Regime shifts in satellite-derived chlorophyll within the Laurentian Great Lakes

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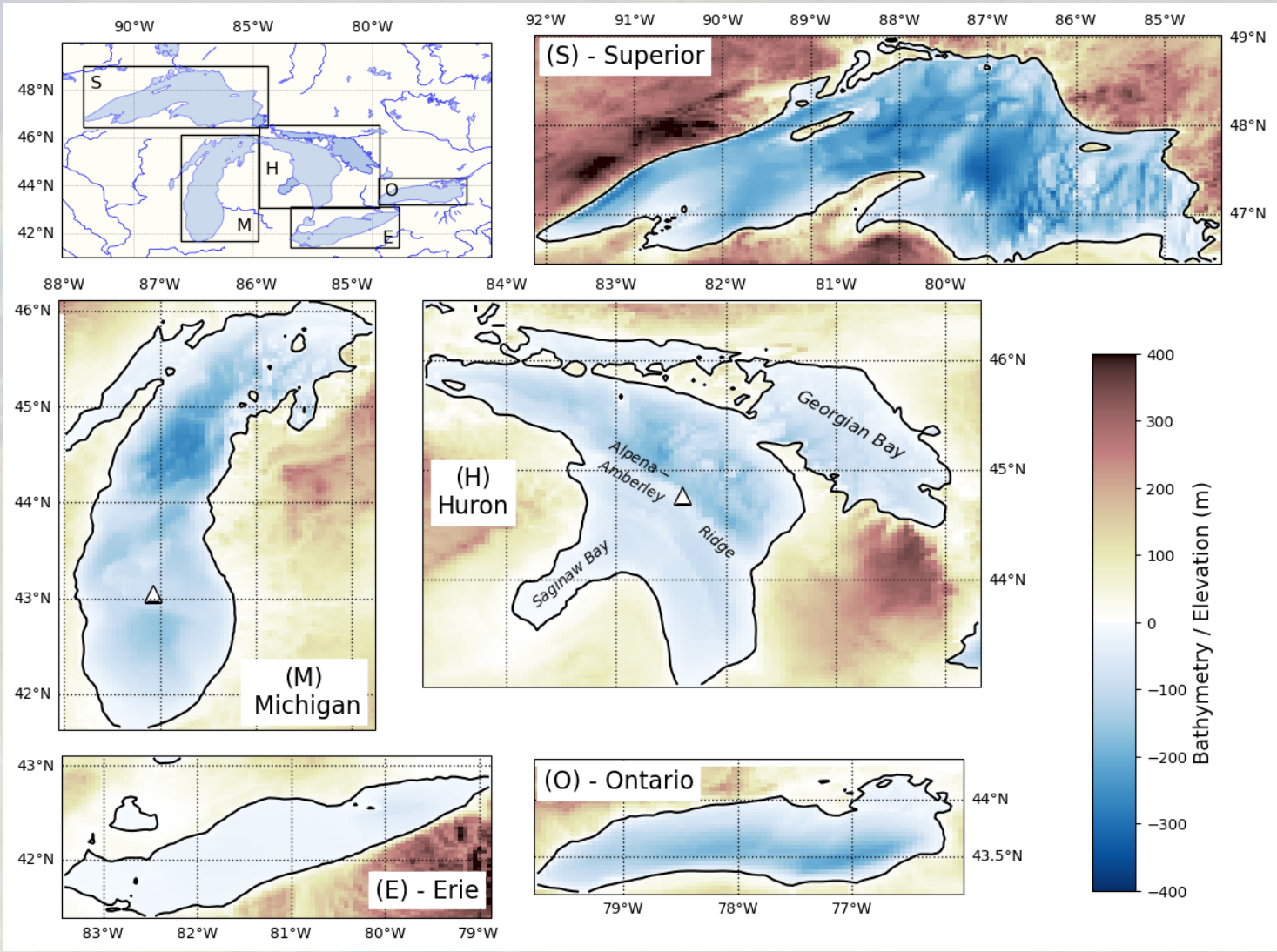
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[c]Cooperative Institute for Satellite Earth System Studies (CISESS)/Earth System Science Interdisciplinary Center (ESSIC), University of Maryland, College Park, MD, USA
[d]Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University, Fort Collins, Colorado, USA
[e]Environment and Climate Change Canada, Canada Centre for Inland Waters, Burlington, Ontario, Canada
[f]NOAA Great Lakes Environmental Research Laboratory, Lake Michigan Field Station, Muskegon, MI, USA
[g]NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI, USA

Laurentian Great Lakes

One of the largest freshwater systems in the world

- Total lake surface area 244,000 km^2
- Catchment area of ~1 million km^2
- 21% of the world's surface fresh water supply

Progressive **eutrophication** since European settlement through to the early 1980s



- As a result of implementation of nutrient management following the binational **Great Lakes Water Quality Agreement in 1972**, the ecosystems within the Laurentian Great Lakes were gradually transforming to lower trophic regimes.

