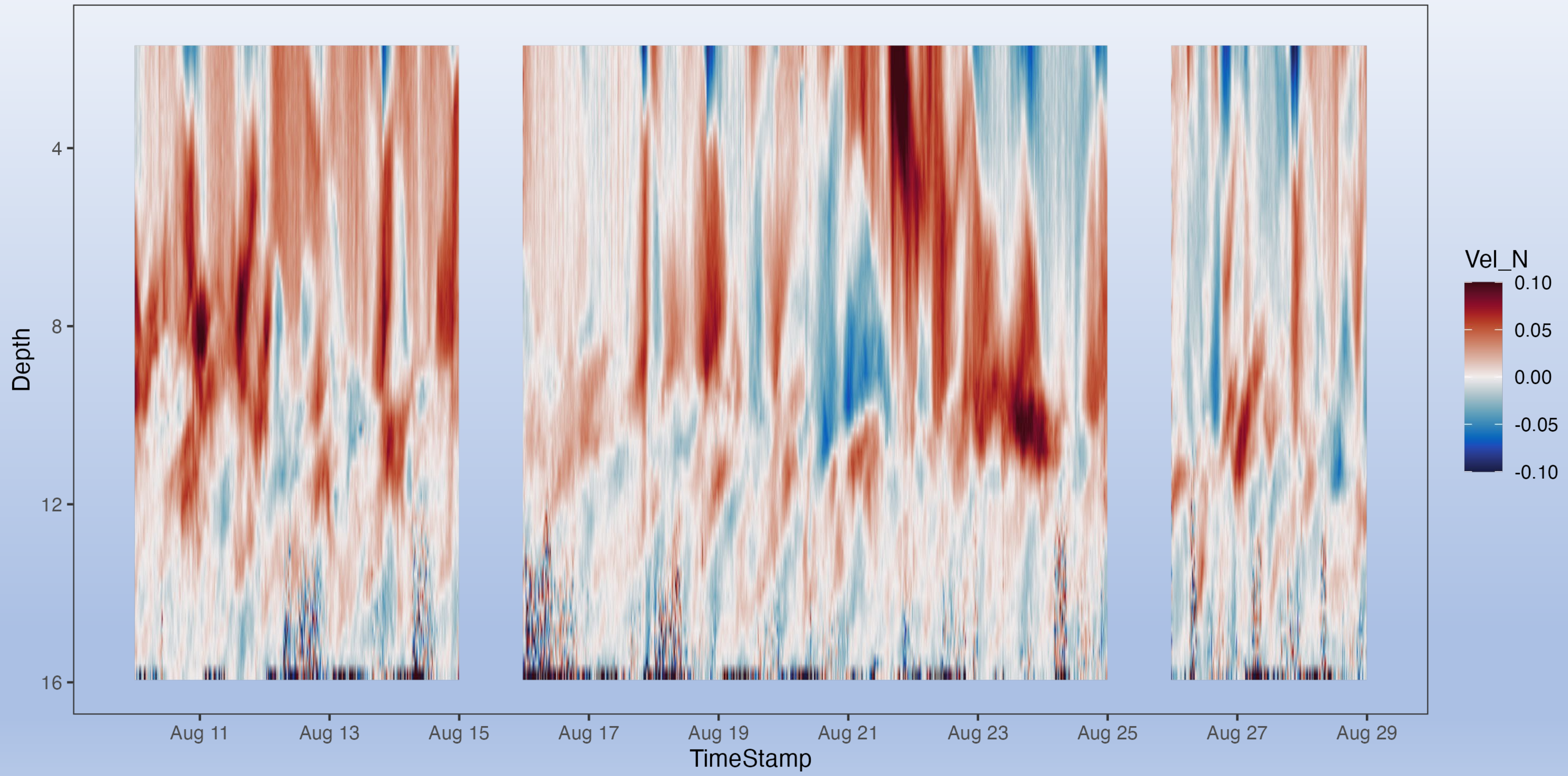
Wells et al. 2019

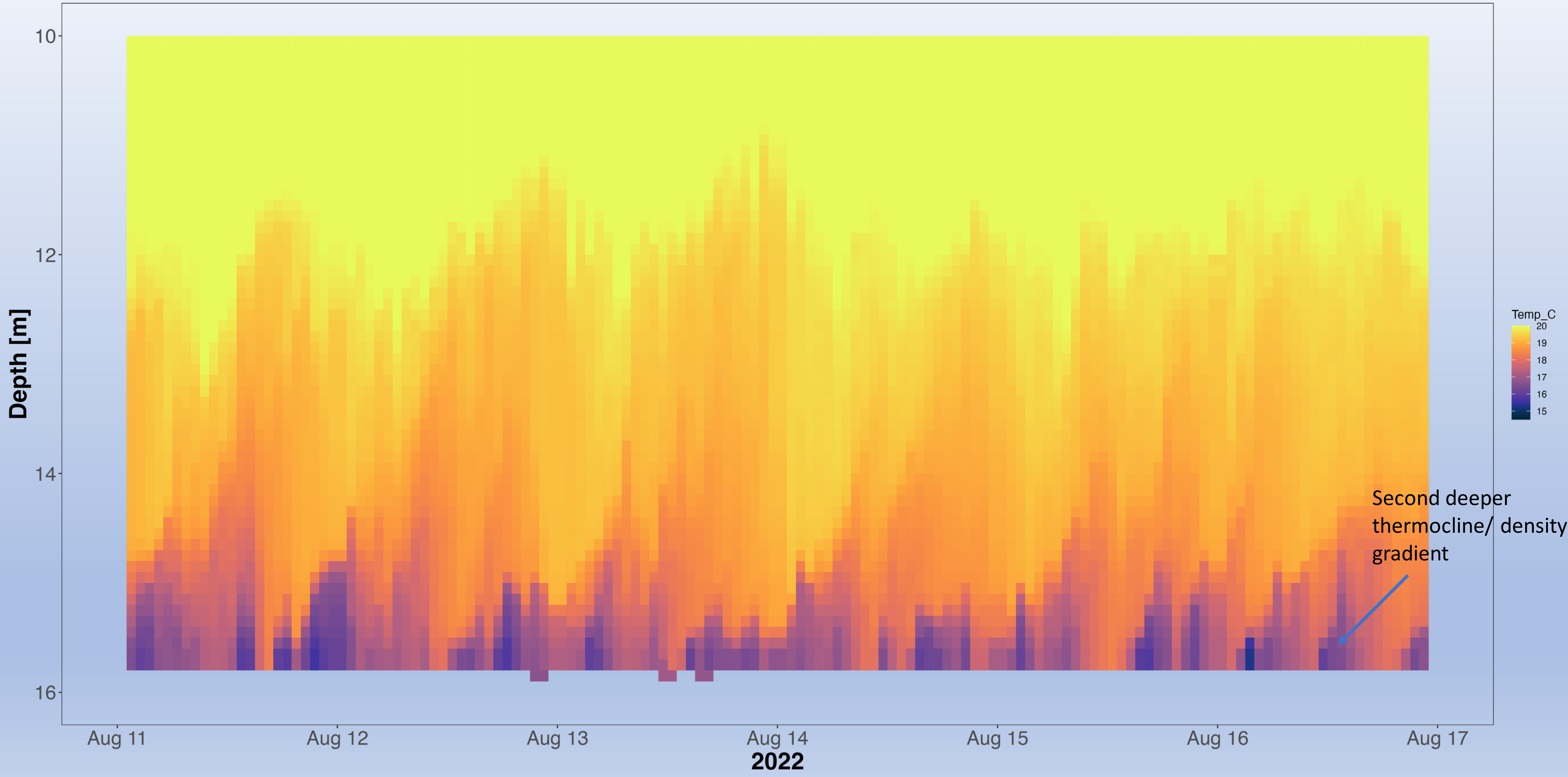
Pulsed Internal Loading



Vertical velocity matches pattern seen in water temperature and conductivity. Alternate upwelling and downwelling of water column as a potential driver pumping pore water in benthic sediments




Vel_N
0.10
0.05
0.00
-0.05
-0.10
Depth
4
8
12
16
Aug 11
Aug 13
Aug 15
Aug 17
Aug 19
Aug 21
Aug 23
Aug 25
Aug 27
Aug 29
TimeStamp


Depth [m]
10
12
14
16
Aug 11
Aug 12
Aug 13
Aug 14
Aug 15
Aug 16
Aug 17
2022
Temp_C
20
19
18
17
16
15
Second deeper thermocline/ density gradient

