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Enhancing Winter Climate Simulations of the Great Lakes: on the Importance of Integrating 3D Hydrodynamics with a Regional Climate Model

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Associate Director, Great Lakes Research Center

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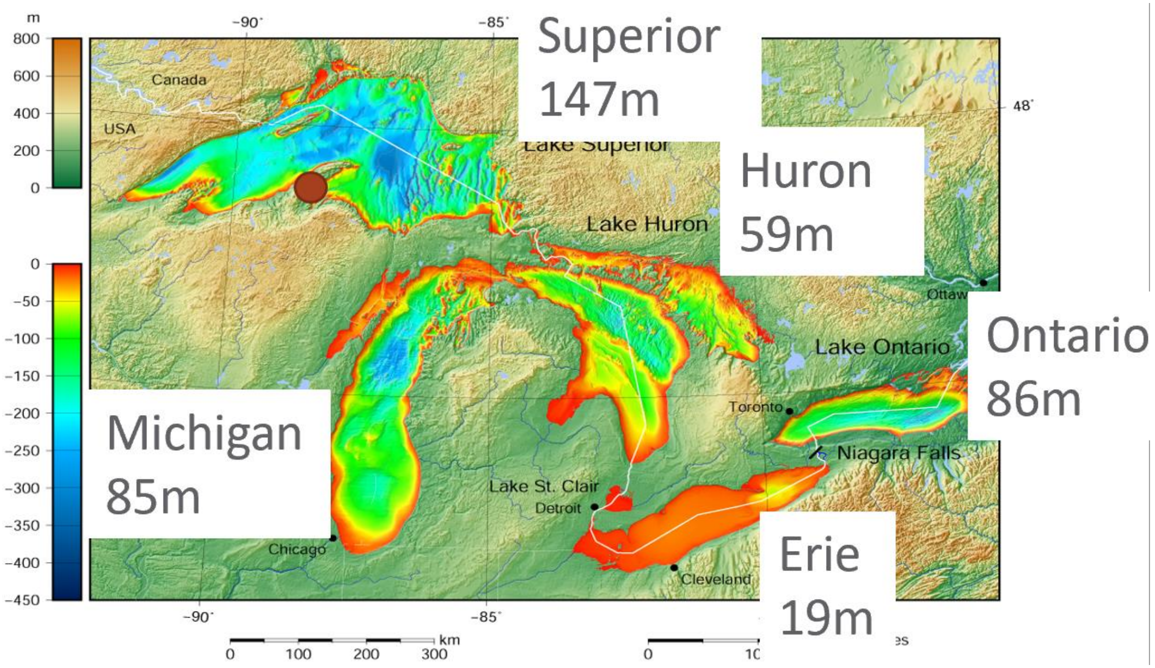
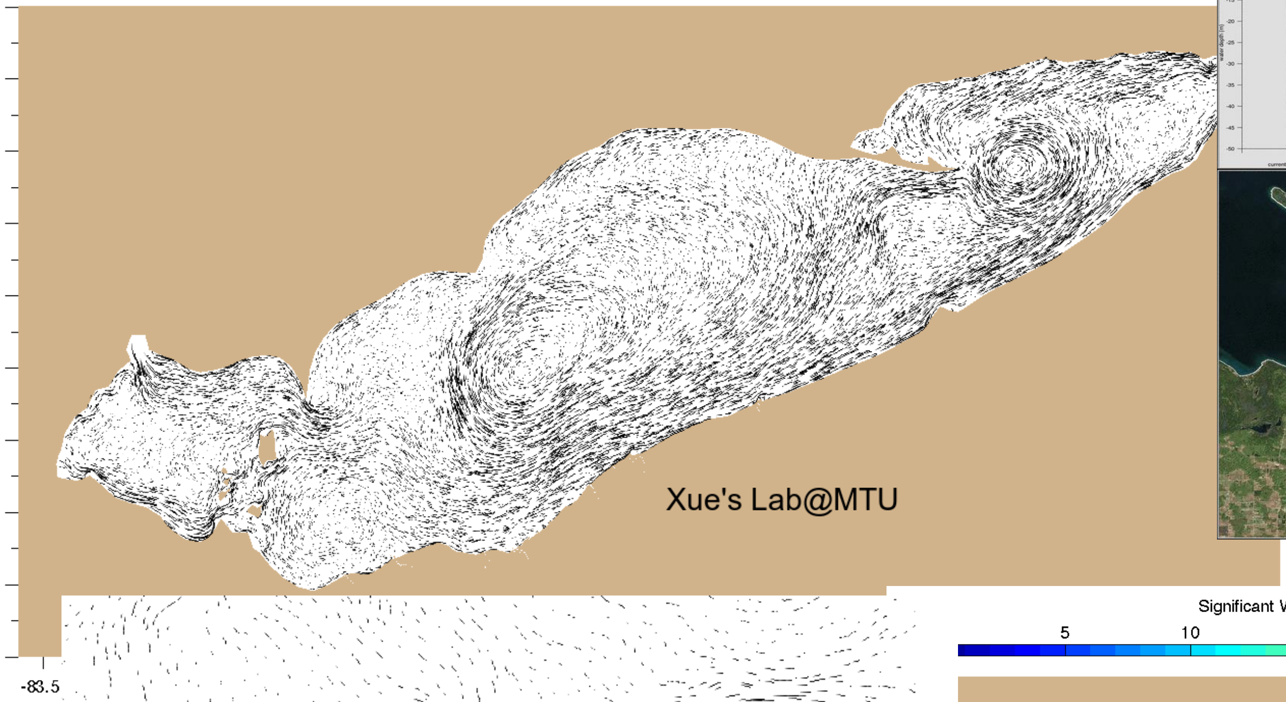
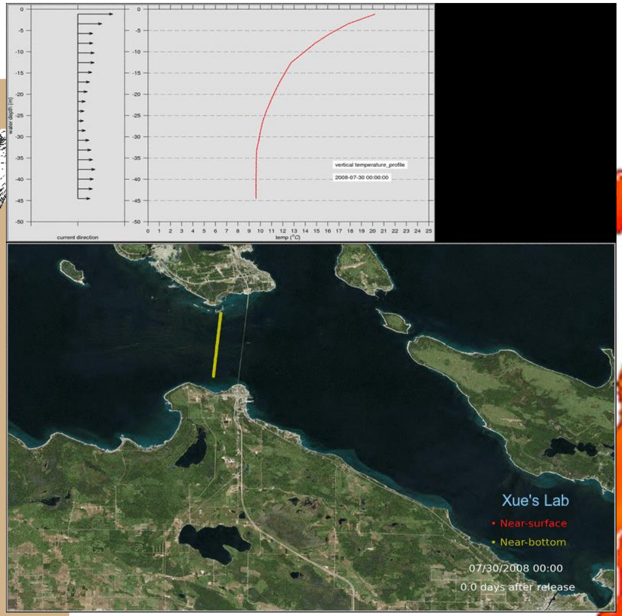
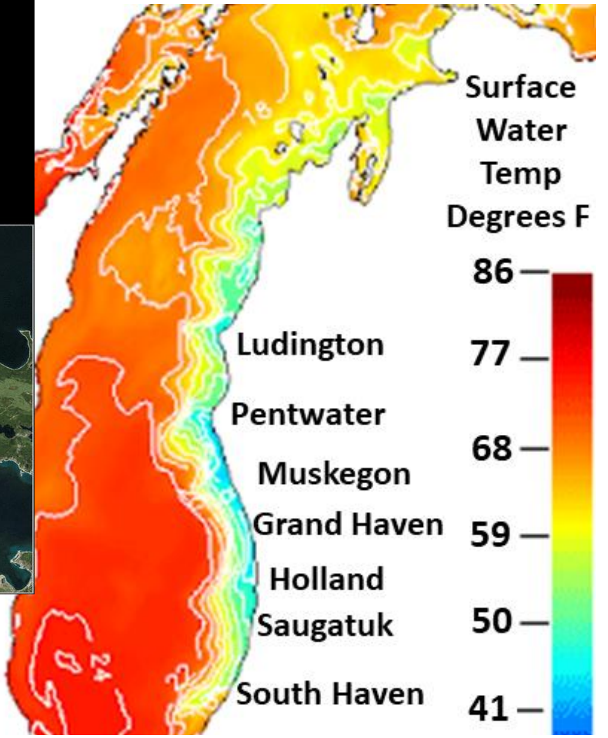
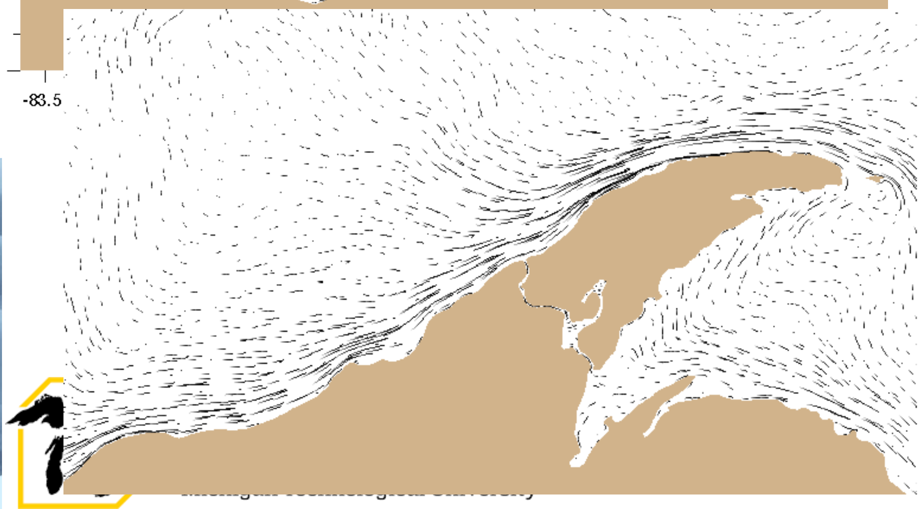