- This transformation dramatically accelerated in the late 1980s after the introduction of two **invasive species** of filter-feeding **mussels** of the genus **Dreissena:**

  - *D. polymorpha* (Pallas, **zebra** mussel)
  - *D. rostriformis bugensis* (Andrusov, **quagga** mussel)



https://whatcomboatinspections.com/aquatic-invasive-species/zebra-and-quagga-mussels

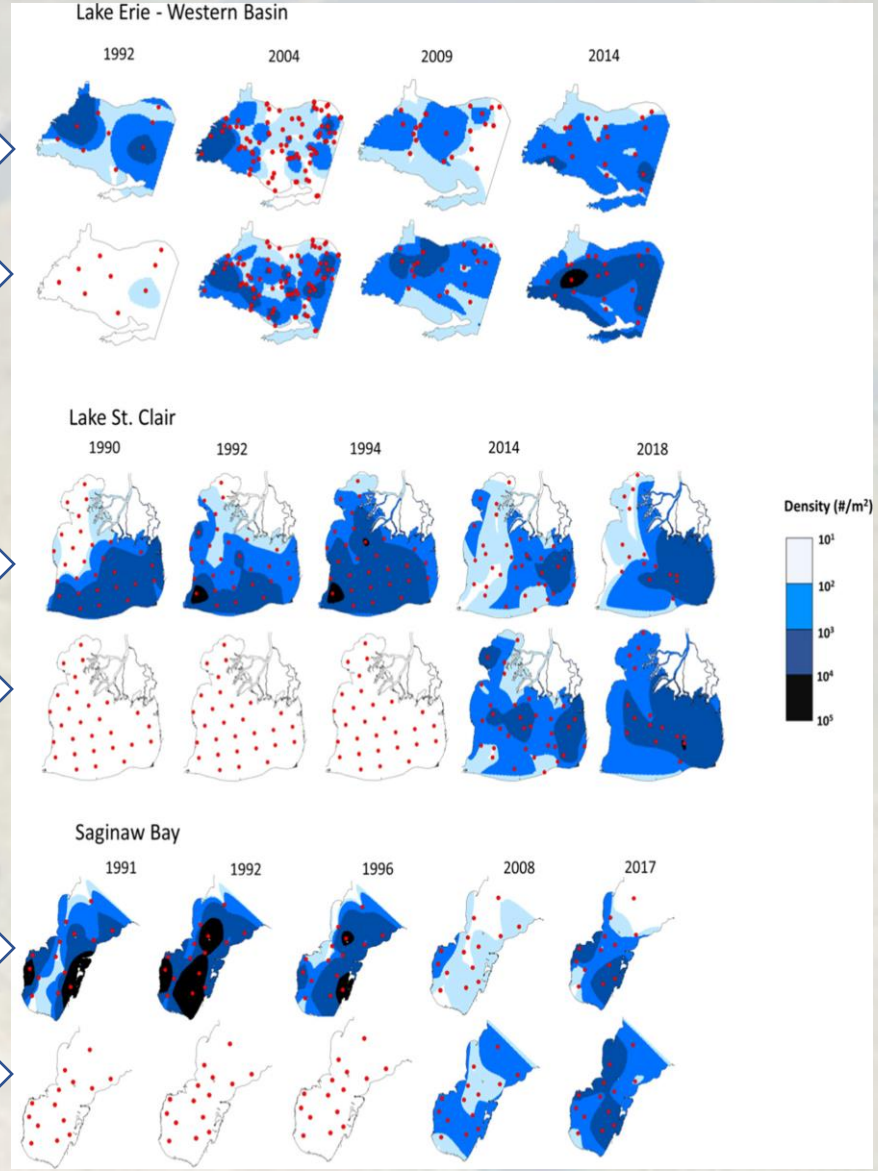


https://www.usgs.gov/media/images/zebra-mussels-dreissena-polymorpha

Many details of spreading of zebra and quagga mussels over the Great Lakes were **well documented**.

