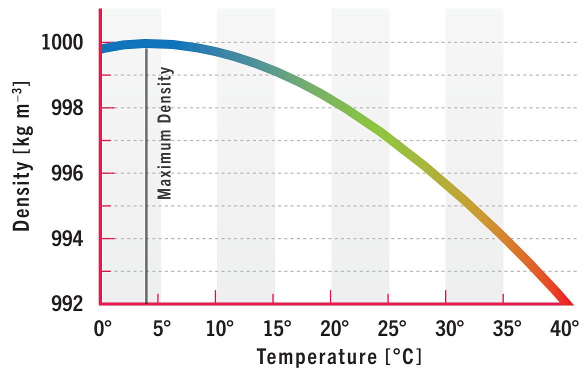
Climate Change and Large Lake Environments

Stages of Stratification

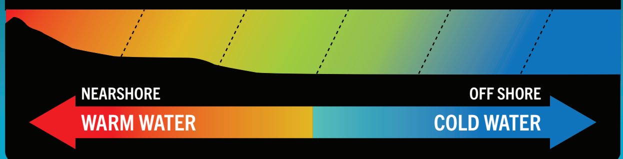
The density of water changes rapidly with small changes in temperature.

Temperature Affects Water Density

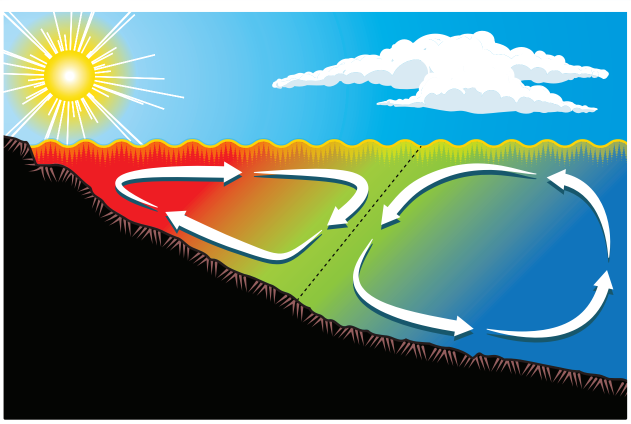


In large lakes, shallow nearshore waters warm more rapidly than deeper offshore waters.

Proximity to Shore Affects Temperature

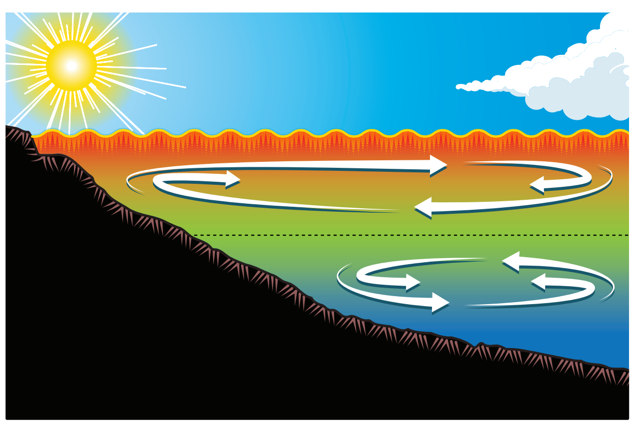


SPRING THERMAL CONDITIONS

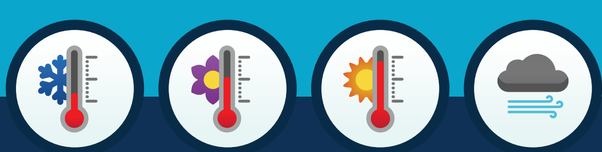


Differences in the thermal density of nearshore and offshore water result in horizontal stratification (i.e., separation), a common feature of large lakes characterized by the spring coastal thermal bar.

SUMMER THERMAL CONDITIONS



As air temperatures increase in early summer, the thermal bar extends offshore. Ultimately, the system then transitions to vertical stratification across the entire lake.



