Long-term vertical temperature change under climate change in a lake, a Seneca Lake example

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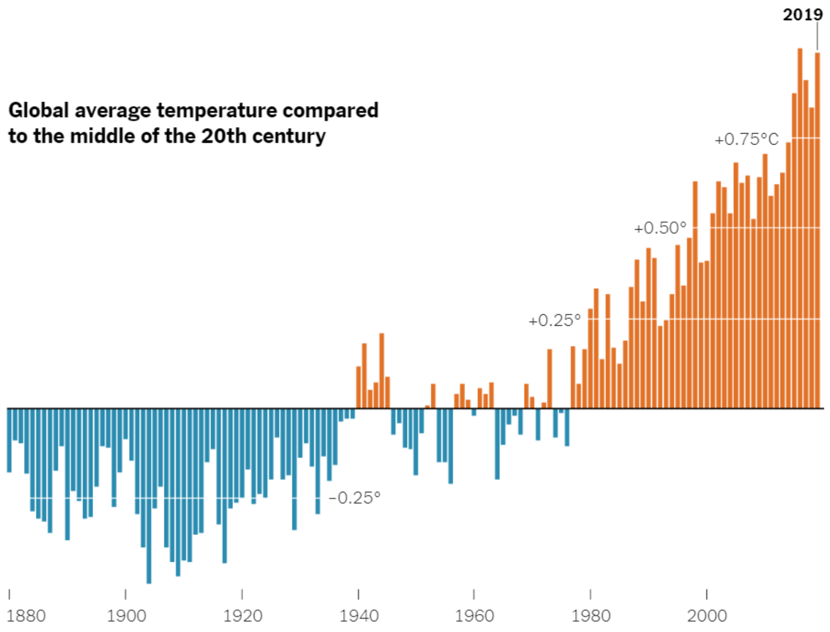
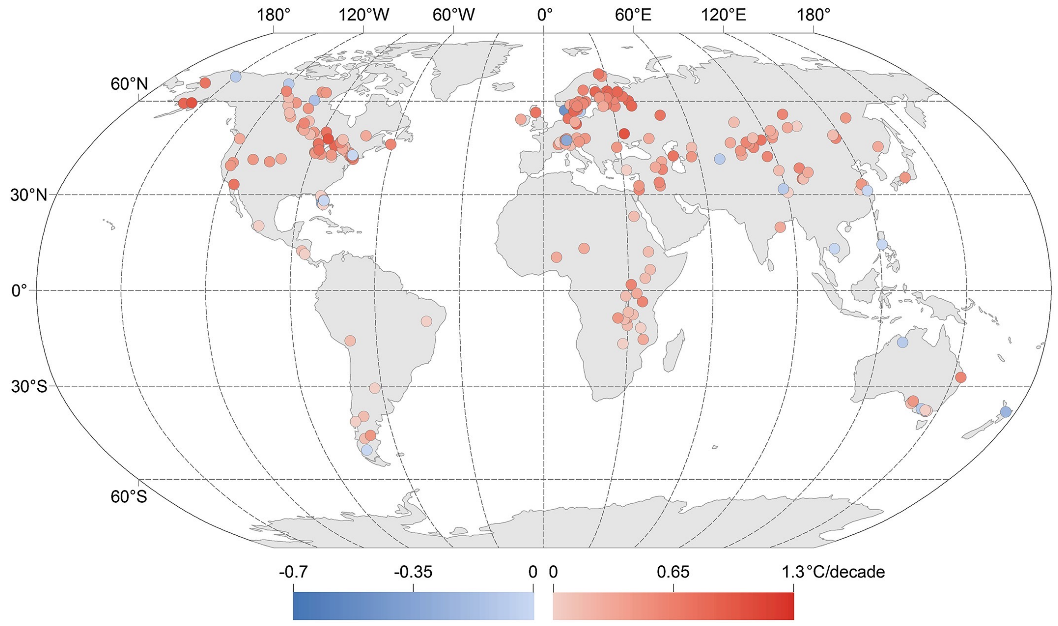
PART ONE

Introduction

Lake surface water temperatures rose rapidly





- Robust scientific consensus that the global temperature has increased at an unprecedented rate over the last century.
- Lake summer surface water temperatures rose rapidly (global mean= 0.34°C decade^{-1}) between 1985 and 2009 (O'Reilly et al., 2015).
- ***However***, surface temperatures are not easily translated into the subsurface conditions since thermal stratification may reduce subsurface mixing!