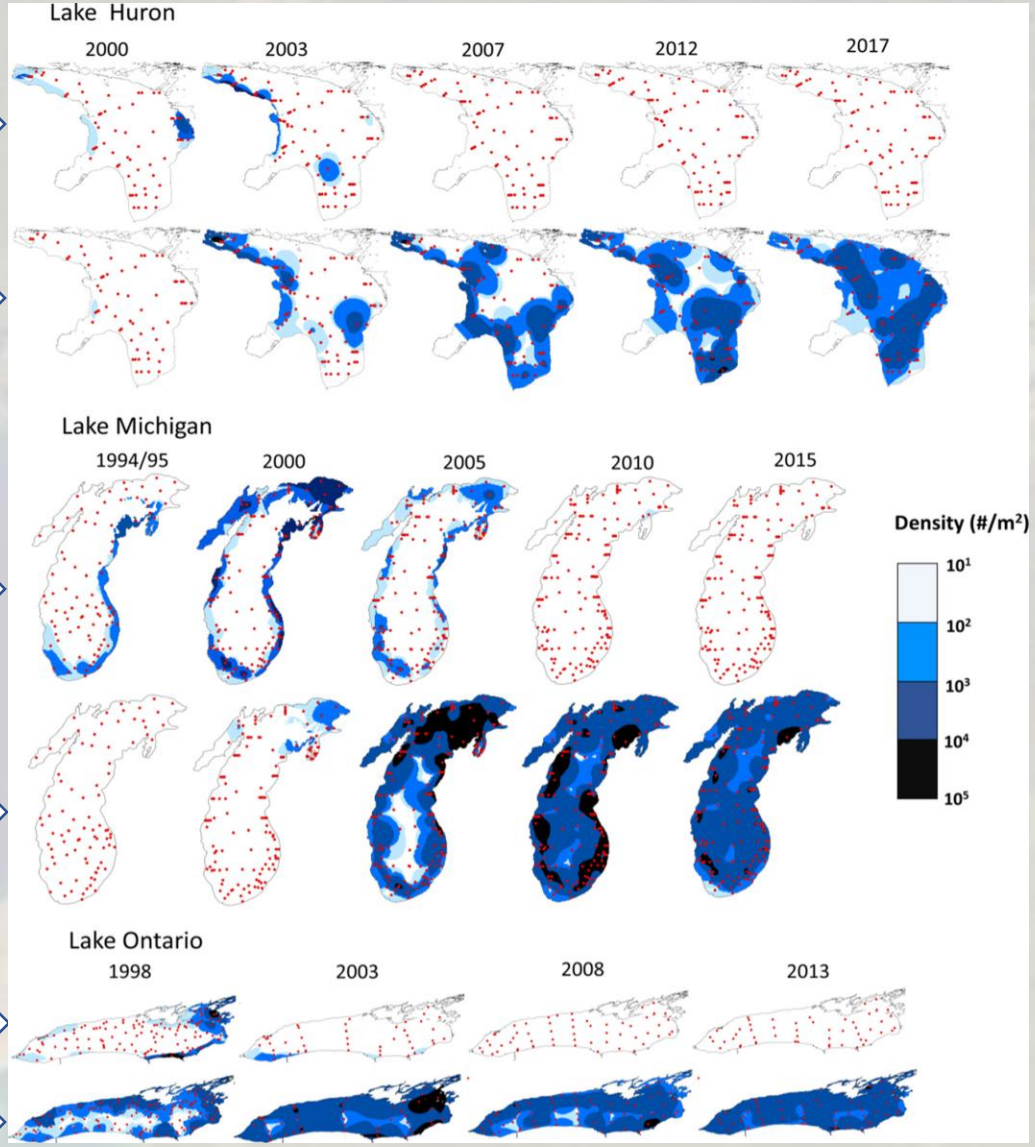
Zebra

Quagga



Zebra

Quagga



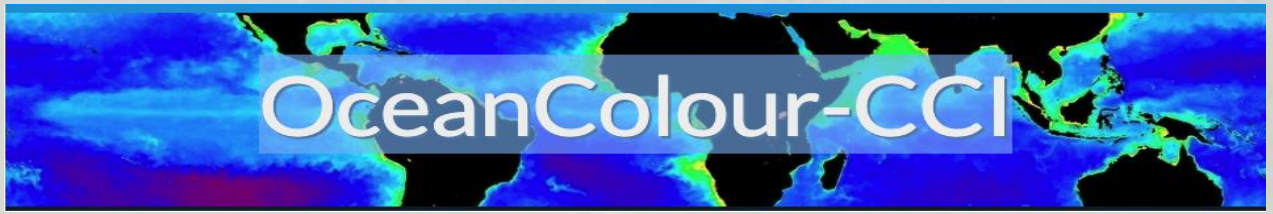
Karatayev *et al.* 2021, *Biol Invasions* **23**, 2489–2514. doi:10.1007/s10530-021-02518-3

- It is still unclear **when and where** bioproductivity (or chlorophyll biomass as its proxy) stabilized at new oligotrophic levels and what was the magnitude of that decrease.

  - The **effect of nutrient regulation** is expected to result in a **gradual decrease** of phytoplankton biomass over **most of the lakes' area**.

  - The **effect of mussel feeding** is expected to be **correlated** with the steps of **colonization** of the lakes by dreissenids.

Data source – satellite Chl-a



https://www.oceancolour.org/

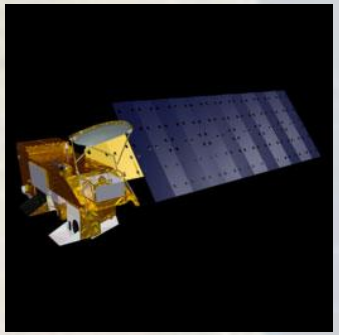
- The **merged dataset** produced by the Ocean Colour Climate Change Initiative (OC-CCI) project includes the data **corrected for the biases** between the reflectances measured by different satellite sensors.
- The most recent version of the OC-CCI dataset covers >25 years (1997-2022) of continuous global observations.
- Monthly 4-km grids transformed to 12-km