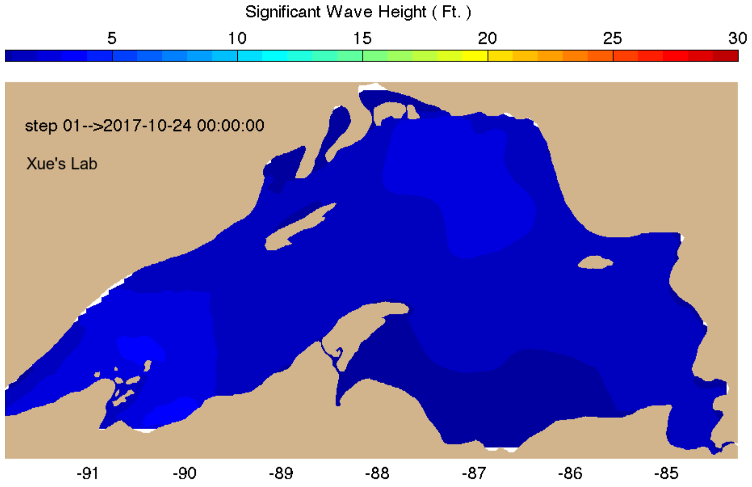
Oceanic features of the Great Lakes

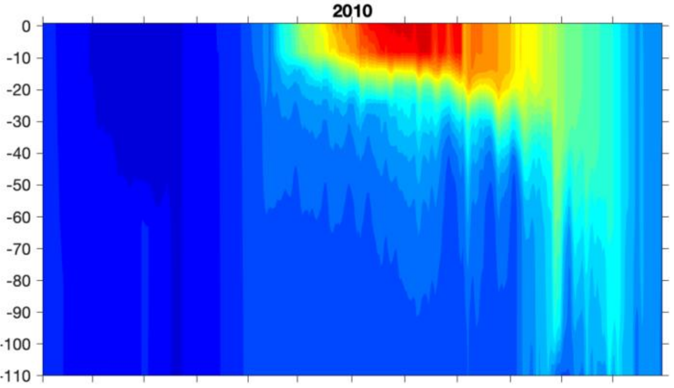




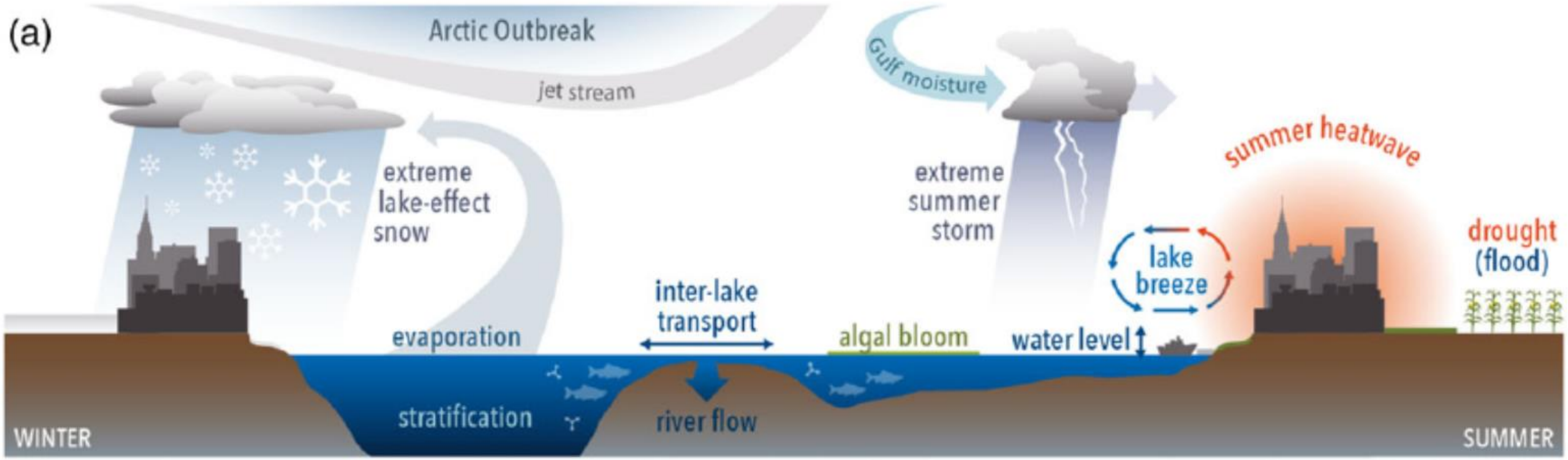








Need for an Integrated Land-Lake-Atmosphere Modeling System



"One of the primary reasons for the lack of an integrated modeling system for the Great Lakes is the difficulty in representing the exchanges and feedbacks between various components of the systems being modeled"

(Sharma et al. 2018 Earth's future (Commentary)

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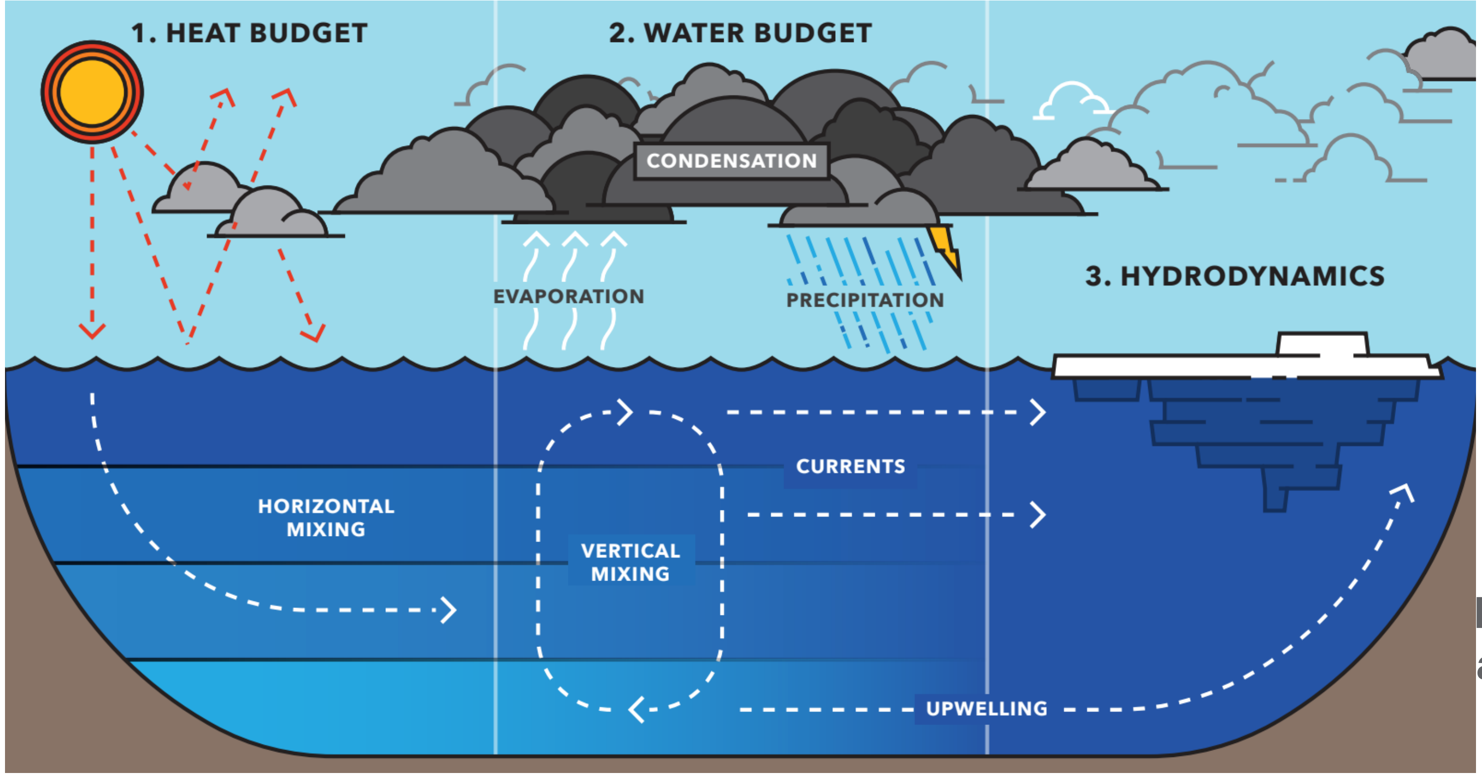
Atmosphere-lake-ice must be two-way *coupled*
3-D lake physical process must be resolved

Previous model limitations:

1) Climate models neglect the GLs or use 1-D column models to represent the GLs

2) 3-D hydrodynamic models are not “two-way” coupled with atmospheric/climate models



The new two-way coupled model is driven by heat budget estimates (how much energy enters the system); that affects the water budget and how much energy is exchanged between a lake and the atmosphere along with large lake processes that are dynamic and seasonally variable.

Interactive processes in a two-way coupled model (MTU news, 2016)

Atmosphere model

3-D hydrodynamic and ice model

Xue et al. 2017 GLARM

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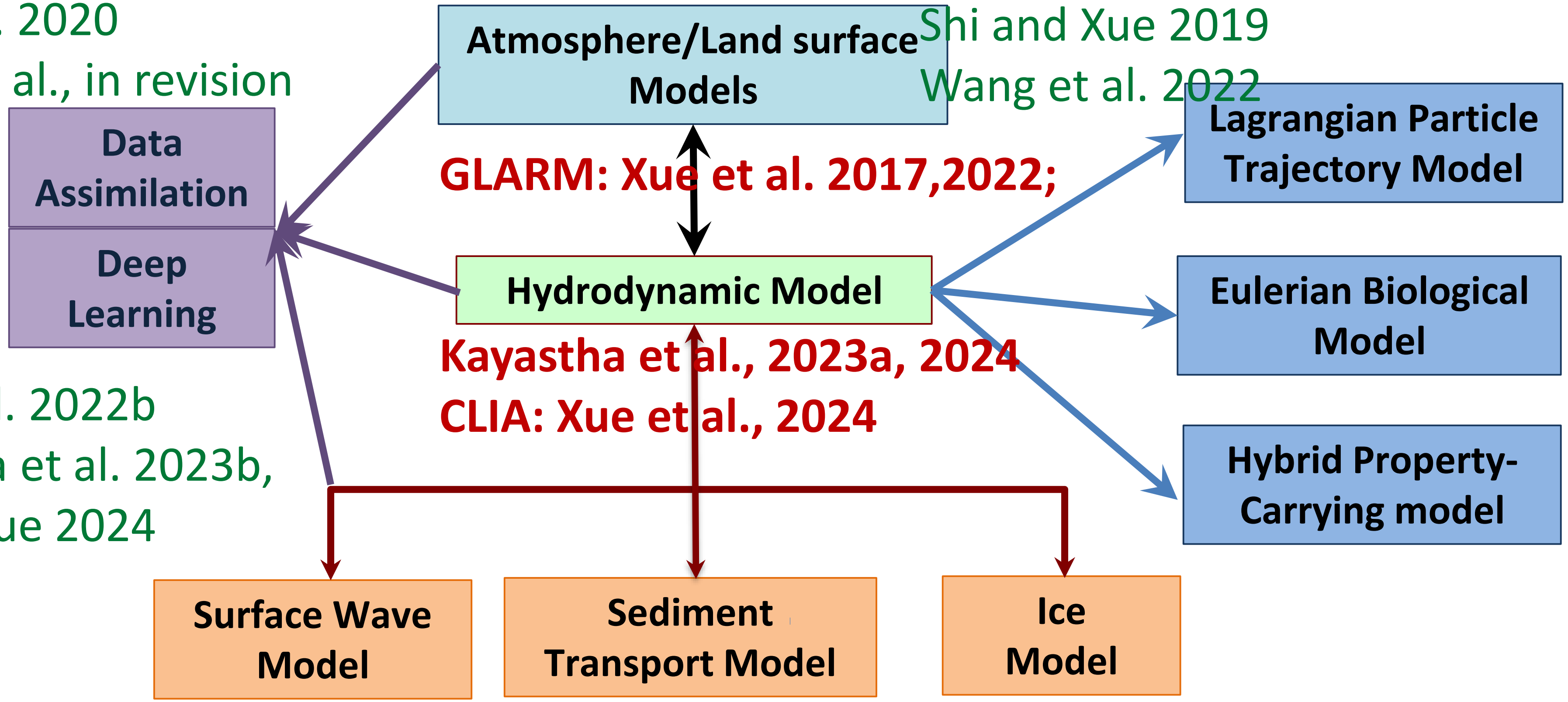
We develop an integrated regional earth system model (IRESM) for the Great Lakes region

Ye et al. 2020
Zhao et al., in revision

Shi and Xue 2019
Wang et al. 2022



Xue et al. 2018,2019; Huang et al., 2019
Zhou et al. 2024 (in revision)
Zhao et al., In-Prep