Does deep water temperature parallel the rapidly increasing lake surface water temperature?

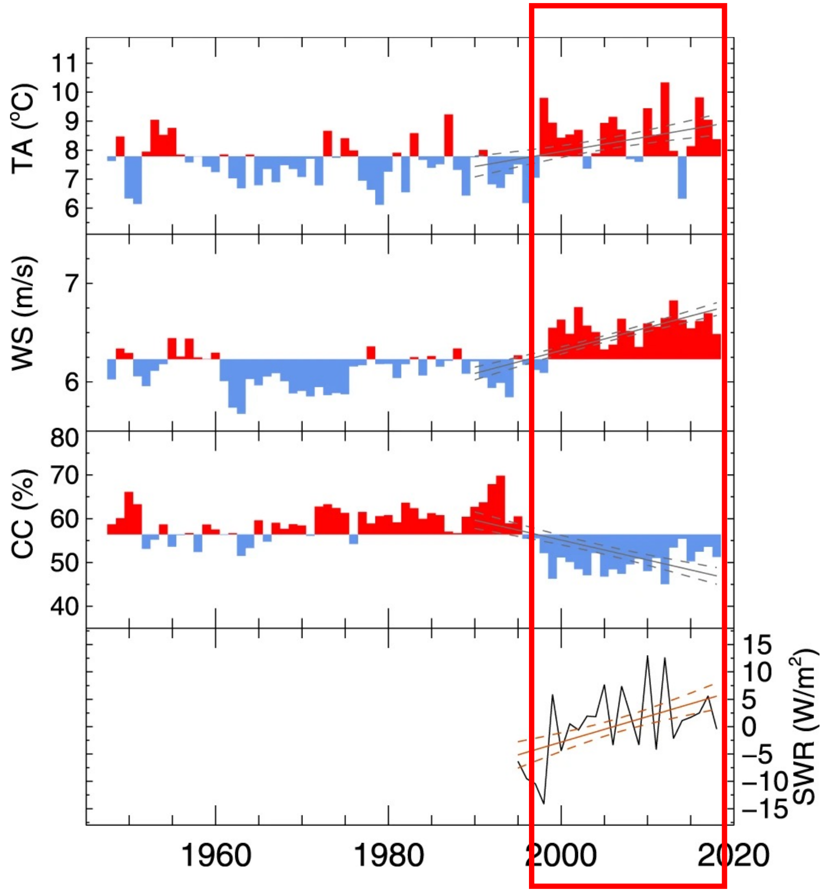
Natural climate warming is a critical driving factor

- There are very few studies on long-term deepwater temperature due to the limited direct observations.
- One recent article from Nature Communication (Anderson et al., 2021) explored one of the largest lakes, Lake Michigan (1995–2019).

Table 1 Long-term water temperature trends at the lake surface and subsurface transects.

	Linear regression	Theil-Sen	STL
Lake-average year-round surface trend	0.34 ± 0.21	0.31 ± 0.18	0.40 ± 0.05
Mooring year-round surface trend	0.40 ± 0.26	0.41 ± 0.20	0.49 ± 0.07
Mooring year-round 30 m trend	0.07 ± 0.18*	0.11 ± 0.13*	−0.02 ± 0.05*
Mooring year-round 60 m trend	0.11 ± 0.09	0.11 ± 0.07	0.09 ± 0.03
Mooring year-round 75 m trend	0.12 ± 0.07	0.11 ± 0.06	0.11 ± 0.02
Mooring year-round 100 m trend	0.11 ± 0.06	0.08 ± 0.04	0.11 ± 0.02
Mooring year-round 110 m trend	0.05 ± 0.06*	0.04 ± 0.04*	0.06 ± 0.01
Mooring year-round 140 m trend	0.00 ± 0.08*	−0.04 ± 0.05*	0.00 ± 0.01*

Estimates are given for three statistical approaches, simple linear regression, a Theil-Sen line, and a linear fit to the STL long-term component with 95% confidence intervals in °C/decade. Confidence intervals that include zero are indicated with "*".



- Although research on several largest lakes is important, smaller lakes may have experienced different water temperature changes. Could we select a more typical lake to examine the long-term trend?

What is the role of human activities in increasing surface and subsurface water temperatures?