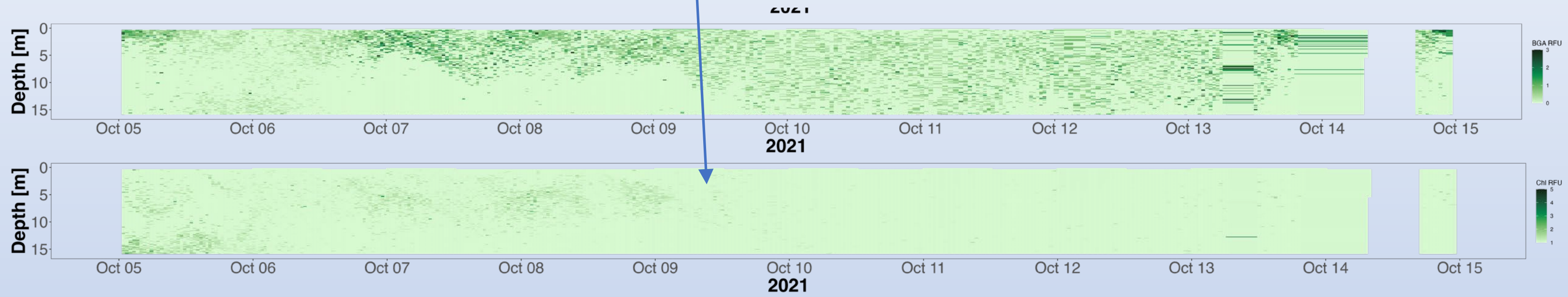
Taking into account the chemical composition of *Ceratium* according to Heaney et al. (1986), the phosphorus incorporated in the cysts which reached the sediments was calculated. It represented 23 kg particulate phosphorus in 1988, a year when *Ceratium* did not form a bloom. The phosphorus incorporated and transported to the epilimnion by the germinated cysts, together with the phosphorus accumulated by the vegetative cells by luxury consumption, may reach 115 kg.

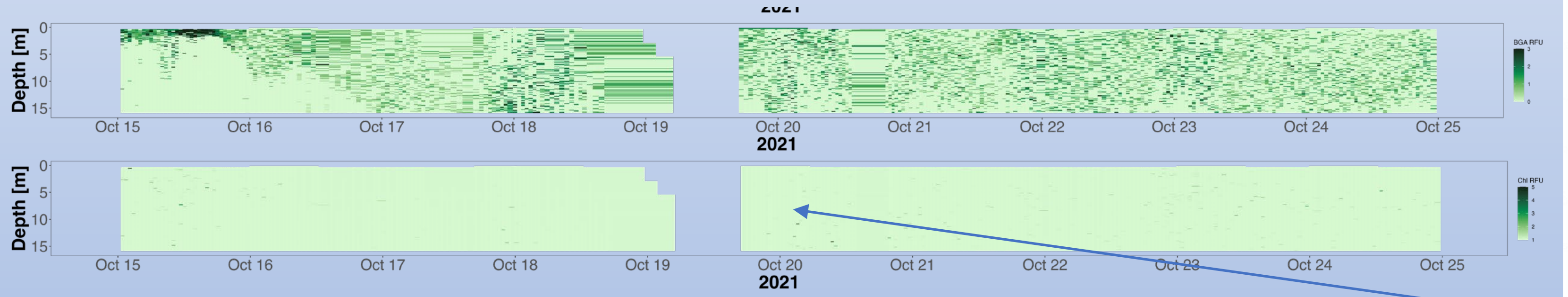
In a "*Ceratium* year", the number of cysts produced is much higher (Livingstone, 1979), and the quantity of transported phosphorus by the cysts and accumulated by the vegetative cells may be 5 or more times higher. Regarding the changes of concentration of particulate phosphorus in the epilimnion of Lake Sempach in 1975 (increase of about 350 kg P km^{-2}, corresponding to more than 300% of the initial phosphorus concentration) during the period of the *Ceratium* bloom in September, the transport capacity of cysts or vegetative cells should not be neglected. It is worth mentioning that the decomposition of the dinoflagellate vegetative cells occurs rapidly in the epilimnion.