Xue et al. 2022b
Kayastha et al. 2023b,
Chen&Xue 2024

Huang et al. 2021a, b; Ye et al. 2019; Zhu et al. 2024 a, b

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Coupled Lake Ice Atmosphere (CLIA) NUWRF (15 and 3 km)-FVCOM (1-4km)

Winter simulation: 2014-11-01 to 2015-03-31

Exchange variables:

NUWRF to FVCOM

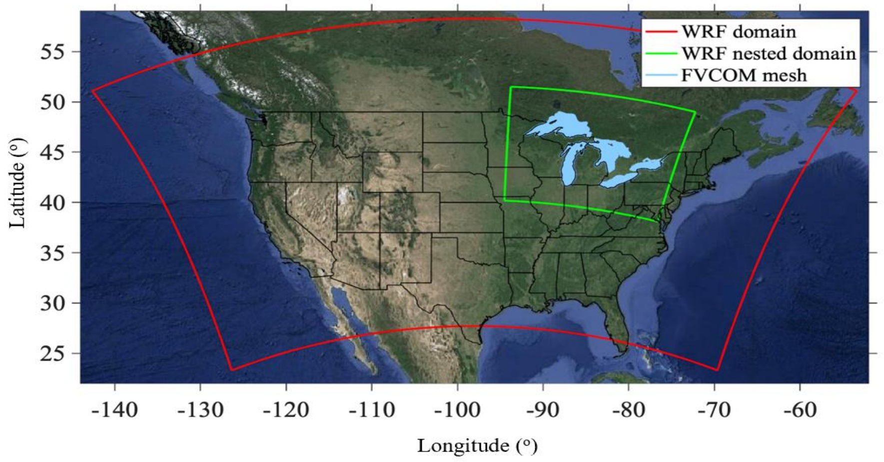
Evaporation, precipitation, air temperature, air pressure, downward shortwave, downward longwave, total cloud cover, specific humidity, relative humidity, U-wind(10m), V-wind(10m)

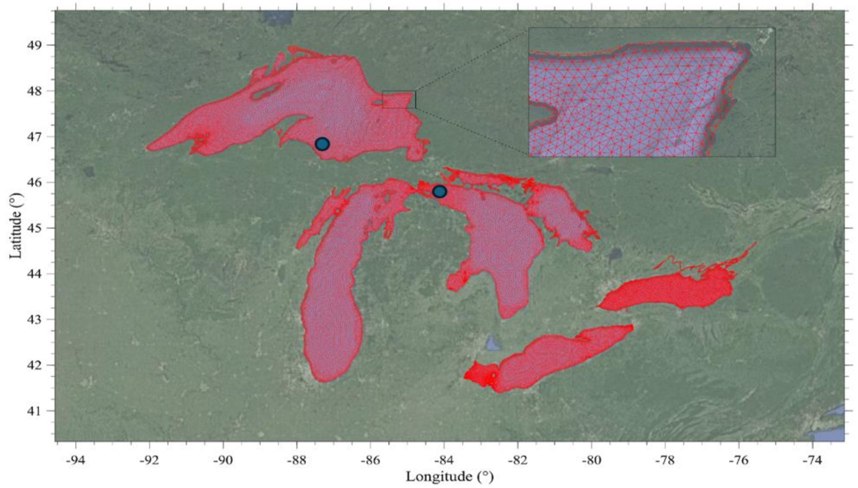
FVCOM to NUWRF

Lake surface temperature, surface ice cover, u-current velocity, v-current velocity,

Information exchange frequency: Hourly

NU-WRF model is also coupled with the default 1D Lake Ice Snow and Sediment Simulator (LISSS) for comparison (Notaro et al., 2021).





FVCOM: 3D hydrodynamics , circulation, thermal strucutre
Ice dynamics, and ice thermodynamics

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What processes are missed in 1D lake models but captured by 3D lake models for the better performance in winter seasons?

Experiment	3D currents	Ice transport	Heat advective transport	Shear production in turbulence	Lake model
C1-1 (Lake3D)	Yes	Yes	Yes	Yes	FVCOM
C1-2 (Lake1D)	No	No	No	No	LISSS
C2-1 (NoIceTransp)	Yes	No	Yes	Yes	FVCOM
C2-2 (NoHeatAdv)	Yes	Yes	No	Yes	FVCOM
C2-3 (NoShearProd)	Yes	Yes	Yes	No	FVCOM