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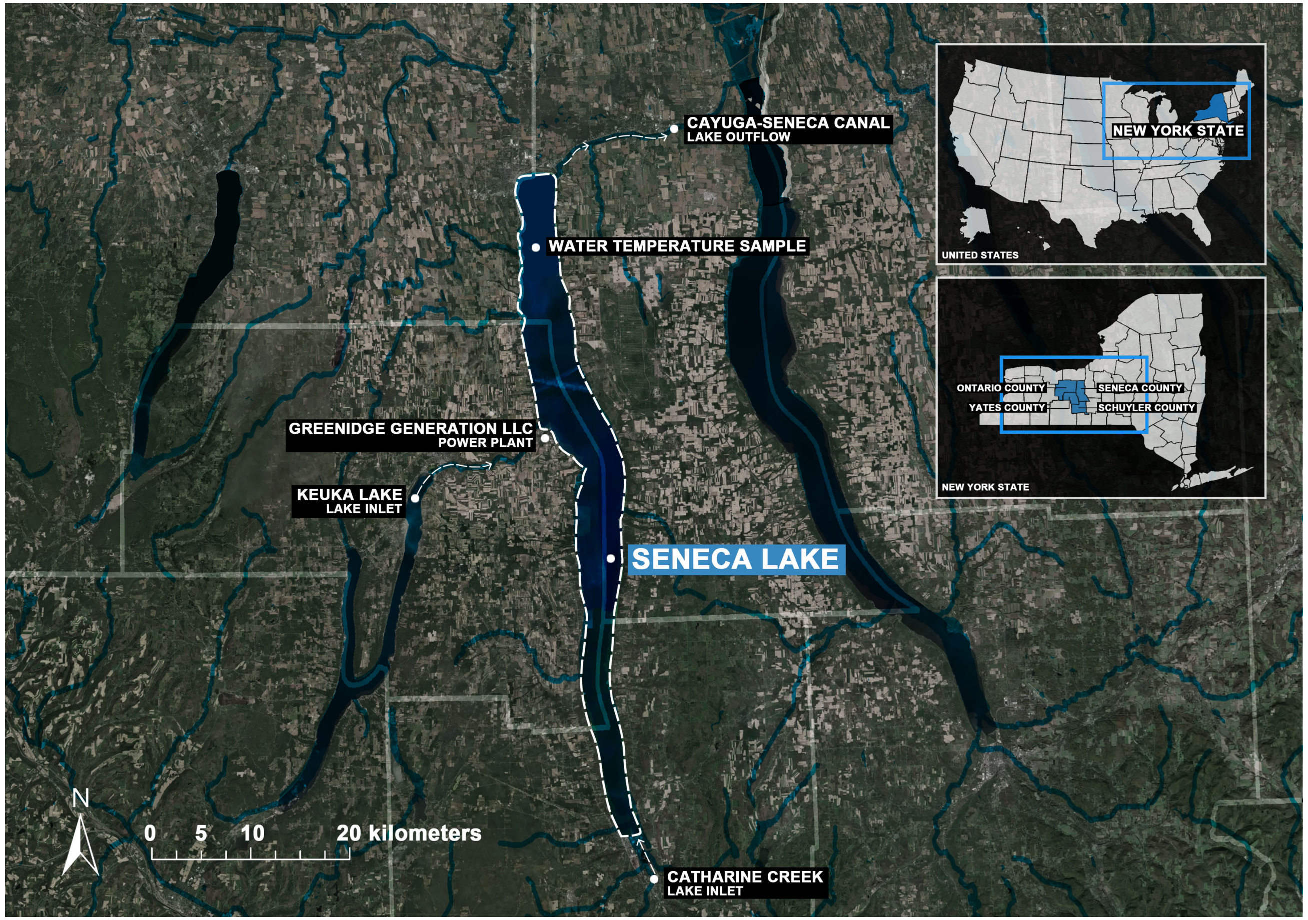
PART TWO

Data and Methodology

Site Information



Seneca Lake

- Maximum depth: 186 m
- Mean depth: 88 m

Deepest in the Finger Lakes

- Surface area: 175 km^2
- Water volume: 15.9 km^3

Largest in the Finger Lakes

- Warm monomictic lake
  - Circulate during the winter
  - Stratify during the summer
- Power plant for bitcoin mining