SeaWiFS
1998-2010



https://en.wikipedia.org/wiki/SeaWiFS

MODIS-Aqua
2002-2019



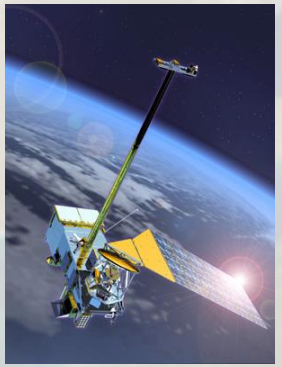
https://ioccg.org/sensor/modis-aqua/

MERIS
2002-2012



https://earth.esa.int/eogateway/instruments/meris

VIIRS-SNPP
2012-present



https://www.ioccg.org/sensors/viirs.html

OLCI-Sentinel-3A/B
2016-present



https://oceancolor.gsfc.nasa.gov/about/missions/s3b/

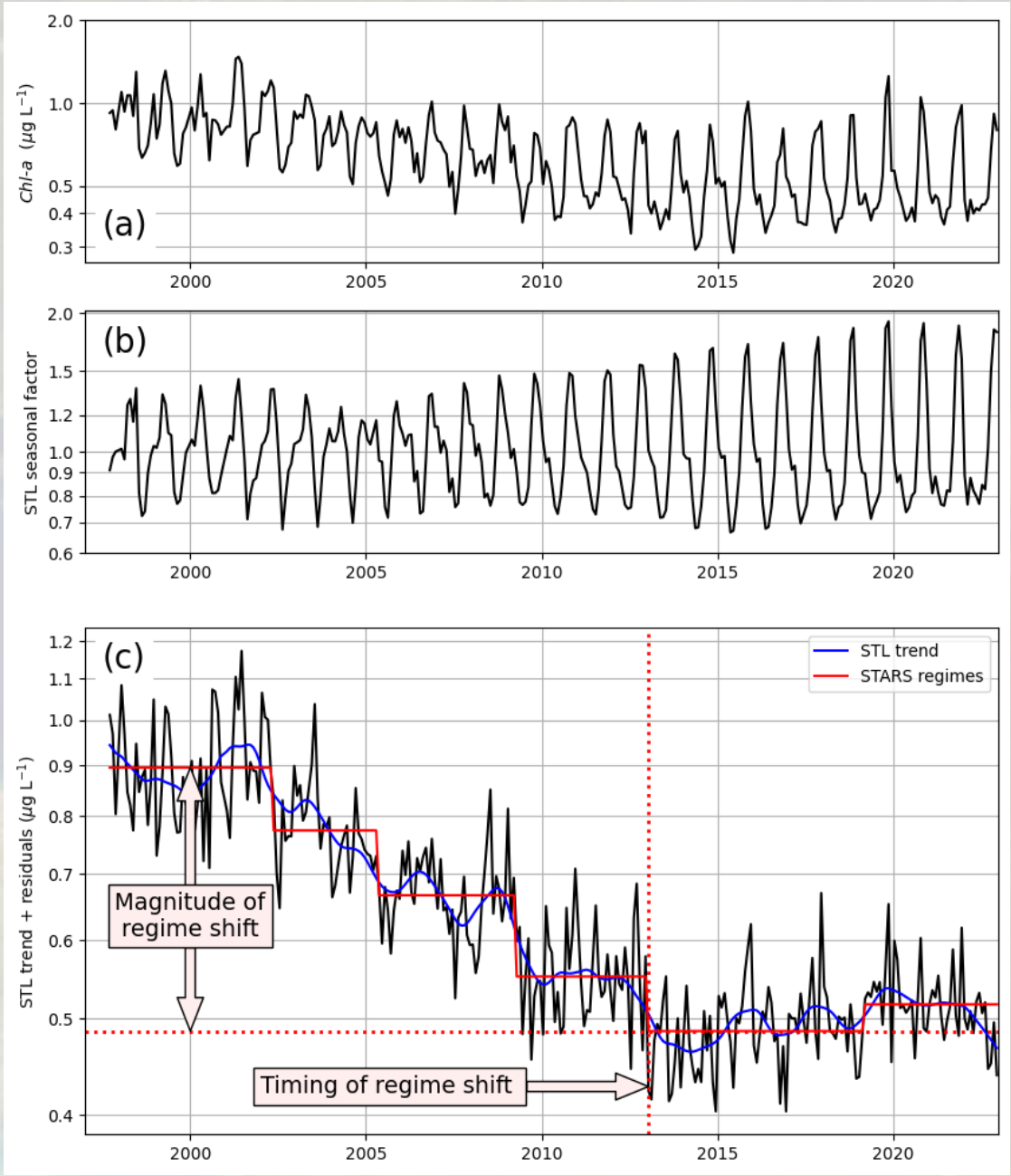
Method of detection

Integrated algorithm including

- Seasonal-Trend decomposition (STL[1])
  - Uses locally estimated scatterplot smoothing (LOESS) method based on local polynomial regressions
  - Detects and removes seasonal variability

- Sequential T-test Analysis of Regime Shifts (STARS[2])
  - Based on Student's *t*-test
  - Detects persistent changes in the system

- Regime shift – when the cascade of decreasing shifts changes to stable state



[1]Cleveland et al., 1990. *Journal of Official Statistics*, *6*(1), 3-73
[2]Rodionov, 2004. *Geophysical Research Letters*, *31*(9). https://doi.org/10.1029/2004GL019448

The objectives of our study:

1. Can the **biases** between the OC-CCI data collected during different periods by **different satellites** be misinterpreted as regime shifts?
2. What are the **timings** (**shift points**) when different regions of the lake ecosystems **stabilized** at new lower trophic regimes?
3. What are the **magnitudes** of the Chl-a decrease in different geographic and bathymetric zones of the lakes?
4. How regime shift affected Chl-a **seasonal cycles** in different parts of the lakes?