The timing of thermal bar formation and subsequent summer vertical stratification is directly influenced by climatic conditions, including preceding winter and spring temperatures and wind-driven mixing.

NOAA GLERL Great Lakes Environmental Research Laboratory
USGS science for a changing world
Michigan Technological University 1885
Sea Grant ILLINOIS–INDIANA
PURDUE UNIVERSITY Extension - Forestry and Natural Resources
Illinois Extension UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Funding provided by USGS Midwest Climate Adaptation Science Centers

IISG-XXX-XXX-XXX

Climate Change and Large Lake Environments

Large Lake Water Currents

The spinning of the earth and friction from wind affects the direction of water

Water currents in large lakes are almost entirely wind-driven but can also change based on seasonal trends in thermal density stratification.

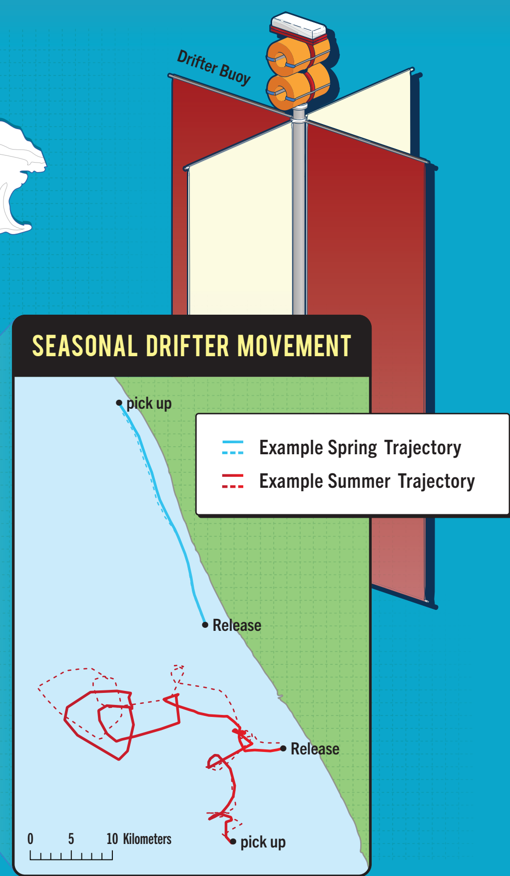
Due to Coriolis force, wind-induced friction in the northern hemisphere directs water currents 90° to the right of prevailing winds (and to the left in the southern hemisphere).

The formation of the spring thermal bar limits water currents moving nearshore to offshore, instead facilitating predominantly alongshore currents and retention of material nearshore.

Summer stratification hinders vertical mixing of the water column but promotes water currents moving between nearshore and offshore.

Consistently strong patterns in wind can induce relatively short-lived coastal upwelling and downwelling events which disrupt vertical stratification.

Source: Beledsky 2001



Source: Höök et al. 2006

There is uncertainty about the potential impacts of climate change on seasonal trends in wind direction and magnitude. However, altered wind patterns, coupled with warmer temperatures, could affect water circulation and patterns of upwelling and downwelling.

NOAA
GLERL
Great Lakes Environmental Research Laboratory
USGS science for a changing world
Michigan Technological University 1885
Sea Grant ILLINOIS–INDIANA
PURDUE UNIVERSITY Extension - Forestry and Natural Resources
Illinois Extension UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

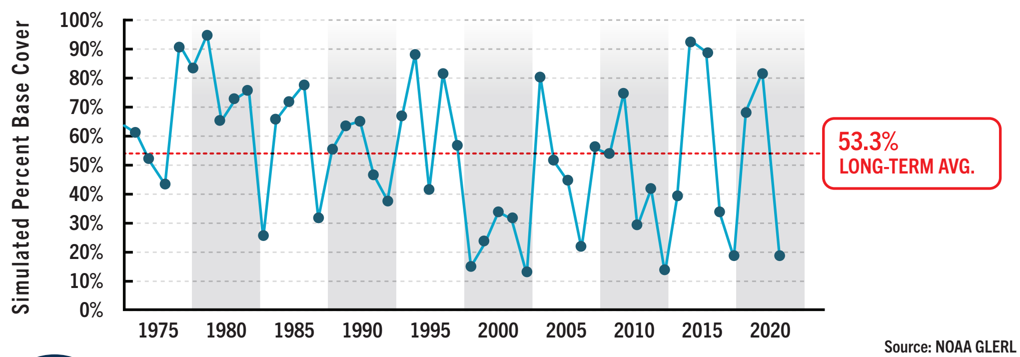
Funding provided by USGS Midwest Climate Adaptation Science Centers