Data Source

Lake Characteristics		
Water Temperature	2006-2021	Seneca Lake Instrument Network
Stream Flow	2006-2021	United States Geological Survey
Environmental Factors		
Air Temperature	2006-2021	North American Land Data Assimilation System
Wind Speed	2006-2021	North American Land Data Assimilation System
Solar Radiation	2006-2021	North American Land Data Assimilation System
Precipitation	2006-2021	North American Land Data Assimilation System
Relative Humidity	2006-2021	Seneca Lake Instrument Network
Human Activity		
Land Cover	2006, 2008, 2011, 2013, 2016, 2019	National Land Cover Database
Cooling Water Discharges	2017-2021	United States Energy Information Administration
Cooling Water Temperature	2017-2021	United States Energy Information Administration

Research Method

- Trend analysis method (Anderson et al., 2021)
  - Simple moving average (smooth out short-term fluctuations)
  - Examine water warming trends:
    - Parametric method: simple linear regression
    - Non-parametric method: Theil–Sen estimates with the Mann Kendall Trend Test
- Contribution analysis method (Yang et al., 2020)
  - Principal component analysis (deal with highly correlated variables)
  - Calculate the contribution rates by forming two linear models ($\Delta R^2 = R_A^2 - R_B^2$)
- Path analysis method (Fatemi & Jebali, 2022, Tran et al., 2022)
  - Describes the direct and indirect relationship between a set of exogenous and endogenous variables
  - Value of the correlation path between the independent variable X_j and dependent variable $Y_{i'}$ ($\rho_{ji'} = \sum_{i=1}^{k} \sum_{z=1}^{l} \beta_{ii'} \beta_{zj} \rho_{zi}$)

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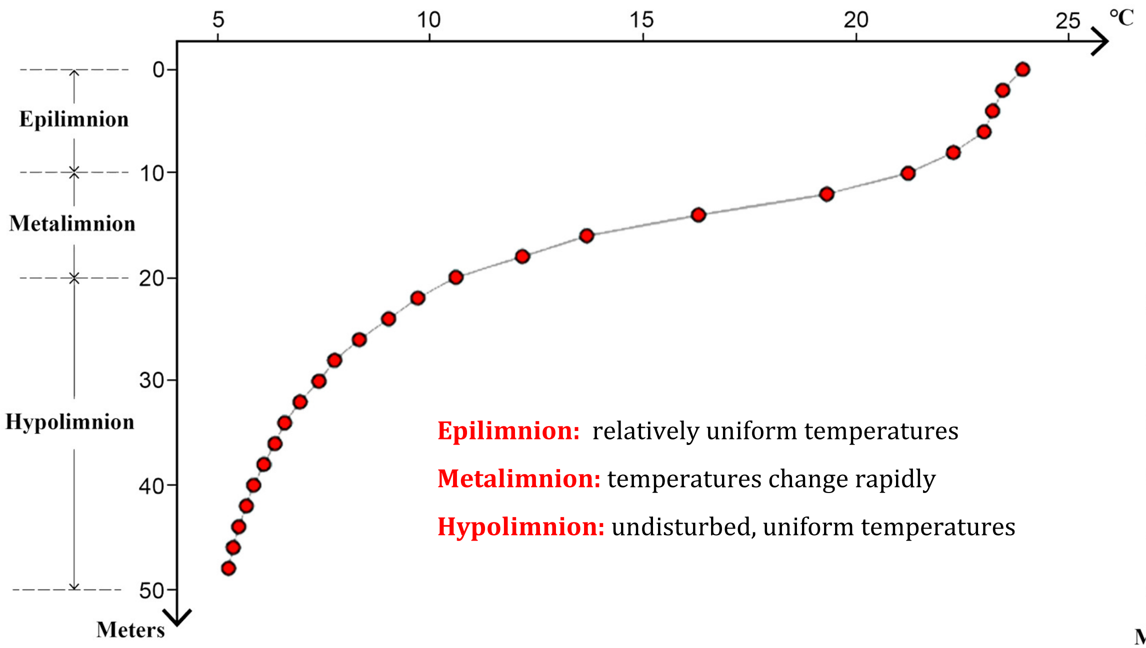
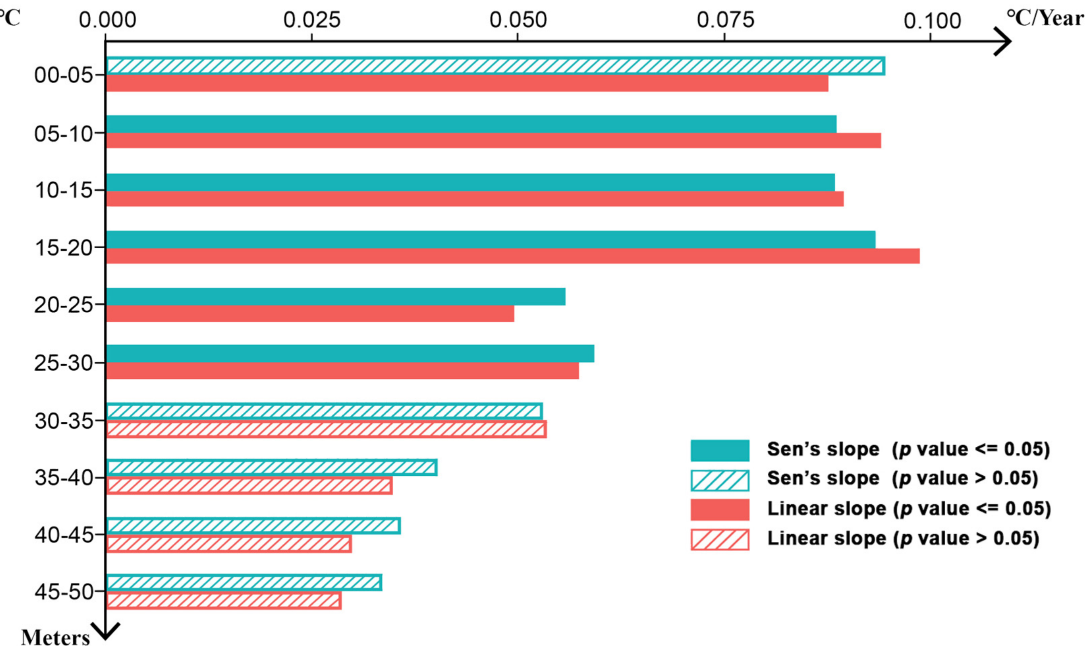
PART THREE