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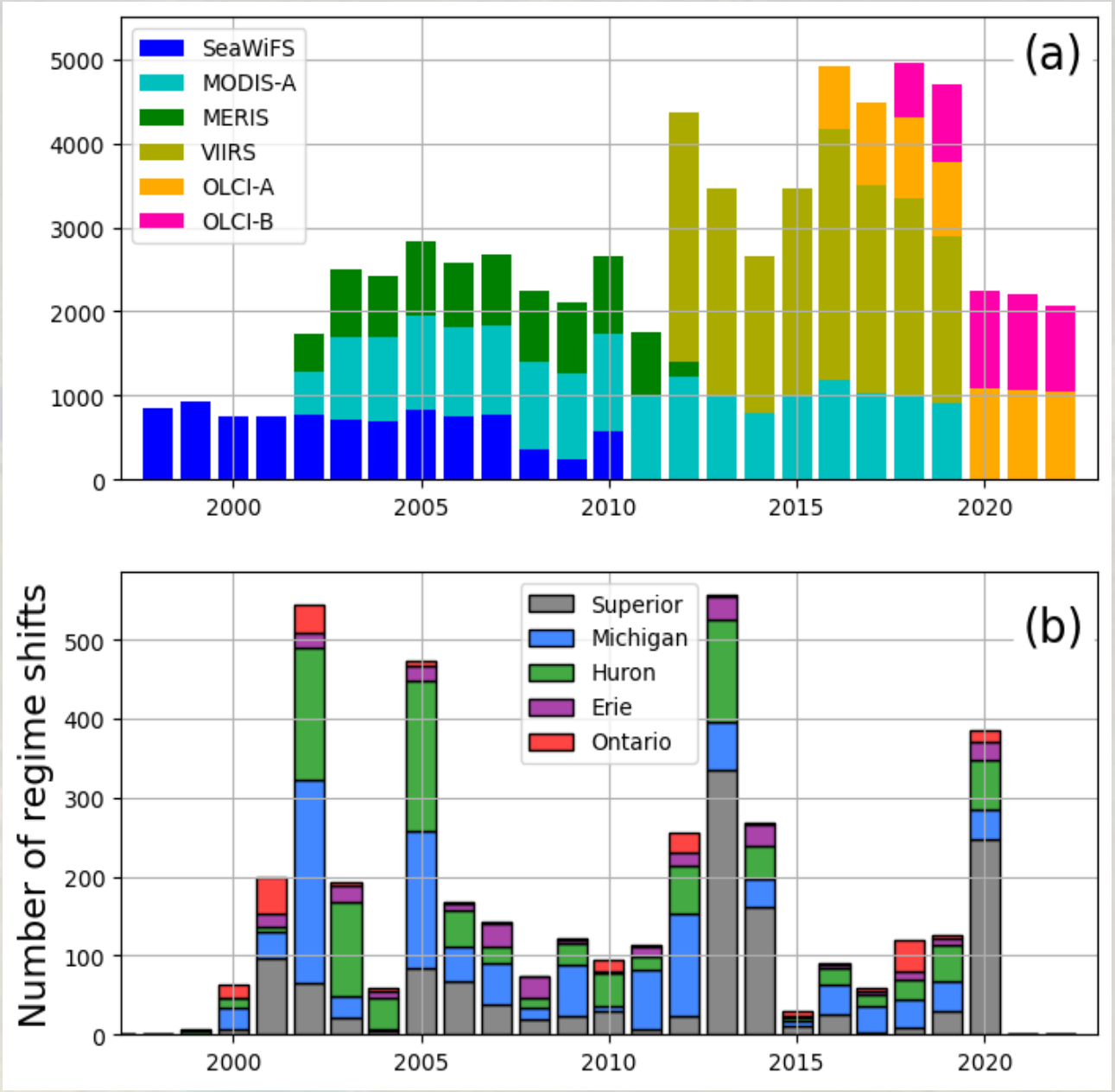
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- **Can the observed changes be explained by the biases between the data collected by different satellite/sensors?**

- ***Yes, but not much…***

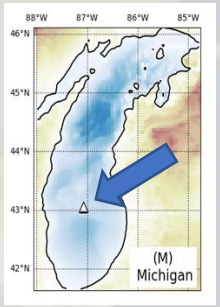
Regime shifts detected in every cell of 12-km grid in all 5 lakes:

- Most regime shifts were detected in **2002, 2013, 2020** – when satellites changed;
- and in **2005** – when 3 satellites continued operations

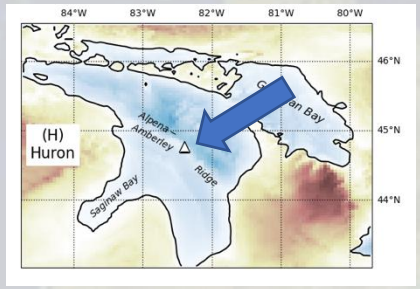


When different satellites detect regime shift?

- Compare 4 time series:
  - OC-CCI
  - SeaWiFS
  - MODIS-Aqua
  - MERIS
- In the centers of