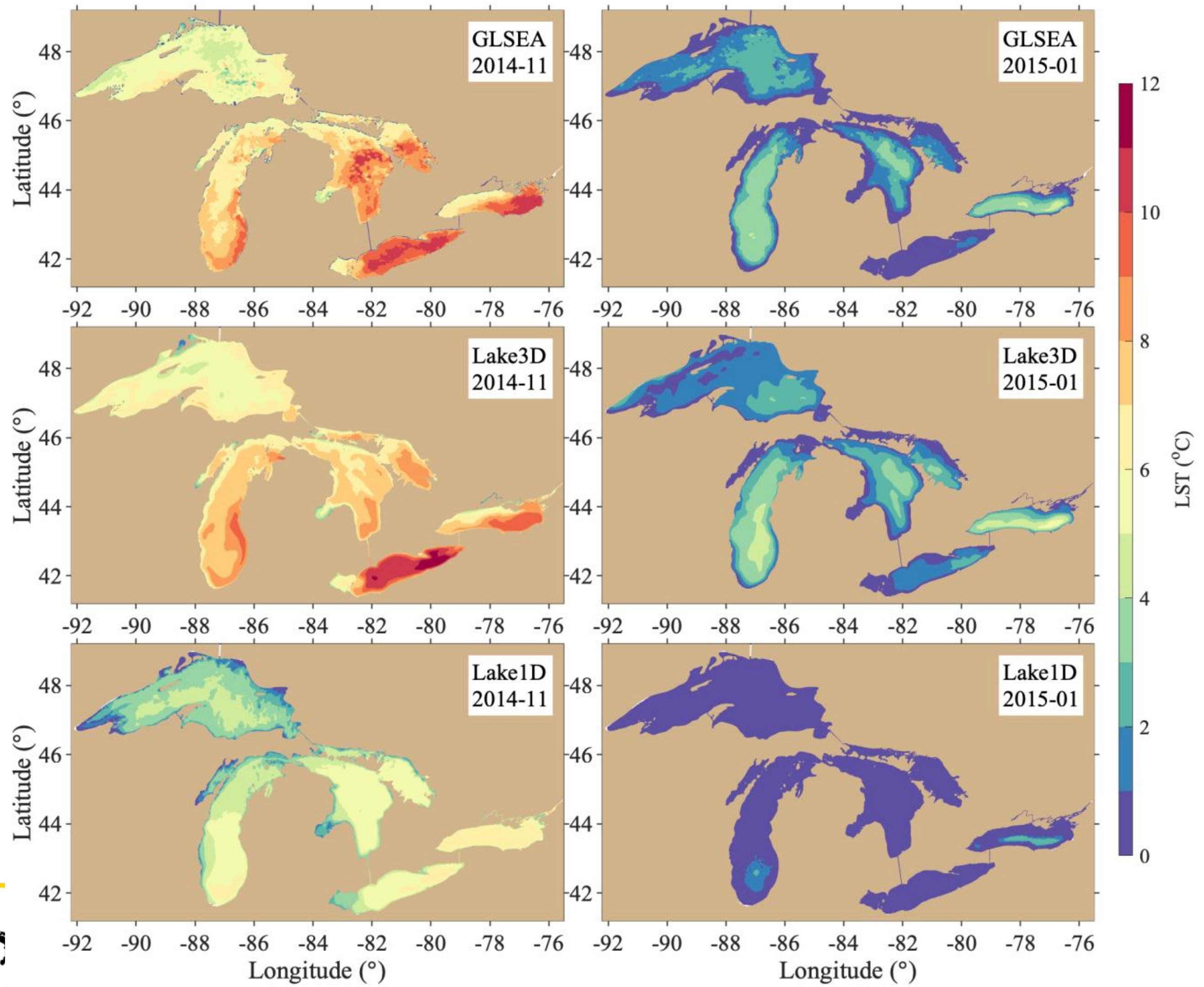
Skill Evaluation

Process-oriented experiments

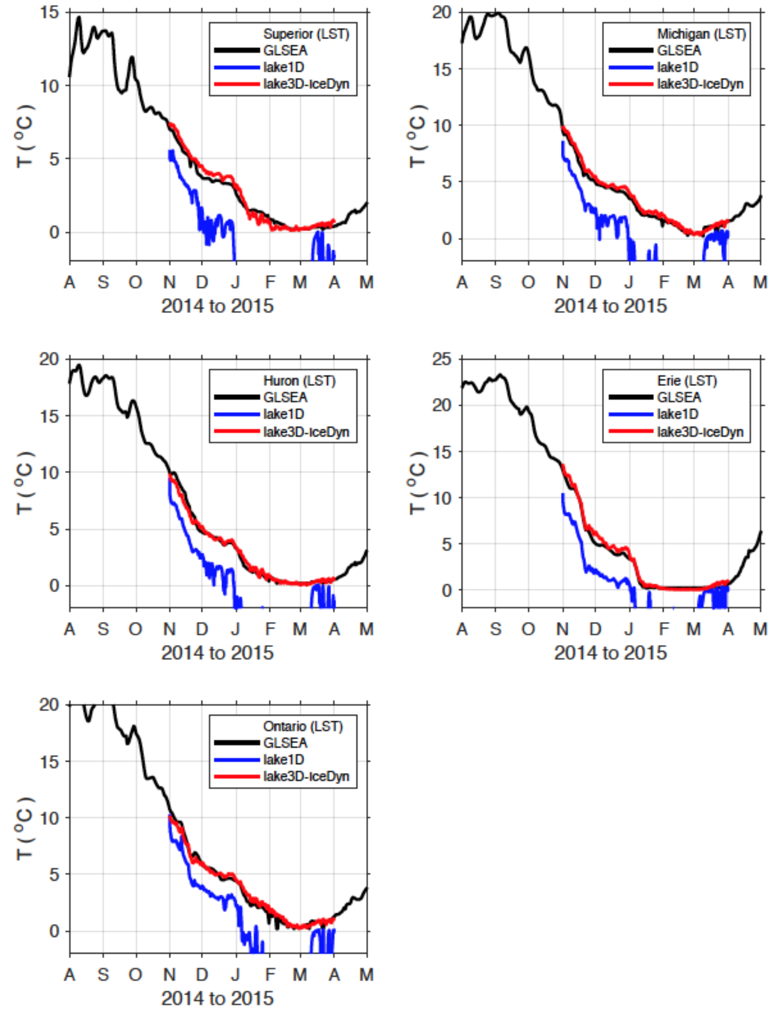
Within lakes

NUWRF-FVCOM captures the lake surface temperature (LST) spatiotemporal pattern

Nov 2014 | Jan 2015

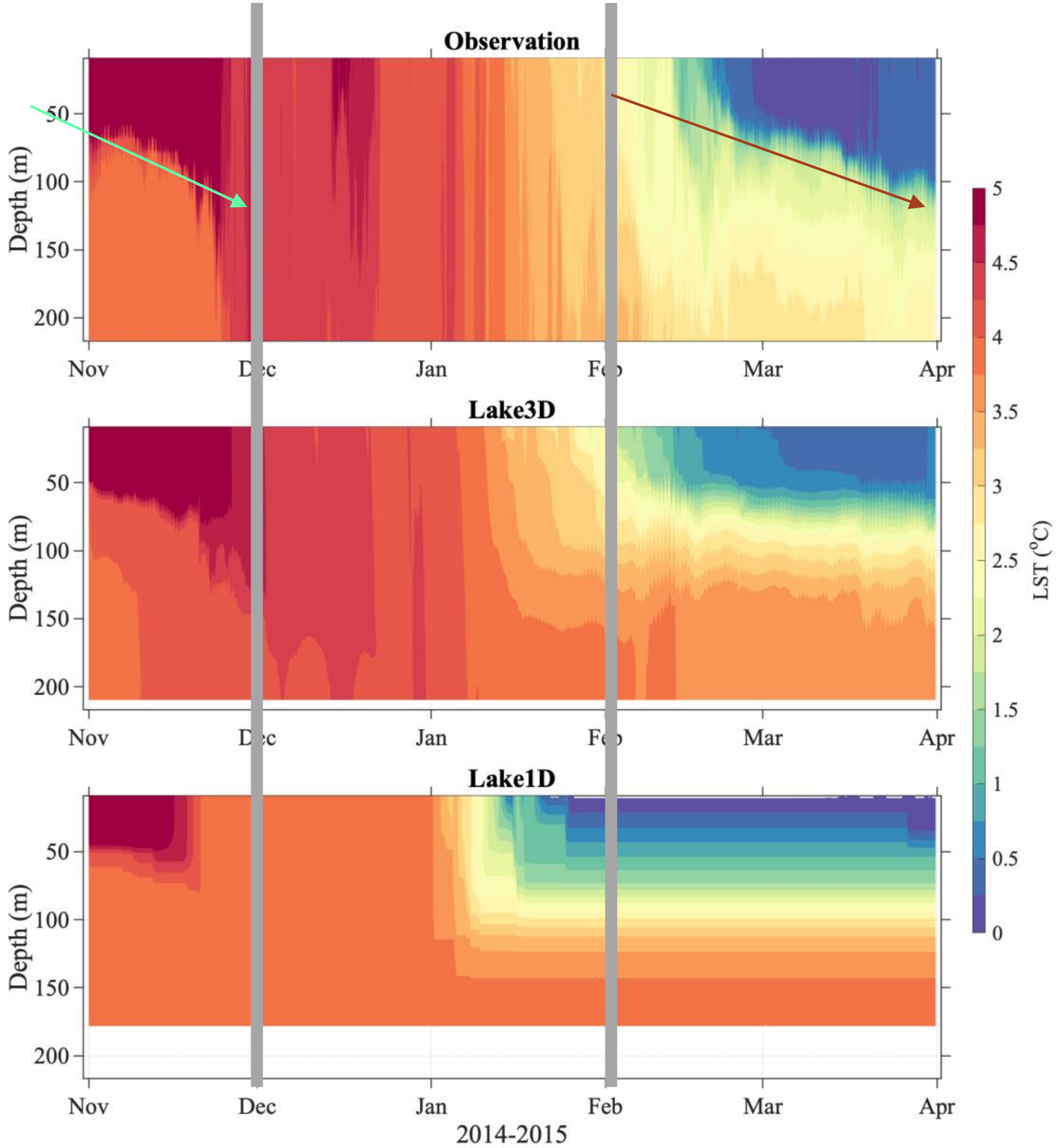


Lake-wide average LST



Within lakes

NUWRF-FVCOM better captured lake thermal structure



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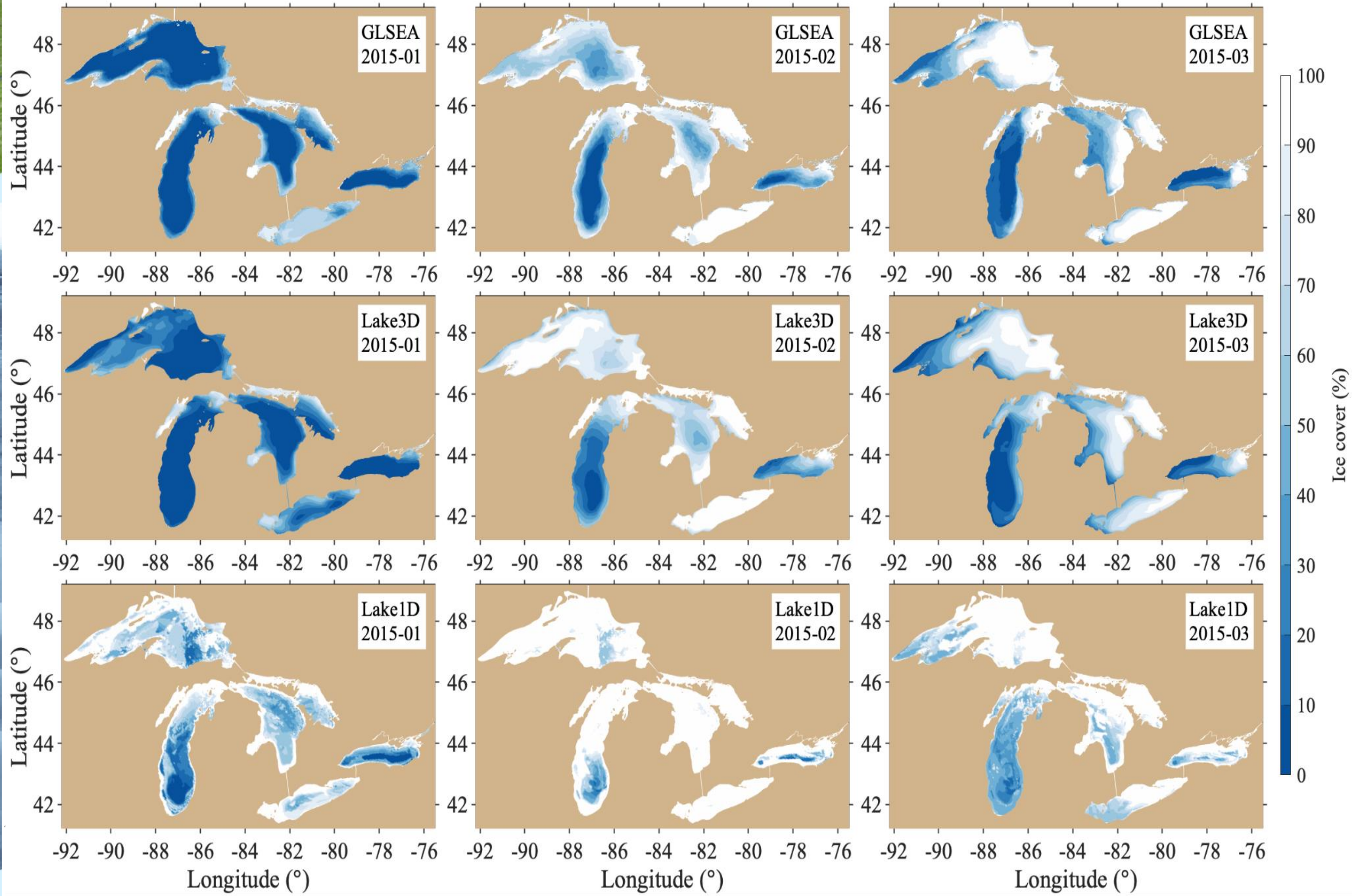
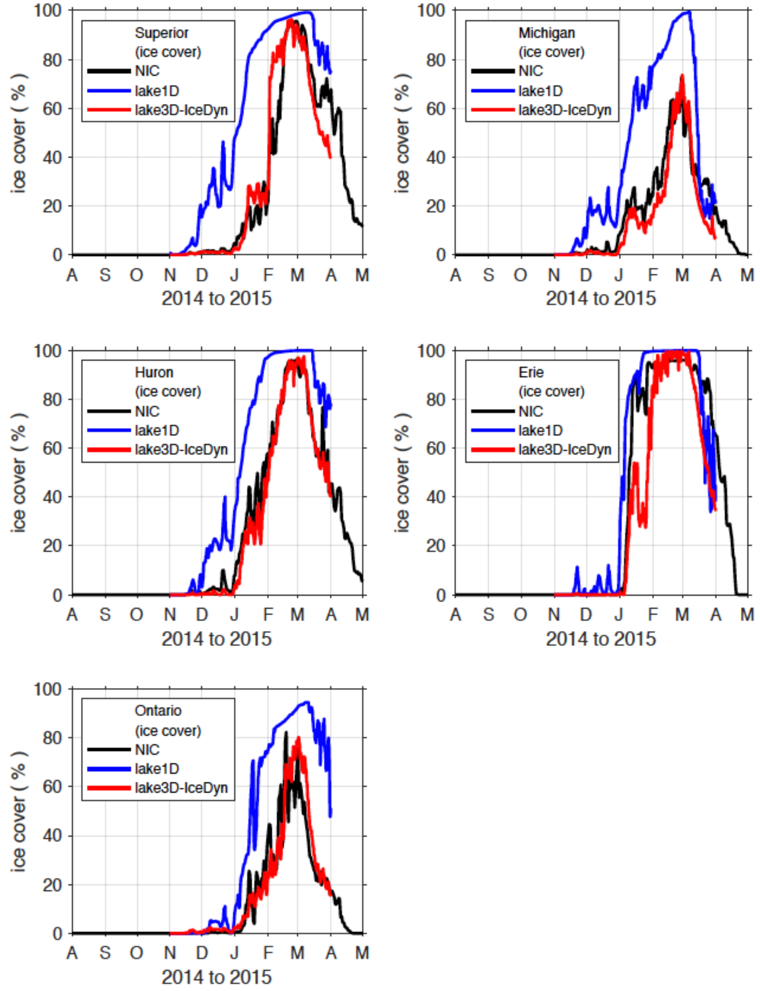
NUWRF-FVCOM corrected excessive ice cover