Results and Discussion

Long-term trends in vertical temperature profiles





- We have detected a monotonically increasing trend in summertime lake water temperatures through the water column.
  - Upward rates in the water column down to 20 m were between 0.85 and 1.0°C per decade (epilimnion + metalimnion)
  - At 20-30 m depths, we detect warming trends at a significance level of 0.05 but weakened to 0.5°C per decade (upper hypolimnion).
  - Change rates at 35-50 depths were still non-negative and between 0.3°C and 0.4°C per decade but insignificant (lower hypolimnion).

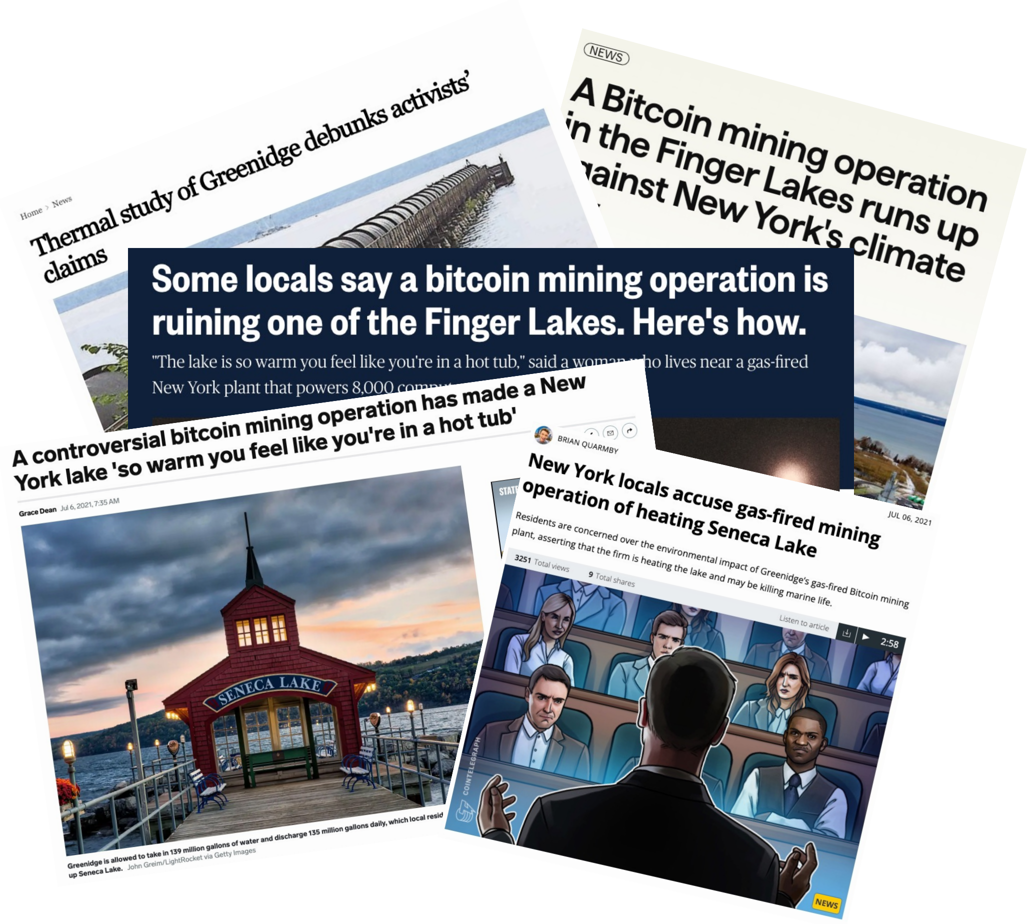
Deep water temperature parallels the rapidly increasing lake surface water temperature!