IISG-XXX-XXX-XXX

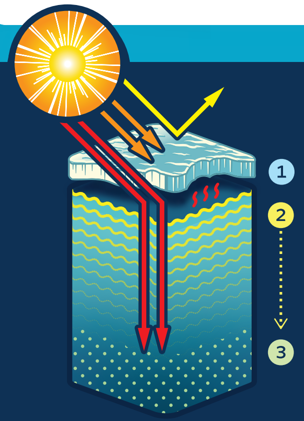
Climate Change and Large Lake Environments ▶ Ice Loss and Lake Warming

The extent and duration of ice cover varies year-to-year but has declined in recent decades.

Great Lakes Annual Maximum Ice Coverage 1973-2020



Source: NOAA GLERL



1 Evaporation

Decreasing ice cover potentially results in high winter evaporation, owing to the prolonged exposure of relatively warm water to cold winter winds.

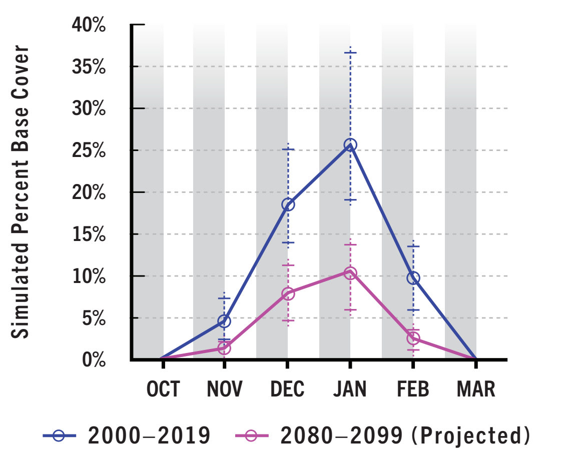
2 Physical Changes

Without winter ice, wind-driven mixing of the water column destabilizes lake physical, chemical, and biological processes, increasing winter light penetration, water temperatures, and nutrient availability.

3 Biological Changes

These changes in winter physical, chemical, and biological processes potentially result in greater winter phytoplankton production and lower spring production.

Declining Ice Cover in Lake Michigan



Source: Xue et al. 2022

Future ice cover in large lakes is expected to continue to decrease, owing to increased warming.

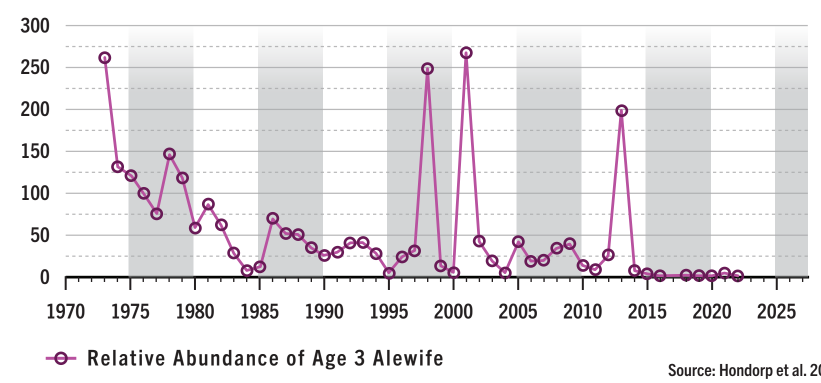
Funding provided by USGS Midwest Climate Adaptation Science Centers