Within lakes



Lake-wide average ice cover



NUWRF-FVCOM improved surface heat fluxes

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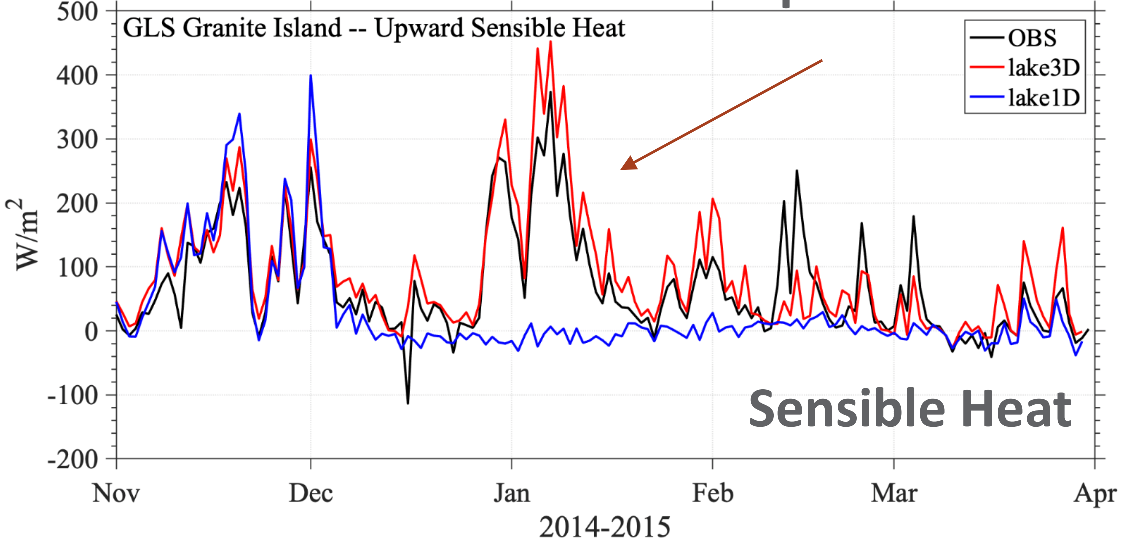
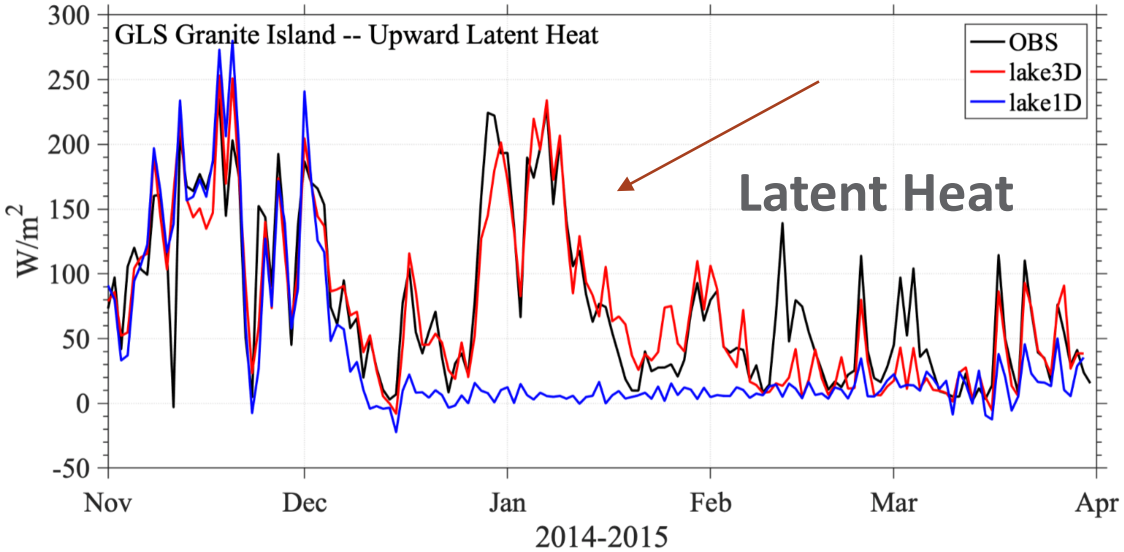
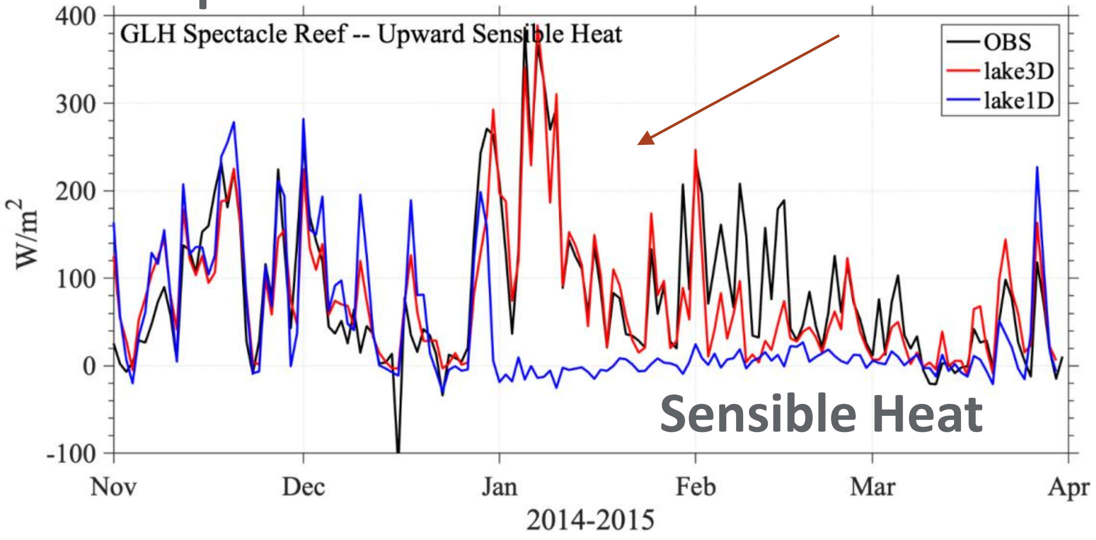
Beyond lakes