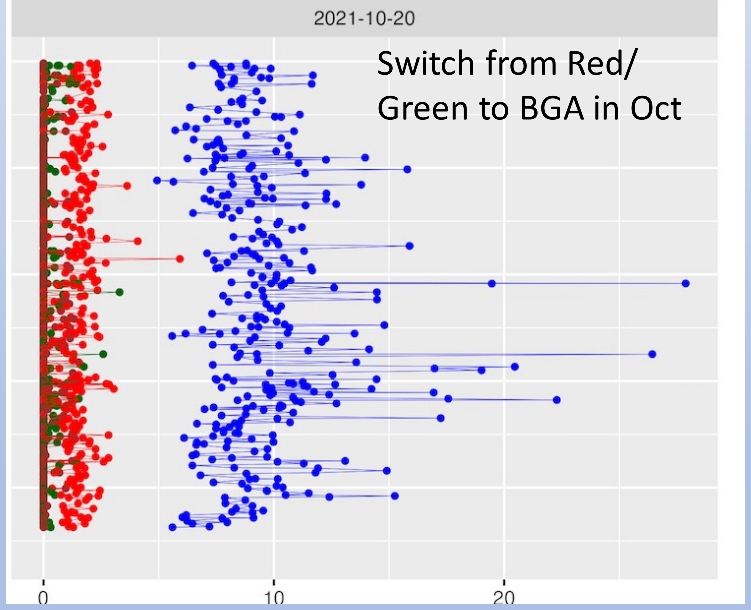
The cysts formed in the epilimnion sink down and the following year part of them return to the upper layers as vegetative cells. Those cells bring up nutrients which they have stored by "luxury consumption" at the mud-water interface. Thus at the beginning of the bloom their development does not depend on the nutrient concentrations in the epilimnion. The cysts which do not return to the epilimnion are decomposed and the nutrients are relased to the sediments. Thus the cyst is a carrier of nutrients in both directions, from down to up, and from up to down.

Oct 10: Chl-a channel is greatly reduced

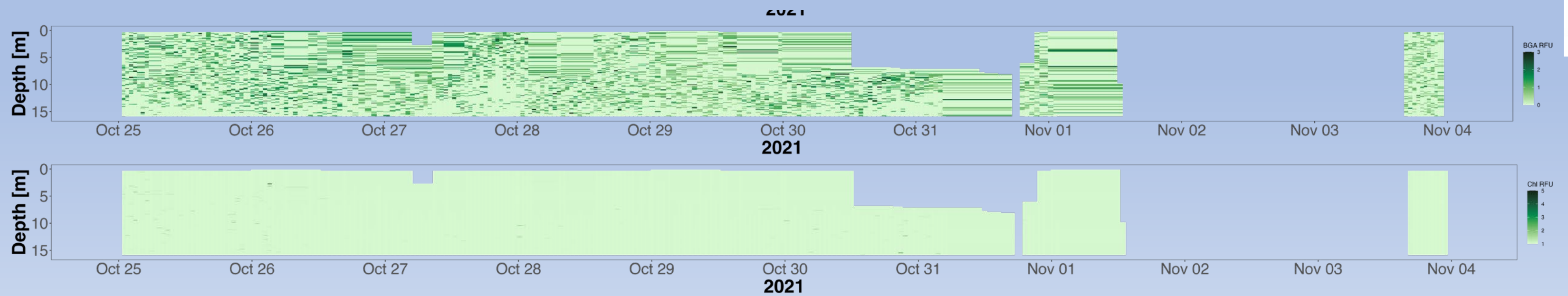
BGA channel increases in early Oct, dominant by 15th