IISG-XXX-XXX-XXX

Climate Change and Large Lake Environments

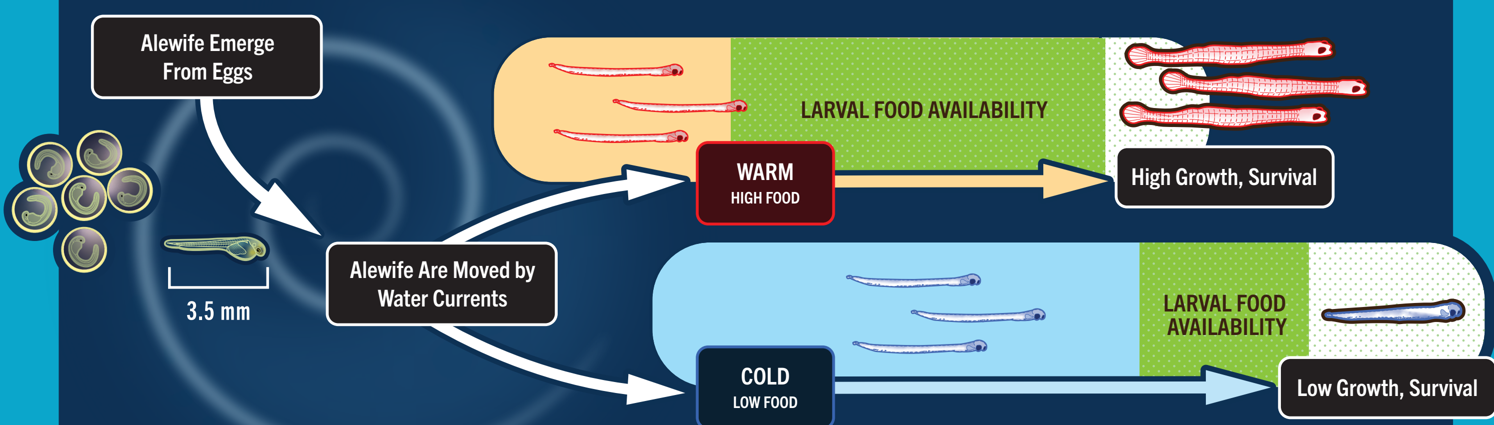
Mechanisms of Fish Recruitment

Abundance of Juvenile Alewife



Source: Hondorp et al. 2024

While many species of fish are capable of producing large numbers of offspring, fish populations often display high year-to-year variability in the number of offspring that grow and survive past early life (recruitment).



Larval Emergence

Larval fish emerge from eggs at small sizes with underdeveloped swimming abilities that leave them largely at the mercy of lake water currents.

Water Current Transport

Water currents may transport larval fish to favorable temperatures and concentrations of prey, or may transport larvae to unfavorable conditions and unfavorable concentrations of prey.

Growth and Survival

Annual climate-driven variability of water currents and the timing of larval emergence affect thermal exposure and prey availability, influencing growth and survival. Synchronized larval emergence with favorable conditions likely facilitate strong recruitment.

Source: Hjort 1914; Cushing 1969, 1990

Increased climatic variability may result in more frequent mismatches between larval emergence and favorable water currents and environmental conditions, leading to consistently poor recruitment.

GLERL Great Lakes Environmental Research Laboratory

USGS science for a changing world

Michigan Technological University

Sea Grant ILLINOIS–INDIANA

PURDUE UNIVERSITY Extension - Forestry and Natural Resources

Illinois Extension UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Funding provided by USGS Midwest Climate Adaptation Science Centers

IISG-XXX-XXX-XXX

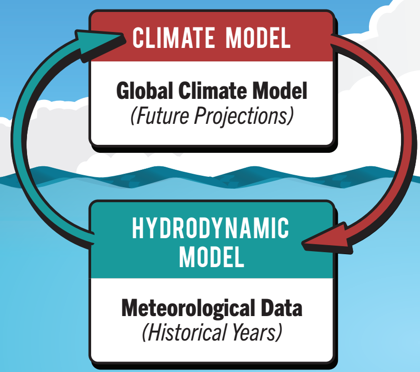
Climate Change and Large Lake Environments