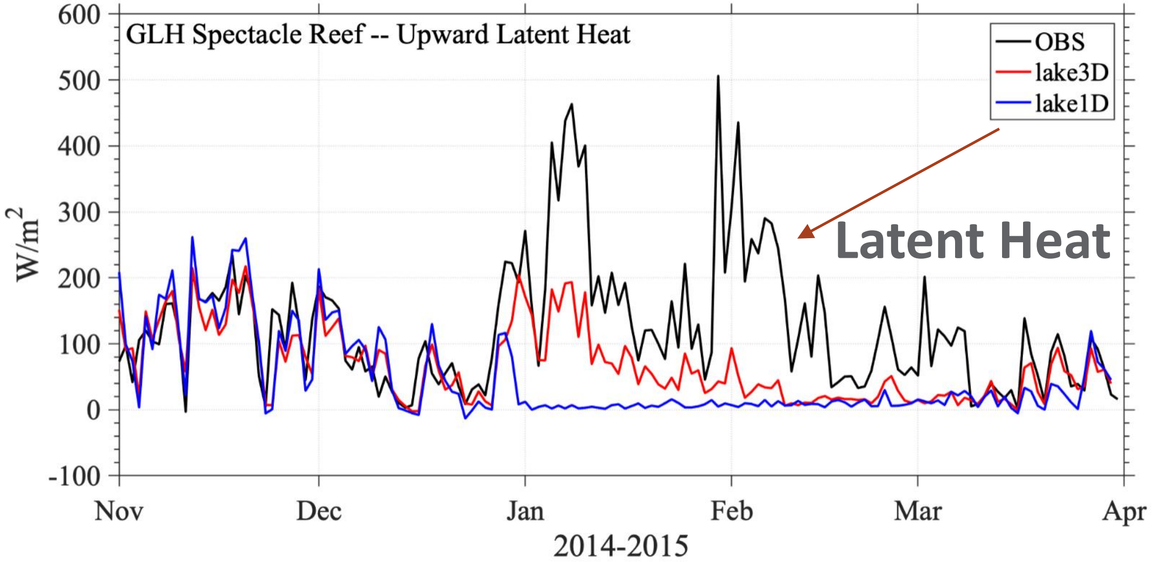
Granite Island Lake Superior



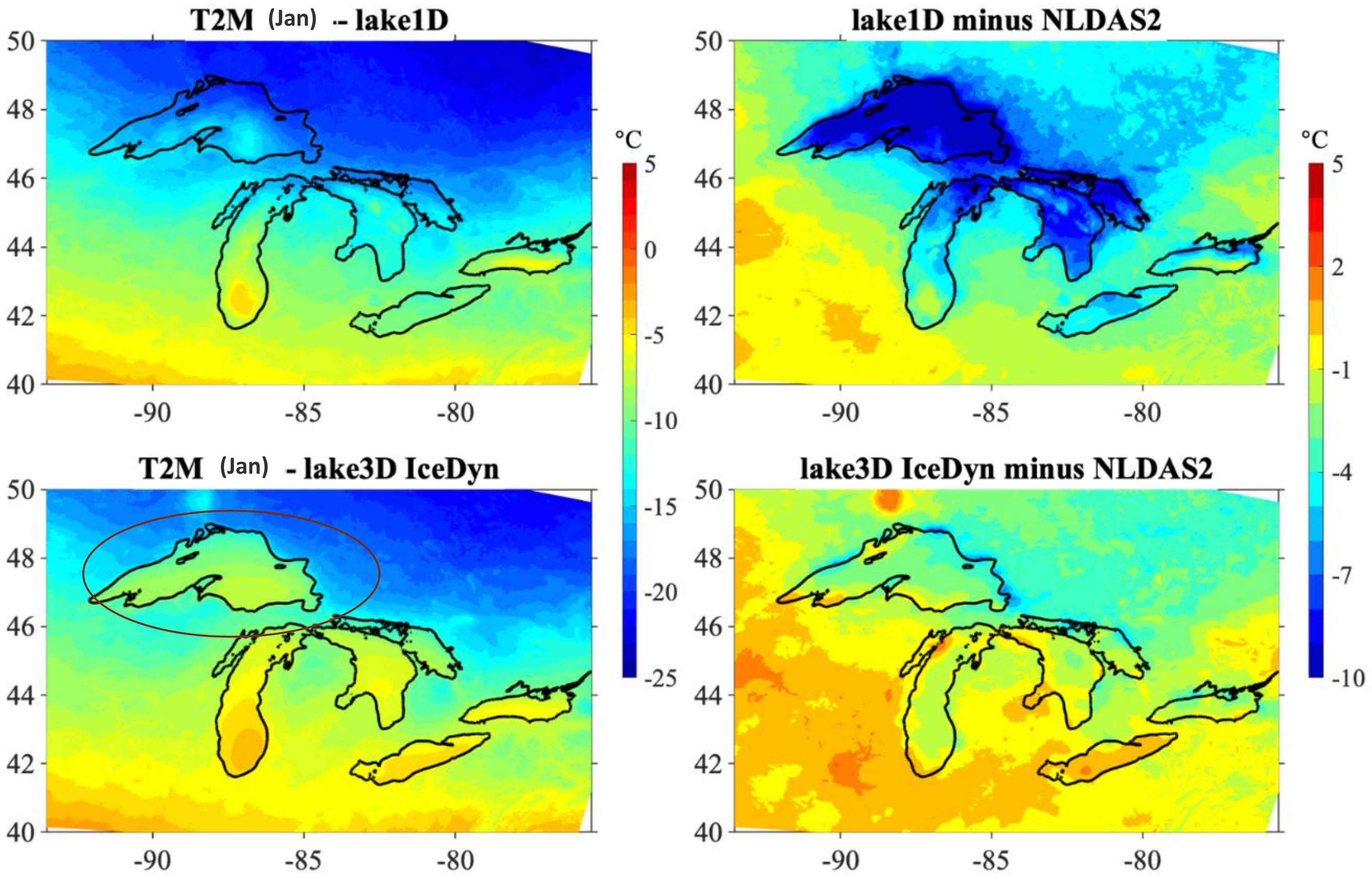


Spectacle Reef Lake Huron





NUWRF-FVCOM reduced cold bias of air temperature in NUWRF-1D lake model



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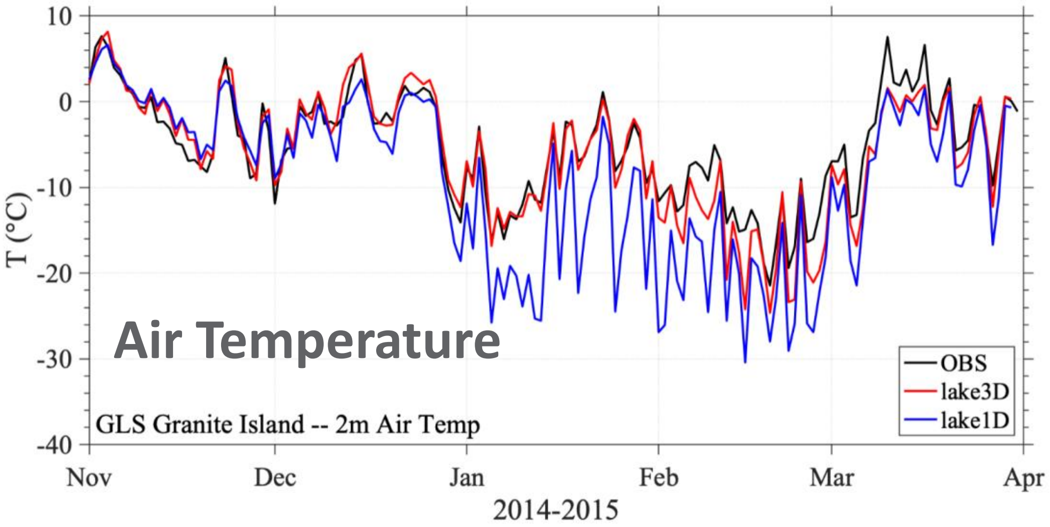
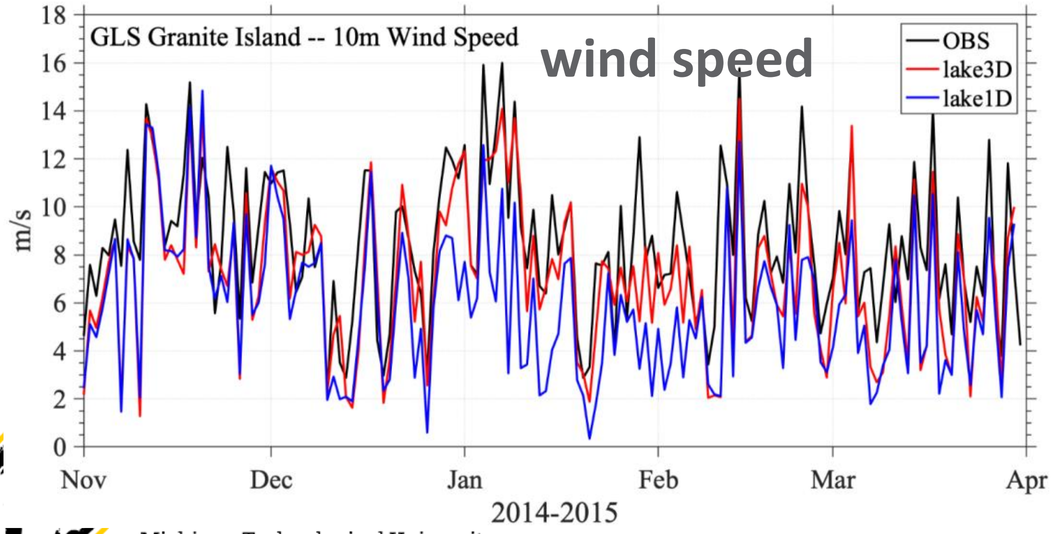
Beyond lakes

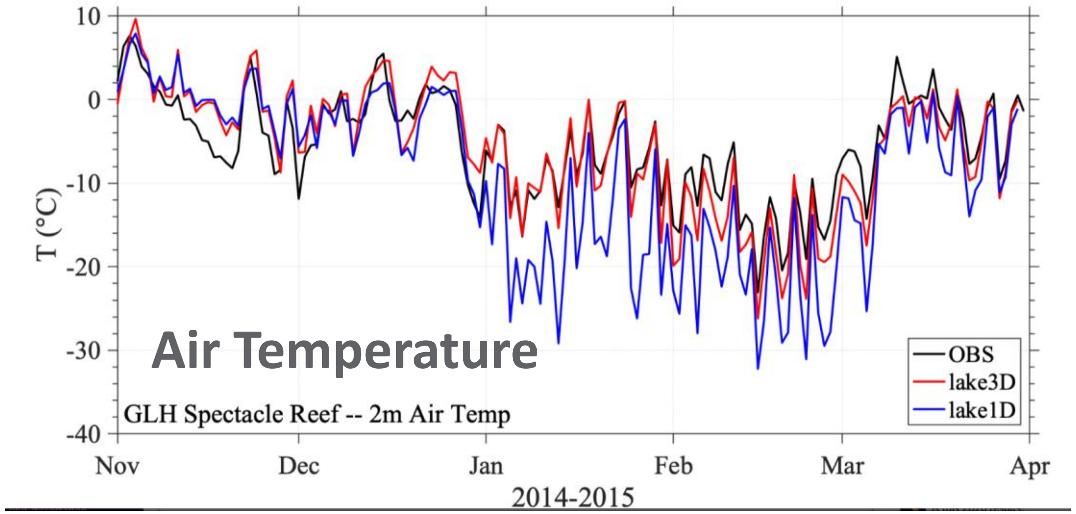
NUWRF-FVCOM improves the air temperature and wind simulations

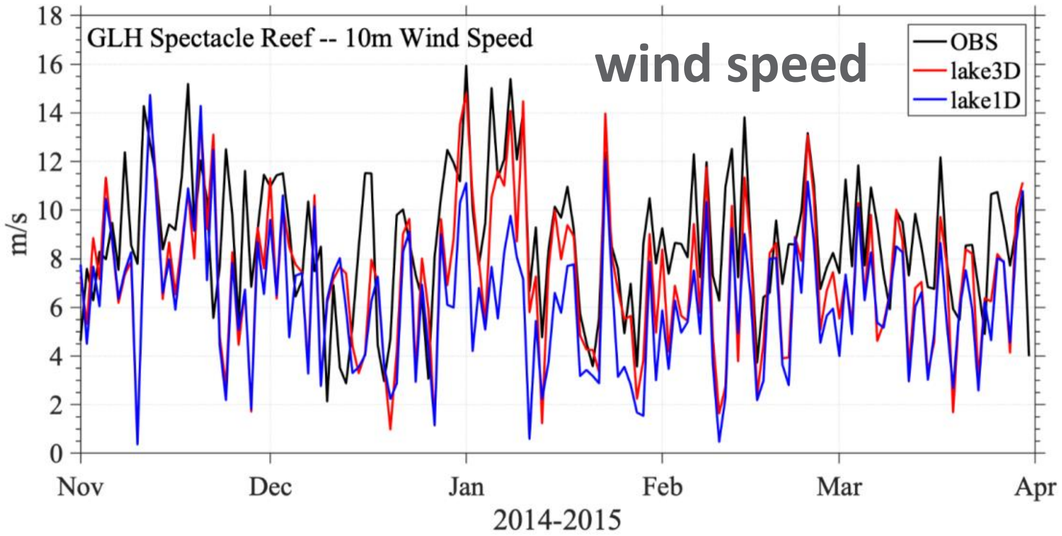
Granite Island Lake Superior





Spectacle Reef Lake Huron





What processes are missed by 1D lake models but captured by 3D lake models for CLIA's better performance in winter climate ?

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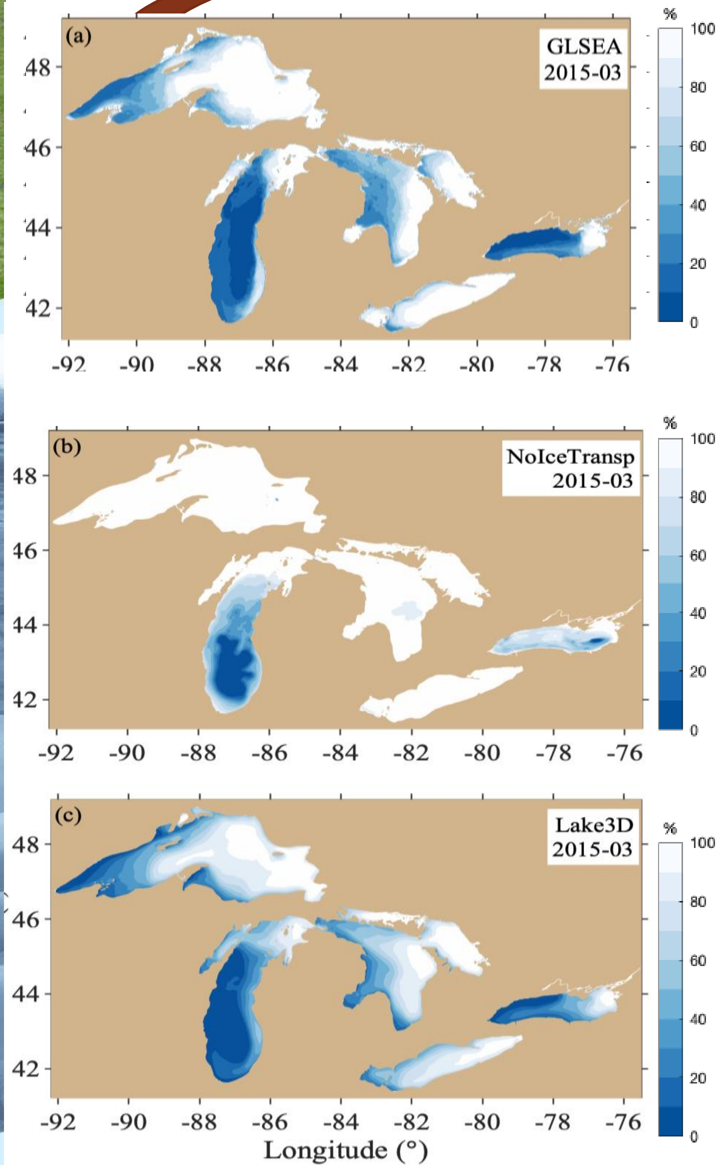
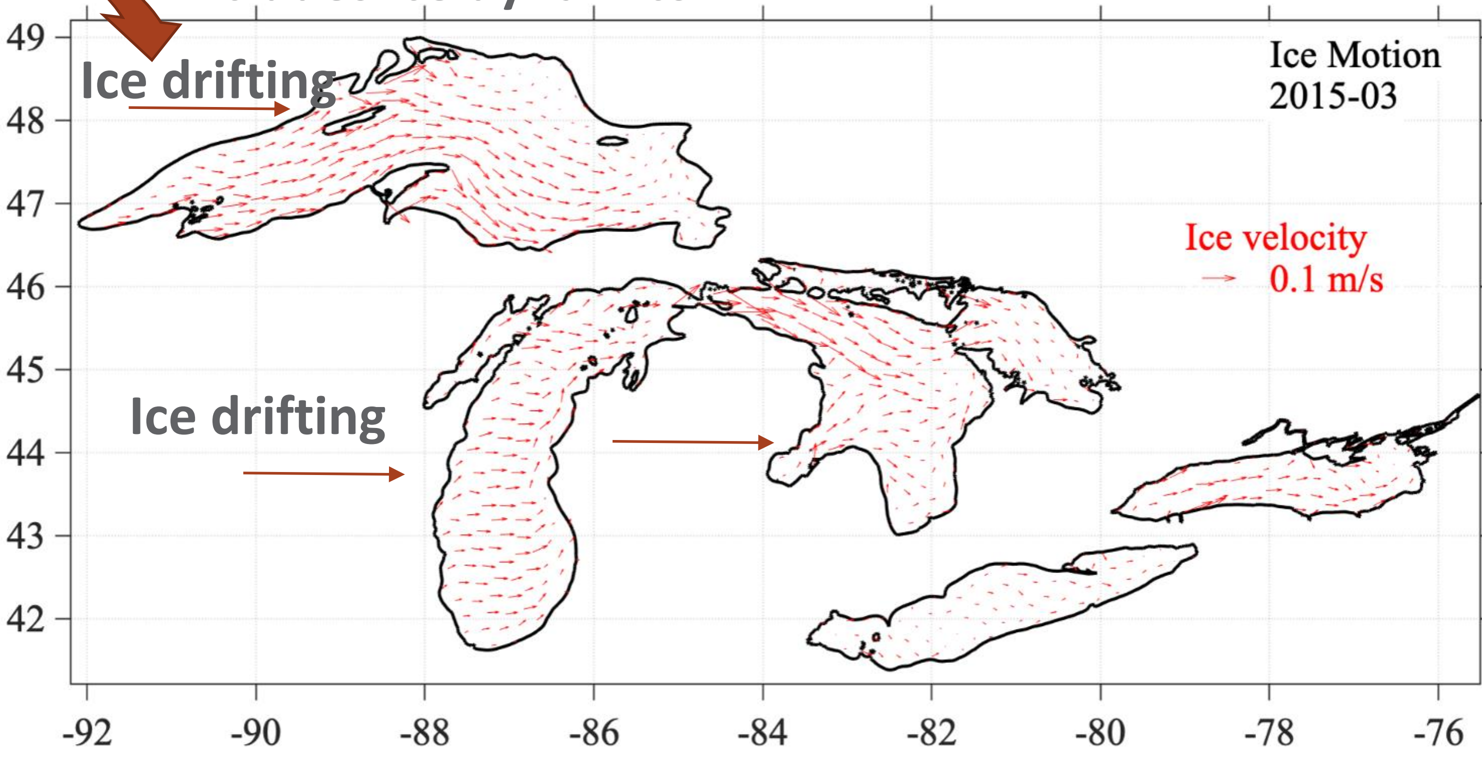
Ice movement that are critical to spatial pattern of ice cover, therefore air-lake energy flux