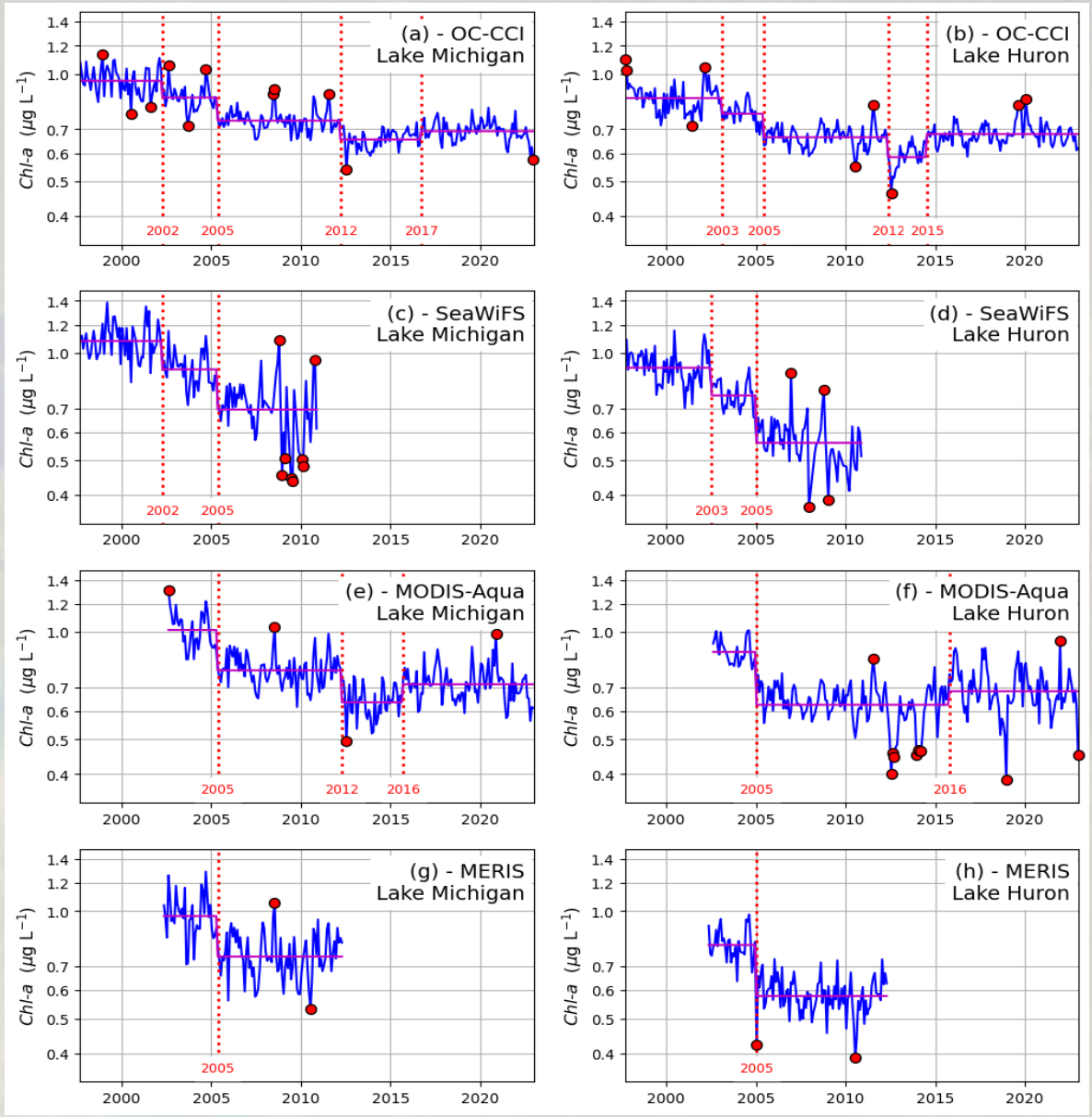


Michigan



Huron

- **Similar** decreasing **trends** and **regime shifts** in all four time series
- Most evident regime shift in **2005**



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Median Chl-a decreased in 3 of in 5 lakes