Understanding Larval Recruitment in Large Lakes Pt.1

HIGH LEVEL MODELING FRAMEWORK

ENVIRONMENTAL MODELING			TRANSPORT AND DISPERSION	LARVAL GROWTH AND SURVIVAL
REGIONAL CLIMATE MODEL ⇄	HYDRODYNAMIC MODEL →	BIOPHYSICAL MODEL →	LAGRANGIAN PARTICLE DISPERSION MODEL →	INDIVIDUAL-BASED BIOENERGETICS MODEL

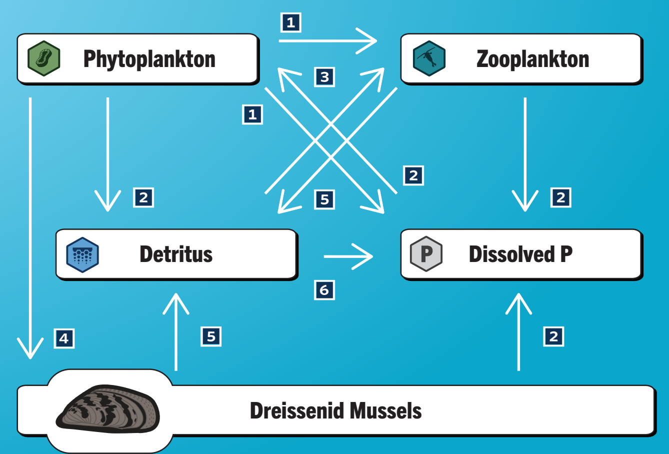
GREAT LAKES ATMOSPHERE REGIONAL MODEL (GLARM)



Source: Xue et al. 2017, 2022

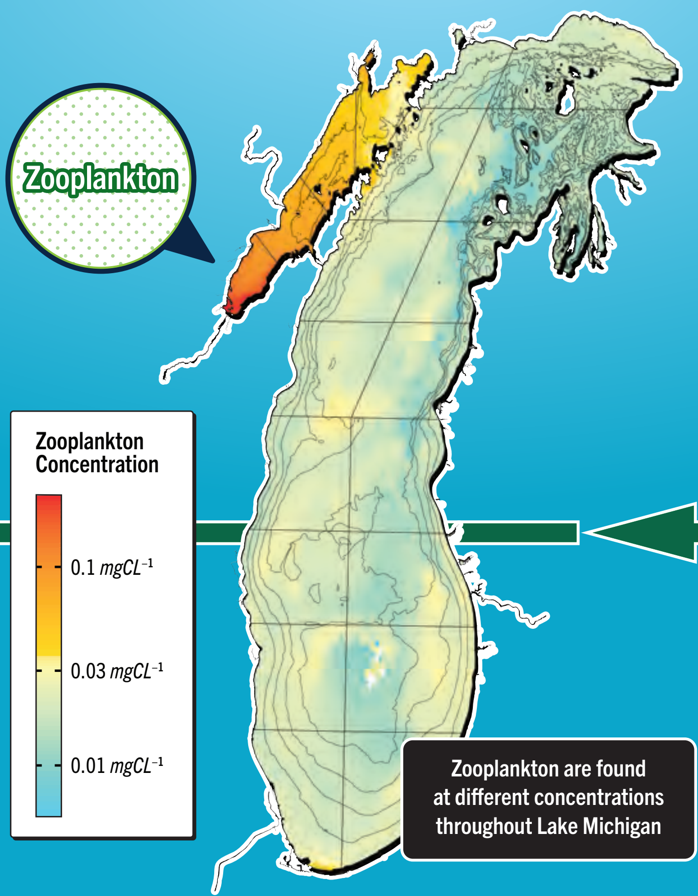
Simulating the historic and potential future physical and biological processes of Lake Michigan, we evaluated how past and future water currents, thermal conditions, and zooplankton prey have generated, and may lead to variable recruitment in two important Lake Michigan fish species, alewife *(Alosa pseudoharengus)* and yellow perch *(Perca flavescens)*.