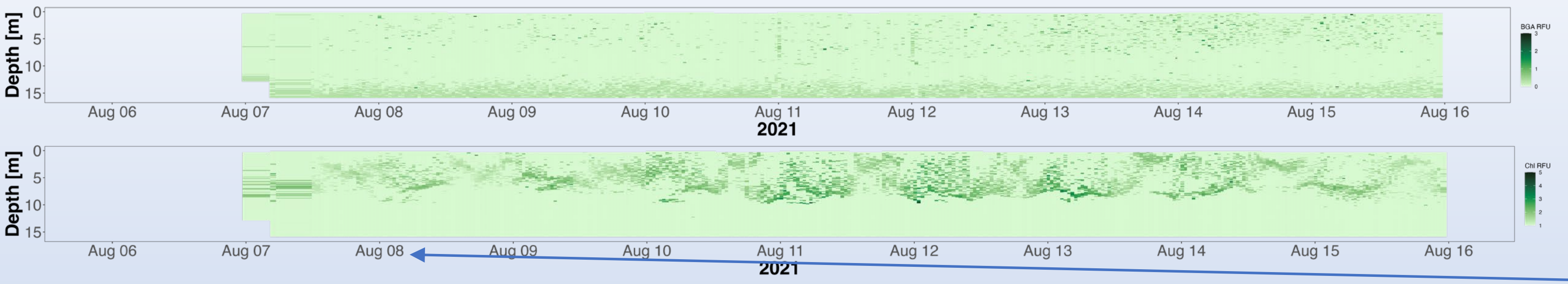


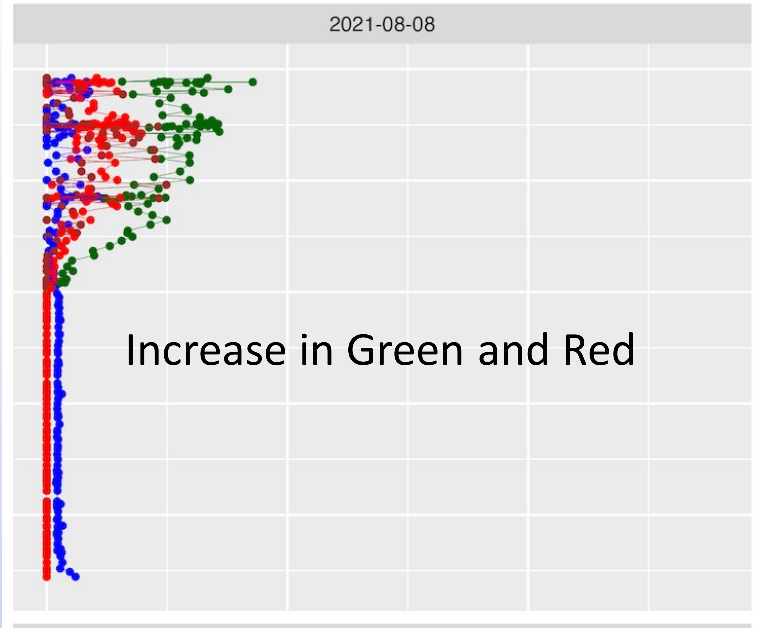


Woronichinia (BGA), Microcystis (BGA)



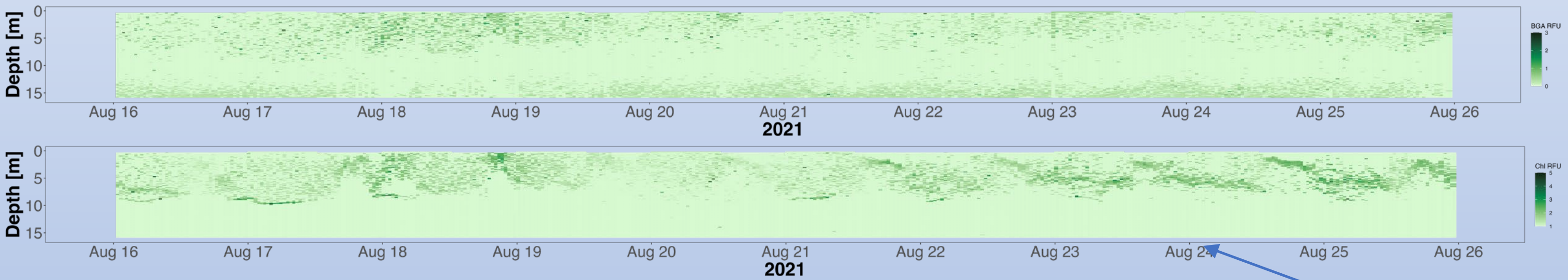
Increase in Green and Red channel coincident with VP Chl-a channel
Observed DVM in Chl-a channel