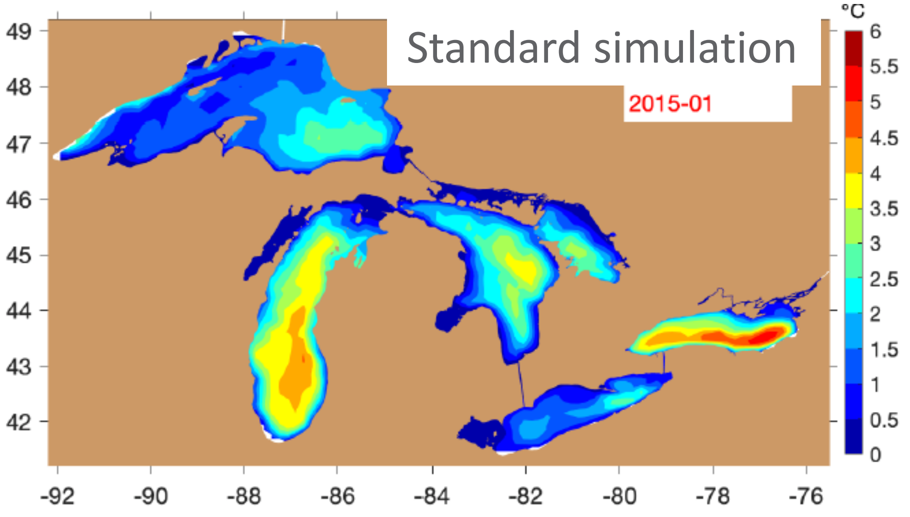


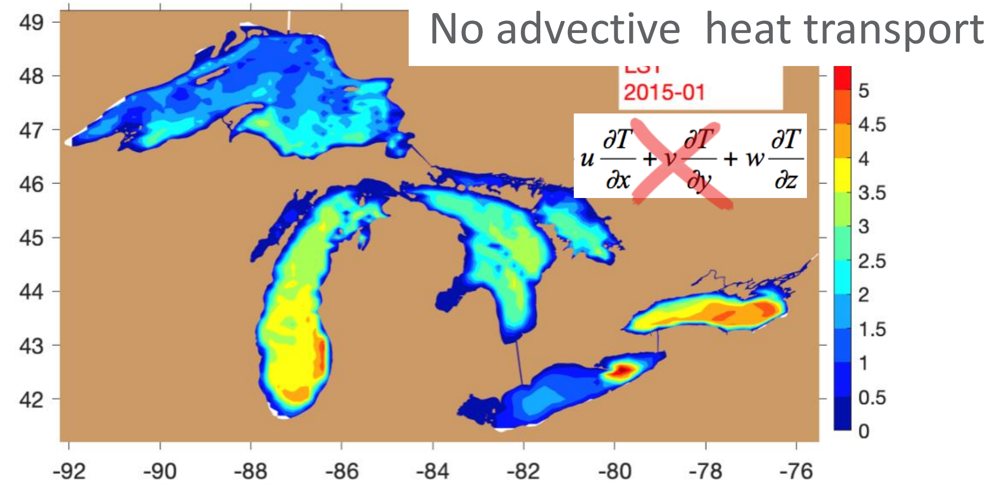
FVCOM 3D hydrodynamic model
Includes ice dynamics

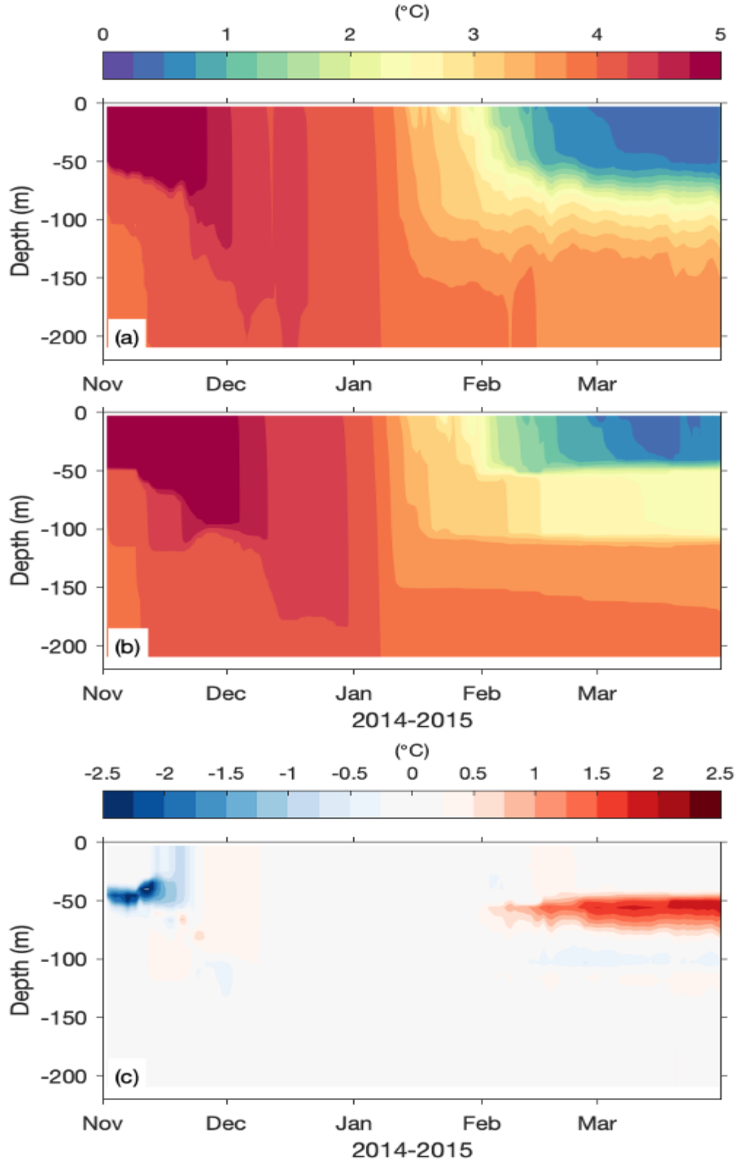
Mar 2015



Advective transport of heat influences subsurface thermal structure







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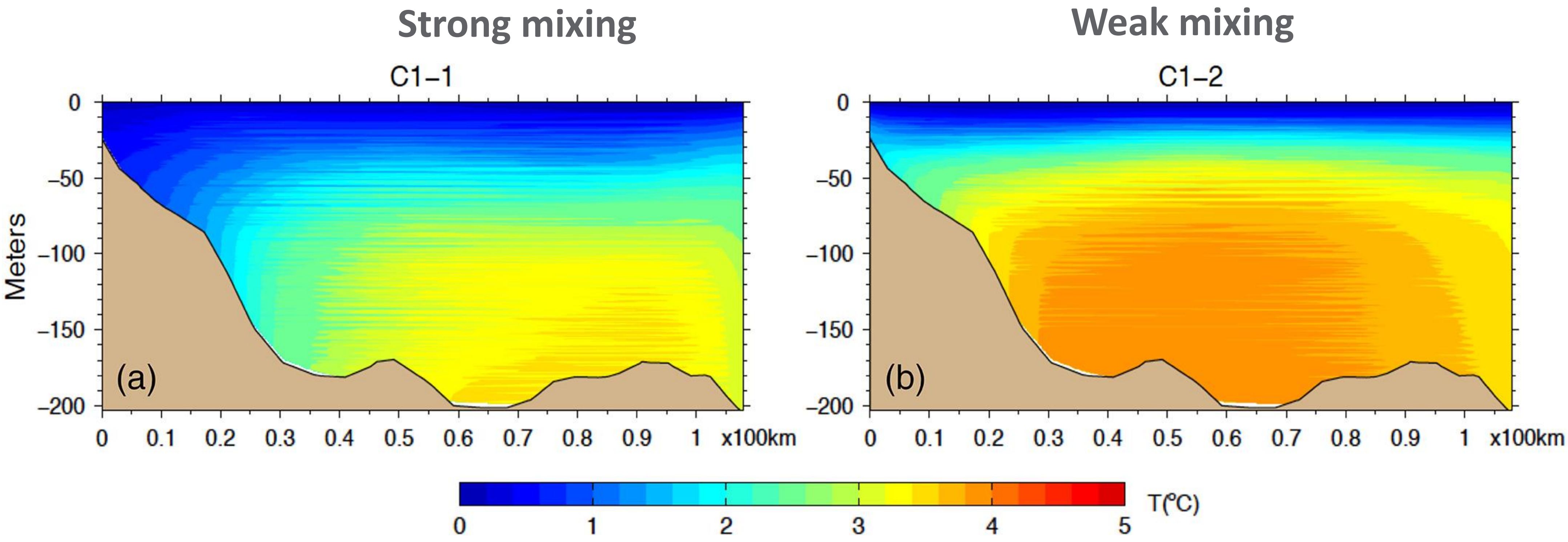
Why 3D lake model performs better?