BIOPHYSICAL MODEL



1 Growth, 2 Mortality and Excretion, 3 Grazing, 4 Filter Feeding
5 Mortality and Egestion, 6 Decomposition

Source: Rowe et al. 2017



Zooplankton are found at different concentrations throughout Lake Michigan

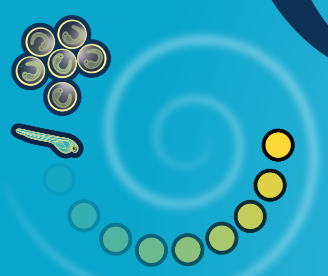
NOAA GLERL Great Lakes Environmental Research Laboratory
USGS science for a changing world
Michigan Technological University 1885
Sea Grant ILLINOIS–INDIANA
PURDUE UNIVERSITY Extension - Forestry and Natural Resources
Illinois Extension UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
Funding provided by USGS Midwest Climate Adaptation Science Centers
IISG-XXX-XXX-XXX

Climate Change and Large Lake Environments

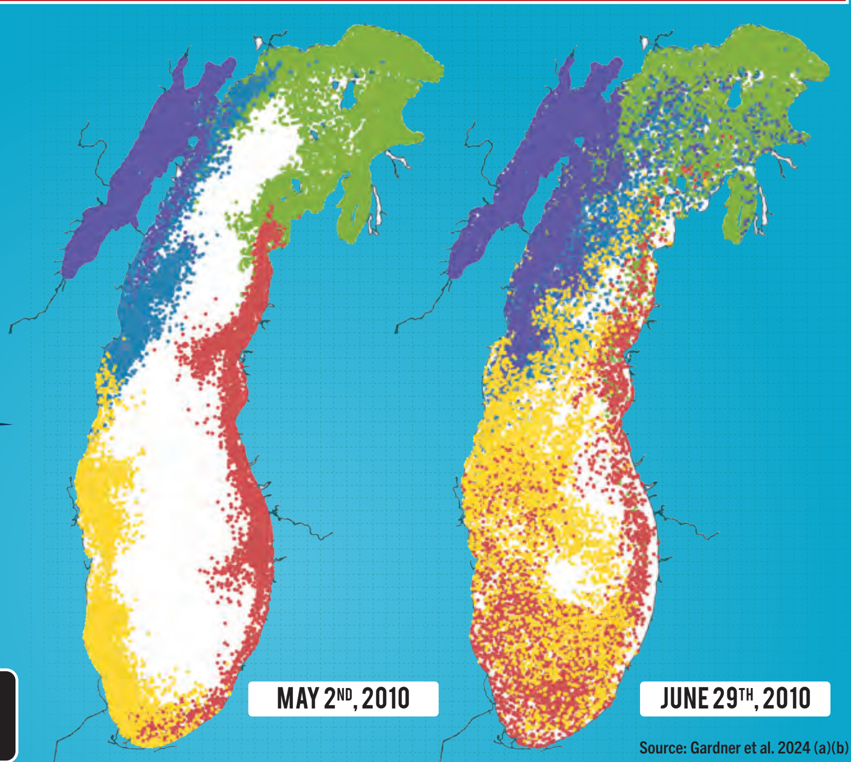
Understanding Larval Recruitment in Large Lakes Pt.2

DISPERSION MODEL

Larval transport patterns were strongly influenced by thermal conditions, with the probability of larvae being transported offshore increasing seasonally and occurring earlier in warm years.



Larval fish are moved by water currents and dispersed



Source: Gardner et al. 2024 (a)(b)

LARVAL GROWTH AND SURVIVAL

The availability of zooplankton and location of larval fish affect growth and survivability.

High Growth, Survival

Low Growth, Survival

Simulated trends in historic recruitment strength (strong vs. weak years) followed observed recruitment patterns.

Future years were characterized by declines in zooplankton that may result in more frequent mismatches between the emergence of larval fish and zooplankton prey.