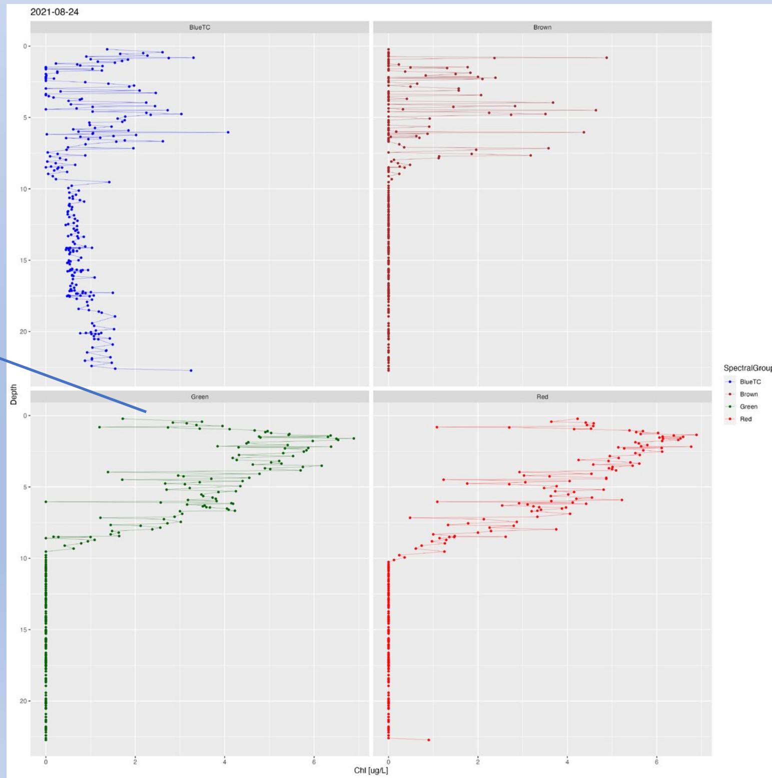




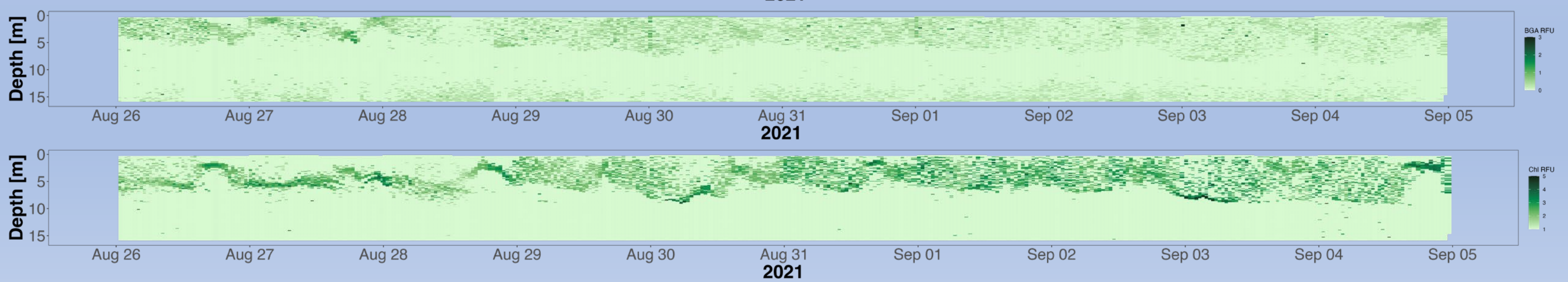
Increase in Green and Red

*Missing Aug phyto sample



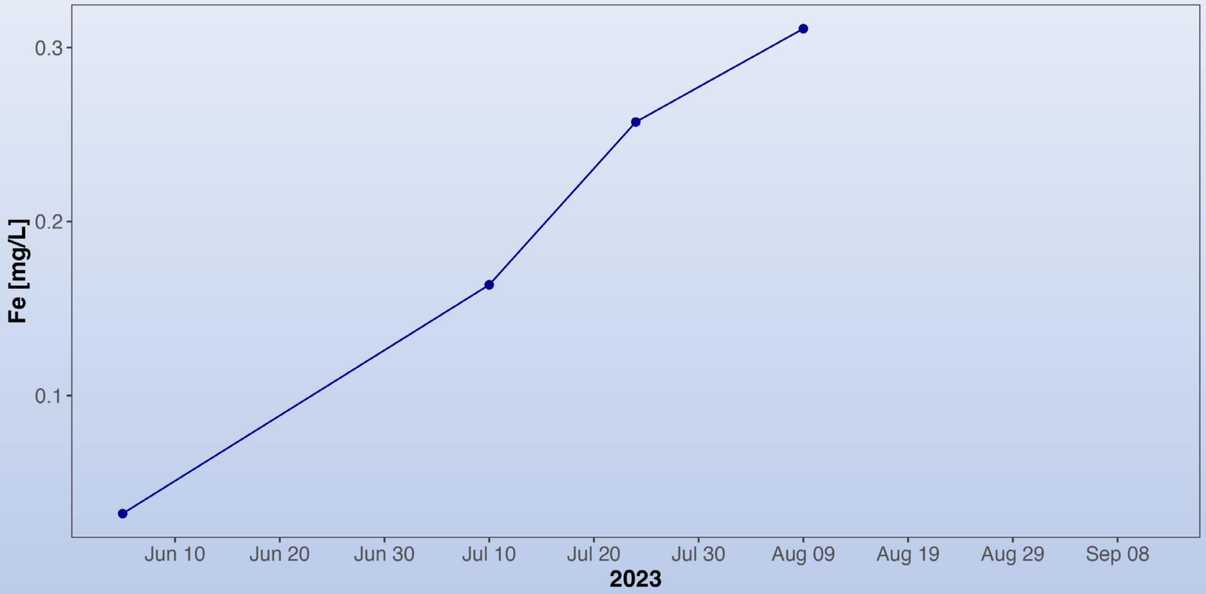


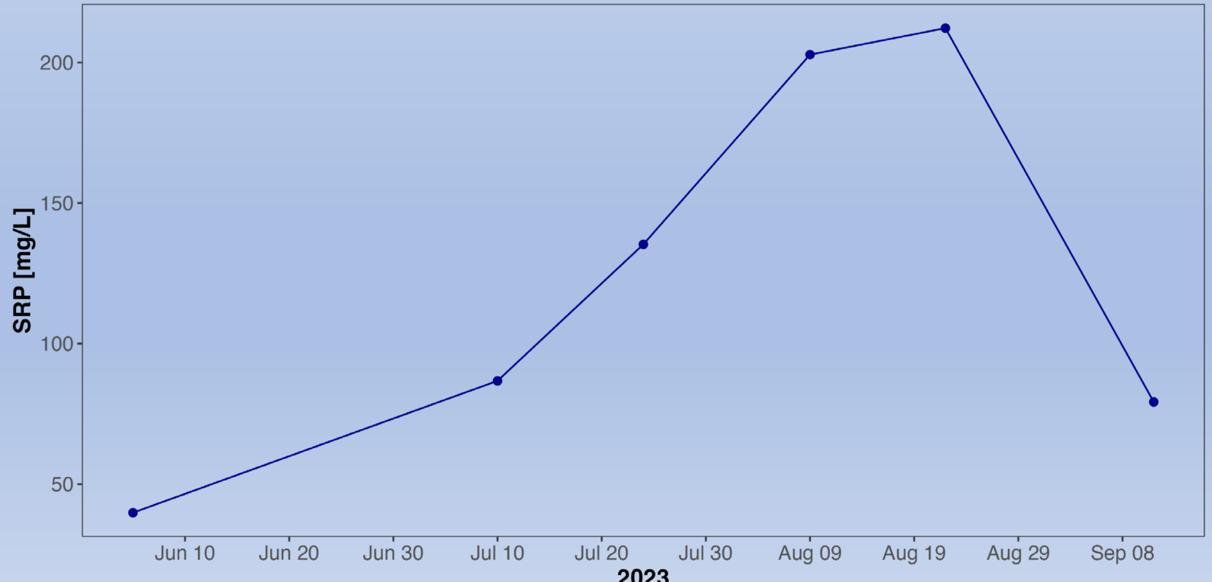
Sep 8th sample suggest this could be Ceratium (Dino with known DVM)
Ceratium seems to register in both Green and Red channels



Internal Loading in the North Basin

Hypolimnetic Fe and SRP increase during stratified period





Can we use SpCond as a proxy measurement/ evidence of a *nutrient pump* and internal loading?

- Mike Kelly
  - Skaneateles 2018

- Late-morning modeling talk
  - Guillaume Auger
  - Mike Henderson