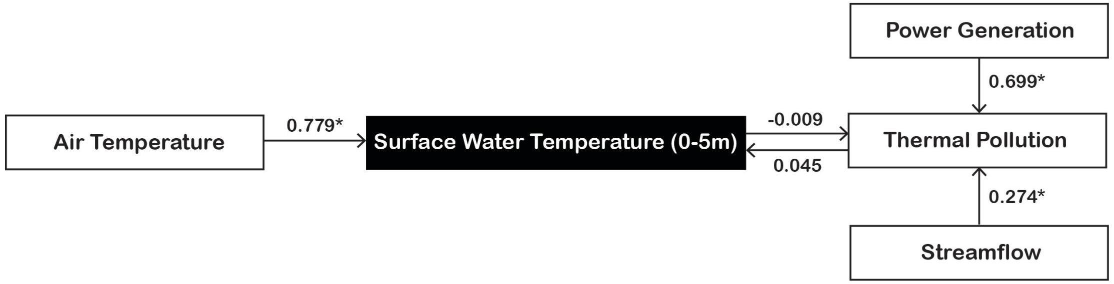
Climate change on long-term water warming

	Water PC1	*Heat* PC2	*Wind* PC3	*Human* PC4
Developed Area	0.32	0.21	-0.14	0.90
Agricultural Land	0.17	0.23	-0.02	0.95
Relative Humidity	0.76	-0.01	0.37	0.34
Lake Outlets	0.90	0.15	-0.04	0.29
Lake Inlets	0.89	0.15	-0.17	0.22
Precipitation	0.88	0.22	-0.03	0.00
Air Temperature	0.20	0.92	0.18	0.18
Wind Speed	-0.04	0.10	0.97	-0.12
Net Radiation	0.14	0.94	-0.04	0.21

Human activities amplify Earth's natural climate change effect on water warming!

Impact of the power plant on recent water warming





- Air temperatures dominate lake surface water warming
- No obvious interaction between thermal pollution and lake warming
- However, cannot exclude the adverse influence of thermal pollution
  - Long distance between the sampling position and the plant
  - Peak temperatures 6-27 °C above lake temperatures
  - Thermal pollution in the winter has a more adverse influence

No obvious impact of thermal discharge on water temperatures several miles north of the plant!

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PART FOUR

Conclusion

Conclusion

- **Take-home message:**
  - Many earlier studies observed pervasive and rapid surface water warming around the world (O’Reilly et al., 2015; Yang et al., 2019, 2020), our results showed that the warming in the surface layer might extend down a few dozen or even hundred meters.
  - Previous studies suggested that climate warming was a critical driving factor for rapidly rising lake water temperatures (O’Reilly et al., 2003, 2015; E. J. Anderson et al., 2021), our results showed that human activities may amplify Earth's natural climate change effect.
- **Potential implication:**
  - Since the deepwater temperature is an essential factor in lake ecological environments (Hampton et al., 2008), our study will offer new insight for improving the lake ecology and supporting lake management.

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Thank you!
Q & A

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