Vertical turbulent mixing plays a key role in heat transfer, lake surface temperature, and ice formation



Ye et al. 2019

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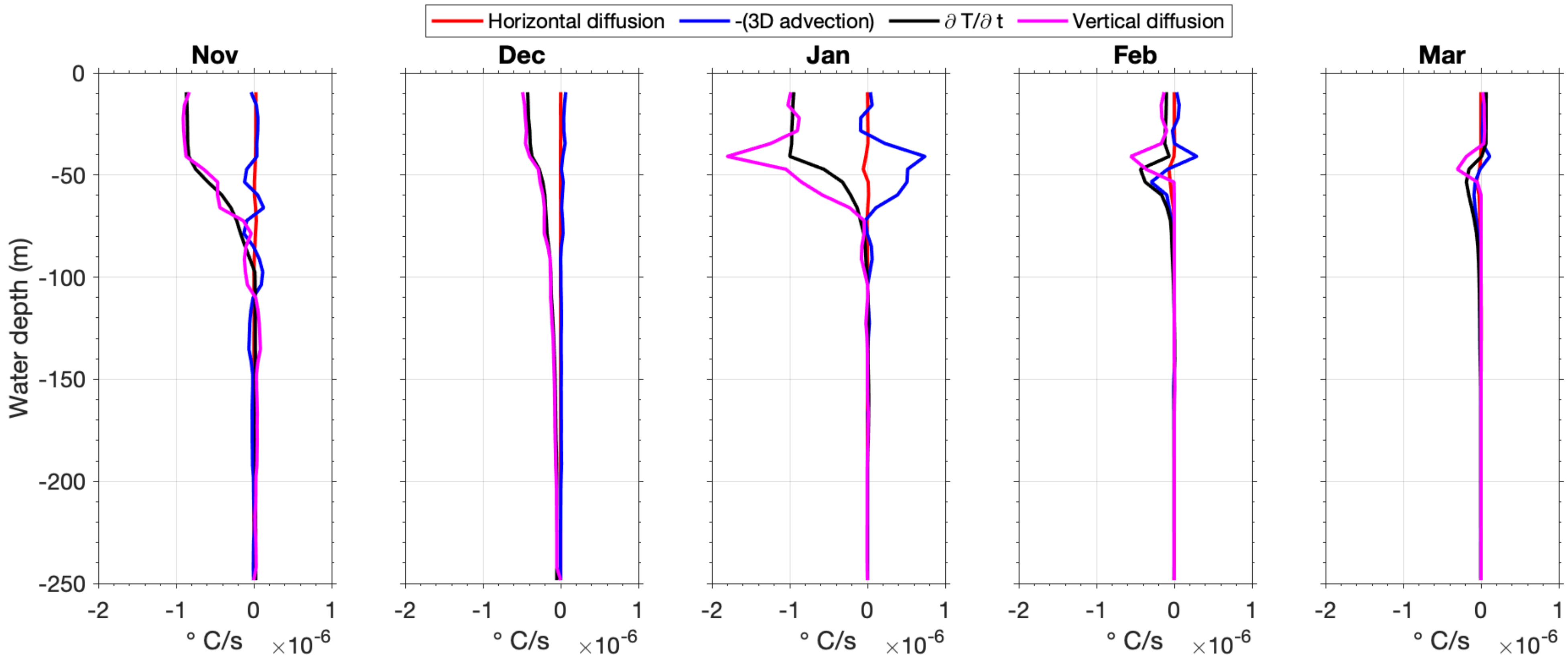
Contribution from each term of temperature governing equation

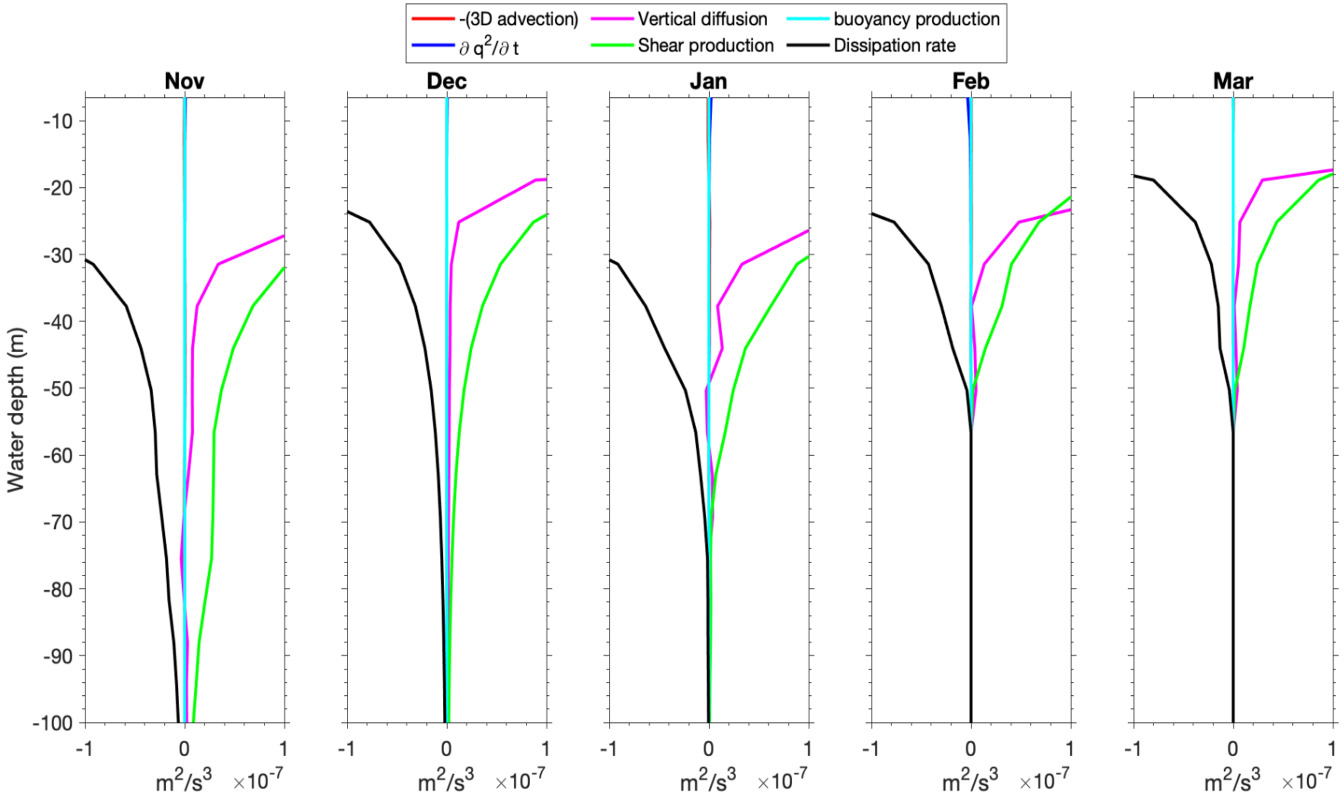
$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\left(K_h \frac{\partial T}{\partial z}\right) + F_T$$



Contribution from each term in TKE equation

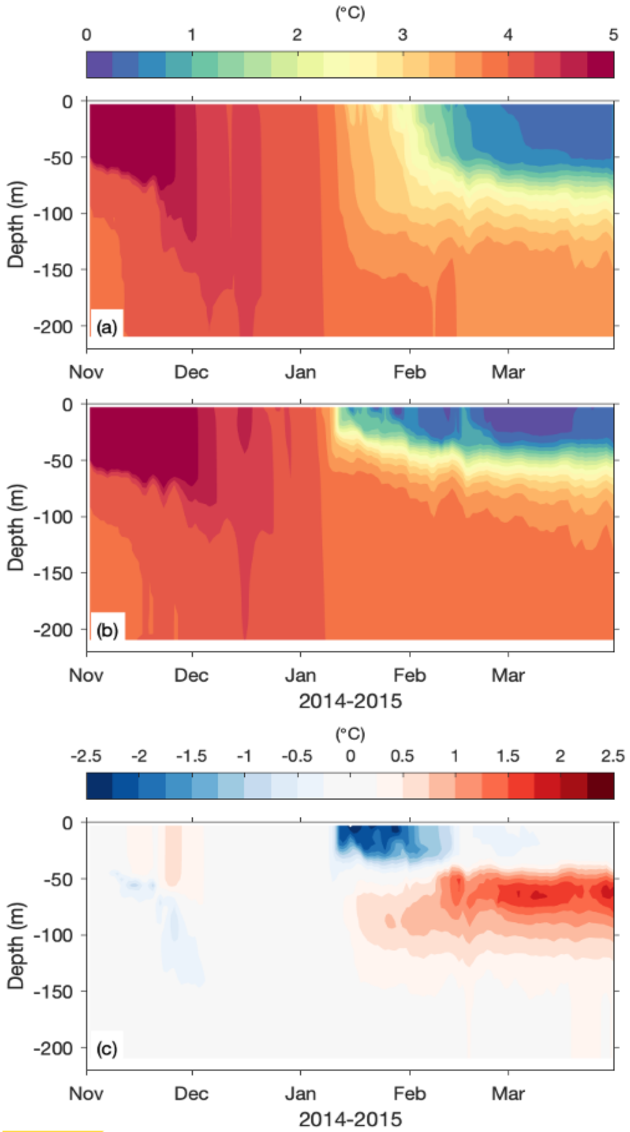
$$\frac{\partial q^2}{\partial t} + u\frac{\partial q^2}{\partial x} + v\frac{\partial q^2}{\partial y} + w\frac{\partial q^2}{\partial z} = P_s + P_b - \epsilon + \frac{\partial}{\partial z}\left(K_q \frac{\partial q^2}{\partial z}\right) + F_q$$

Shear production is often approximated as $P_s = K_m((\frac{\partial u}{\partial z})^2 + (\frac{\partial v}{\partial z})^2)$



TKE dissipation rate $\epsilon = q^3/Bl$

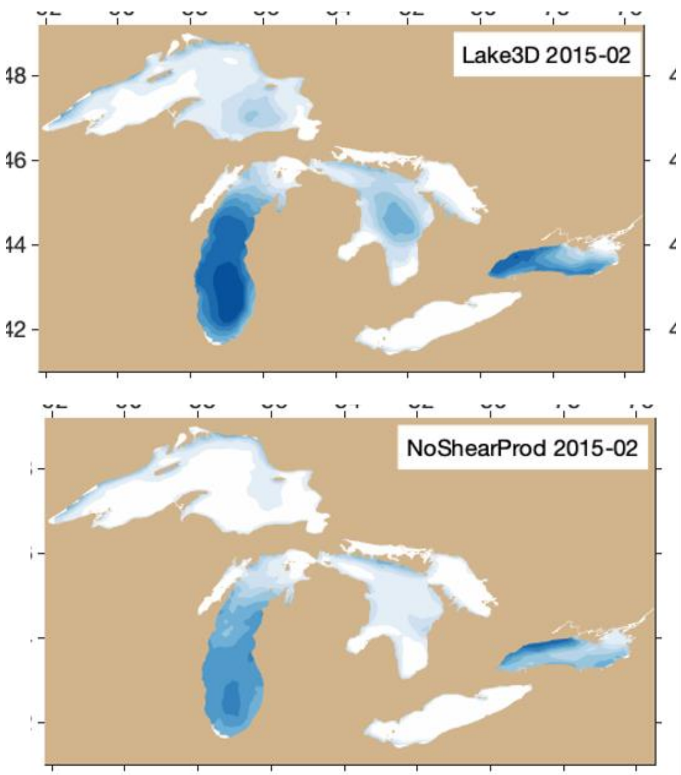
Without properly resolving share production reduces turbulent mixing



(Lake3D)

(NoShearProd)

their difference



Summary

This study has highlighted some key physical processes that differentiate the large, deep Great Lakes from small, shallow inland lakes.

Coupled lake-ice-atmosphere (CLIAv1) modeling system for the Great Lakes: U.S. National Aeronautics and Space Administration (NASA)-Unified Weather Research and Forecasting (NU-WRF) with the three-dimensional (3D) Finite Volume Community Ocean Model (FVCOM)

We identify key 3D hydrodynamic processes—ice transport, heat advection, and shear production in turbulence—that explain the superiority of 3D lake models over 1D lake models.

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C-CHARM
Center for Climate Driven Hazard Adaptation, Resilience, and Mitigation in Great Lakes Rural Communities

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- Thank you!

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