Simulations indicated that historically favorable sites (i.e., those where larvae displayed high growth and survival) may shift northward with increasing temperatures.

Source: Gardner et al. 2024 (a)(b)

NOAA GLERL Great Lakes Environmental Research Laboratory
USGS science for a changing world
Michigan Technological University 1885
Sea Grant ILLINOIS–INDIANA
PURDUE UNIVERSITY Extension - Forestry and Natural Resources
Illinois Extension UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Funding provided by USGS Midwest Climate Adaptation Science Centers

IISG-XXX-XXX-XXX

Climate Change and Large Lake Environments

References:

Beletsky, D., and D.J. Schwab. 2001. Modeling circulation and thermal structure in Lake Michigan: annual cycle and interannual variability. Journal of Geophysical Research 106(c9):19745-19771.

Cushing, D.H. 1969. The regularity of the spawning season of some fishes. Extrait Du Journal du Conseil International pour L'exploration de la Mer 33:81–92.

Cushing, D.H. 1990. Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. Advances in Marine Biology. 26:249-293.

Gardner, S.T., M.D. Row, P. Xue, X. Zhou, P.J. Alsip, D.B. Bunnell, P.D. Collingsworth, E.S. Rutherford, and T.O. Höök. 2024 (a). Climate-influenced phenology of larval fish transport in a large lake. DOI: 10.1002/lol2.10414

Gardner, S.T., M.D. Row, P. Xue, X. Zhou, P.J. Alsip, D.B. Bunnell, P.D. Collingsworth, E.S. Rutherford, and T.O. Höök. 2024 (b). Climate-influenced phenology of larval fish transport in a large lake. Purdue University Research Repository. Version 2. DOI: 10.4231/DK82-0T58.

Hjort, J. 1914. Fluctuations in the great fisheries of northern Europe viewed in the light of biological research. Rapports et Proces-Verbaux des Reunions Consell International pour l'Exploration de la Mer 2:1-228.

Hondorp, D.W., Bunnell, D., Madenjian, C.P., and Honsey, A.E., 2024, Bottom Trawl Catch Alewife Densities and Ages in Lakes Michigan and Huron: U.S. Geological Survey data release, DOI:10.5066/P95KVYGG

Höök, T. O., M. J. McCormick, E. S. Rutherford, D. M. Mason, and G. S. Carter. 2006. Short-term water mass movement in Lake Michigan: implications for larval fish transport. Journal of Great Lakes research. 32:728-737.

NOAA GLERL. https://www.glerl.noaa.gov/data/ice/

Rowe, M.D., E.J. Anderson, H.A. Vanderploeg, S.A. Pothoven, A.K. Elgin, J.W. Wang, and F. Yousef. 2017. Influence of invasive quagga mussels, phosphorous loads, and climate on spatial and temporal patterns of productivity in Lake Michigan: a biophysical modeling study. Limnology and Oceanography. 62:2629-2649

Stadig, M.H., P.D. Collingsworth, B.M. Lesht, and T.O. Höök. 2019. Spatially heterogeneous trends in nearshore and offshore chlorophyll a concentration in lakes Michigan and Huron (1998–2013). Freshwater Biology. 65: 366–378. https://doi.org/10.1111/fwb.13430

Xue, P., J.S. Pal, X. Ye, J.D. Lenters, C. Huang, and P.Y. Chu. 2017. Improving the simulation of large lakes in regional climate modeling: two-way lake-atmosphere coupling with a 3D hydrodynamic model of the Great Lakes. Journal of Climate. 30:1605-1627. DOI: 10.1175/JCLI-D-16-0225.1

Xue, P., X. Ye, J.S. Pal, P.Y. Chu, M.B. Kayastha, and C. Huang. 2022. Climate projections over the Great Lakes Region: using two-way coupling of a regional climate model with a 3-D lake model. Geoscience Model Development. 15:4425-4446. DOI:10.5194/gmd-15-4425-2022.

Funding provided by USGS Midwest Climate Adaptation Science Centers

IISG-XXX-XXX-XXX