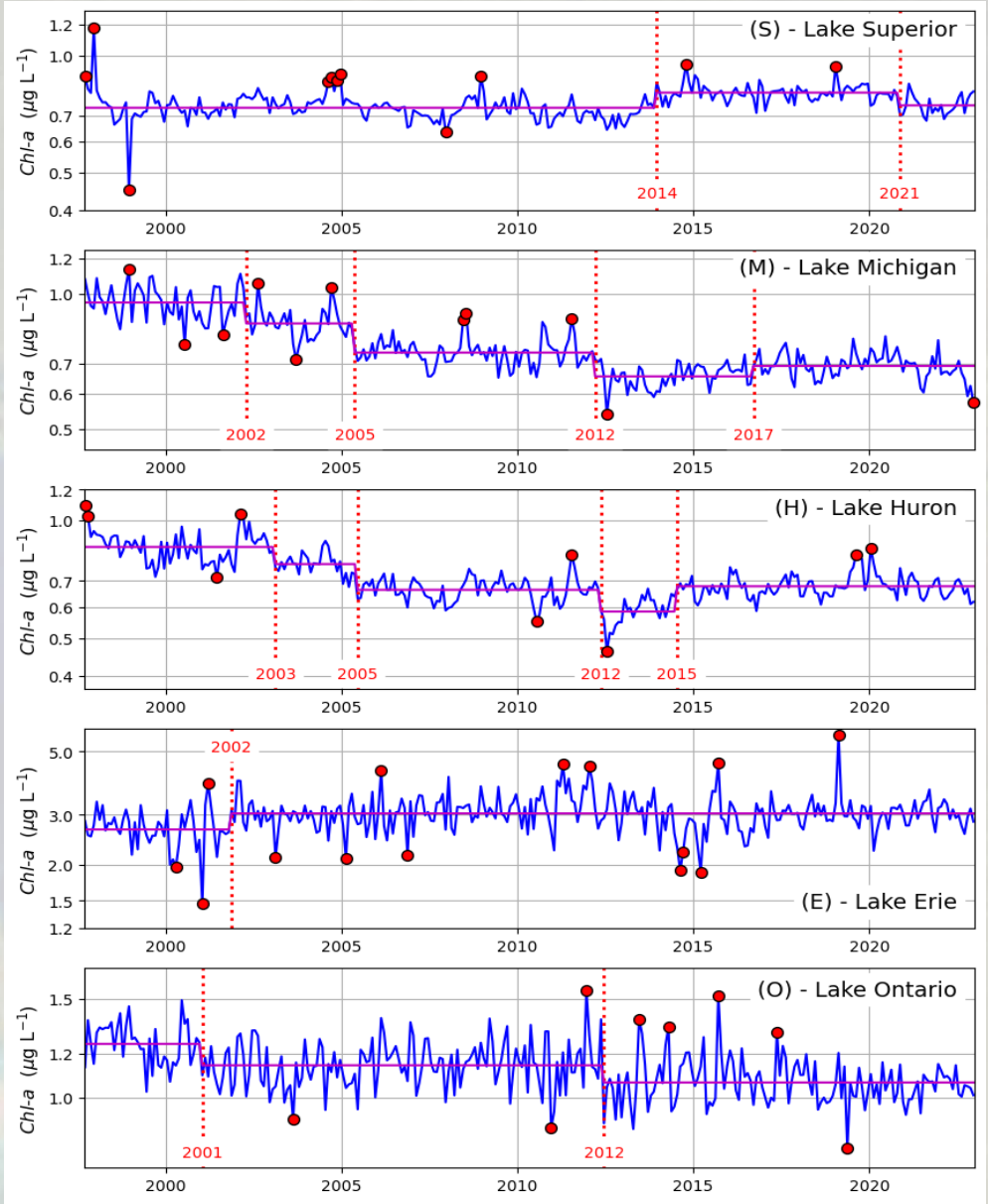
Lake Superior – no trend

Lake Michigan – decreasing trend

Lake Huron – decreasing trend

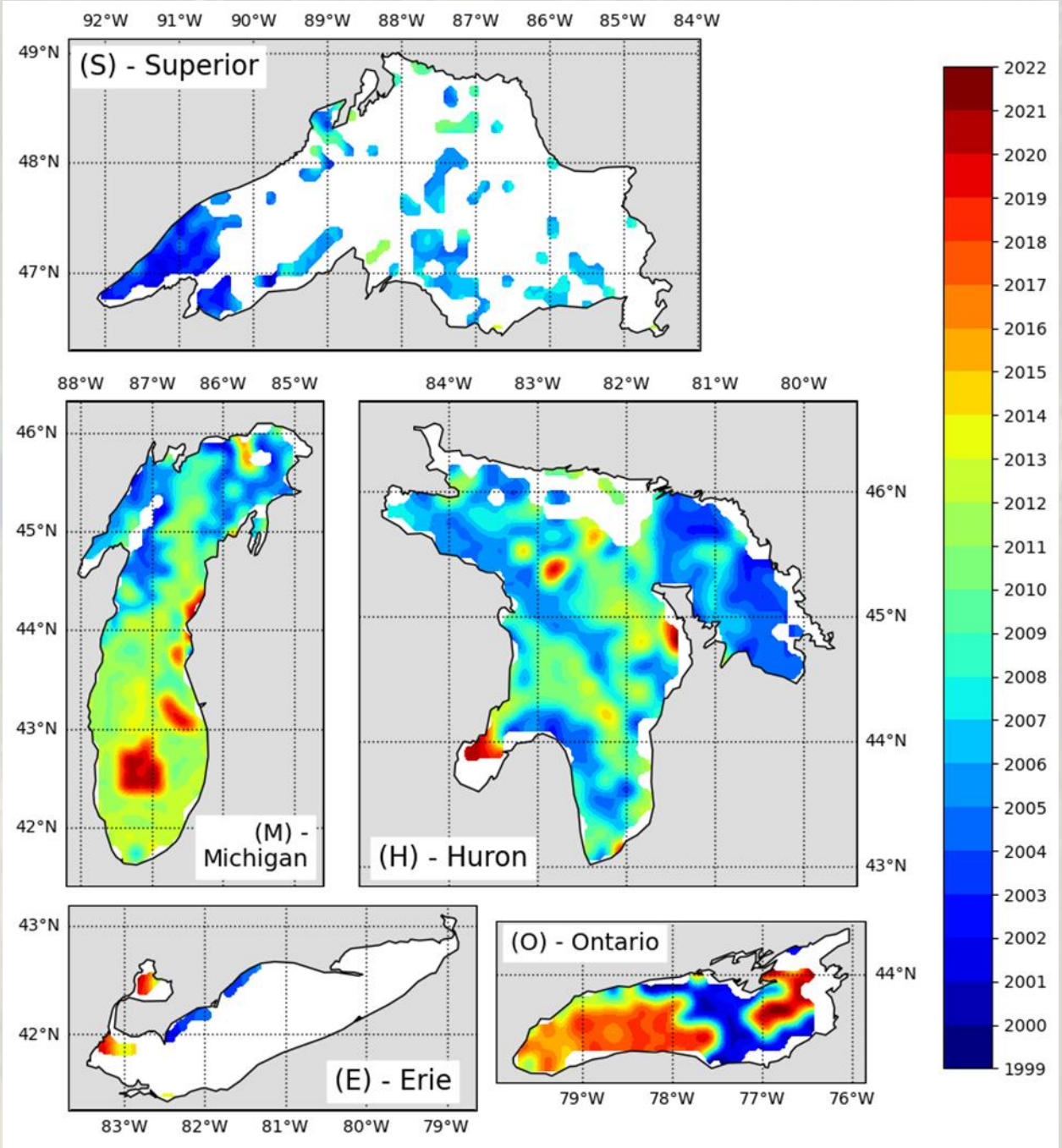
Lake ERIE – no trend

Lake Ontario – decreasing trend



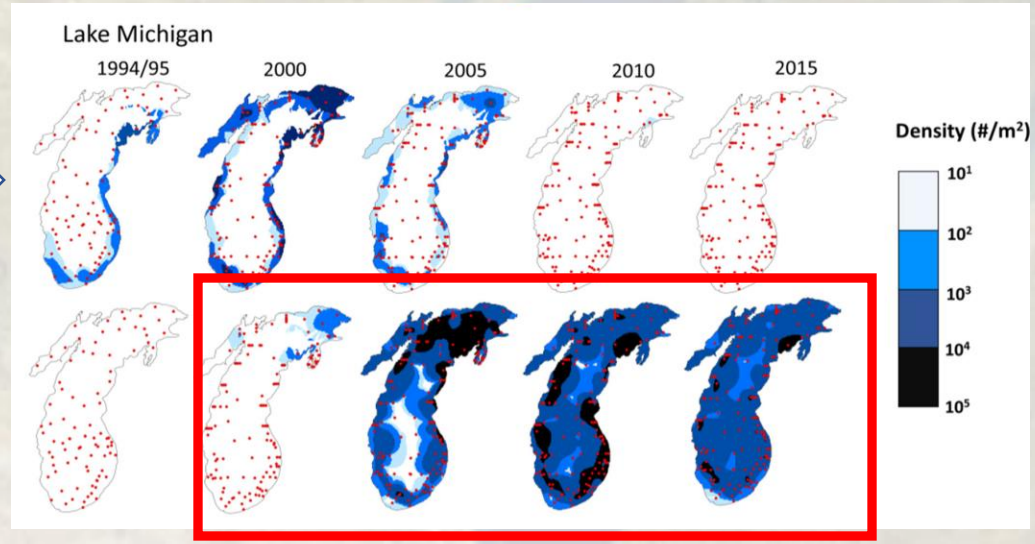
The timings (regime shift points) when Chl-a decreasing trend changed to stable state

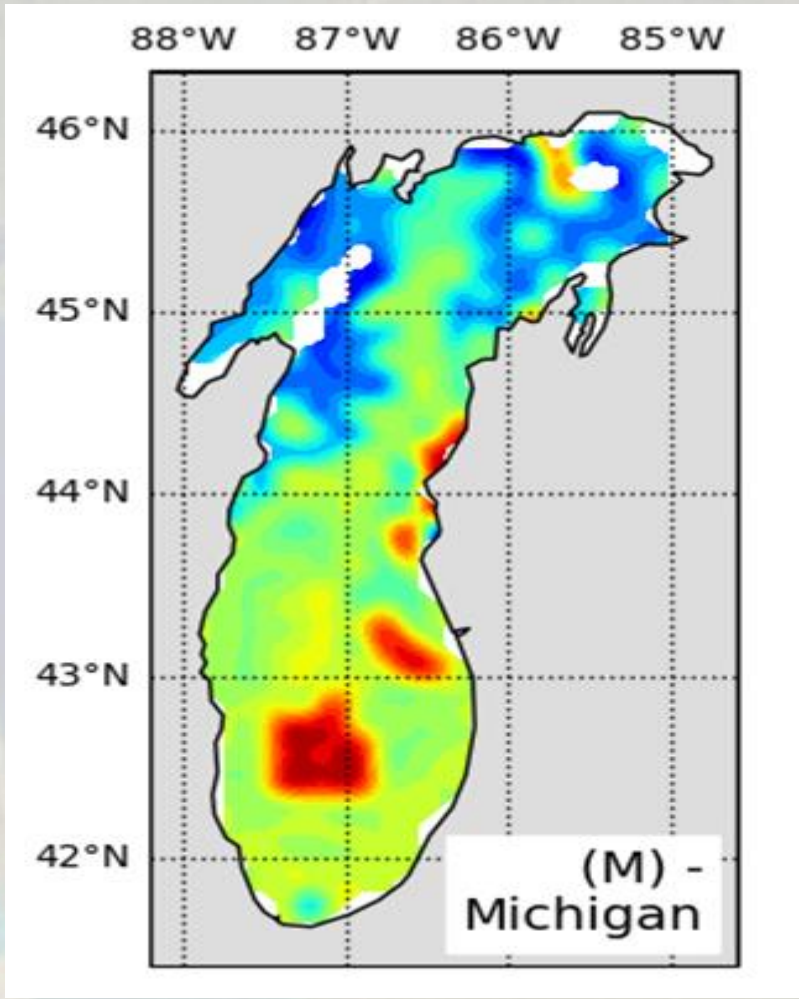
- **No regime shifts** detected in Lakes **Superior** and **Erie**
- In most of Lake **Ontario**, the process of regime transformation lasted **by 2018-2020**

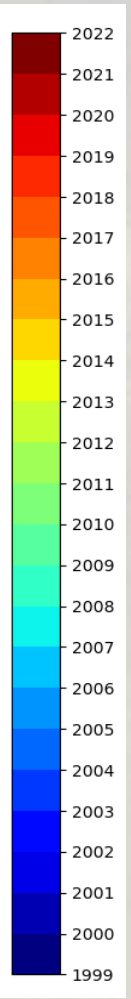


In Lake Michigan, Chl-a changed to new regime:

- about 2005 in northern part nearshore
- about 2012 in the northern part offshore and in the southern part nearshore
- in 2014-2020 in the southern part offshore

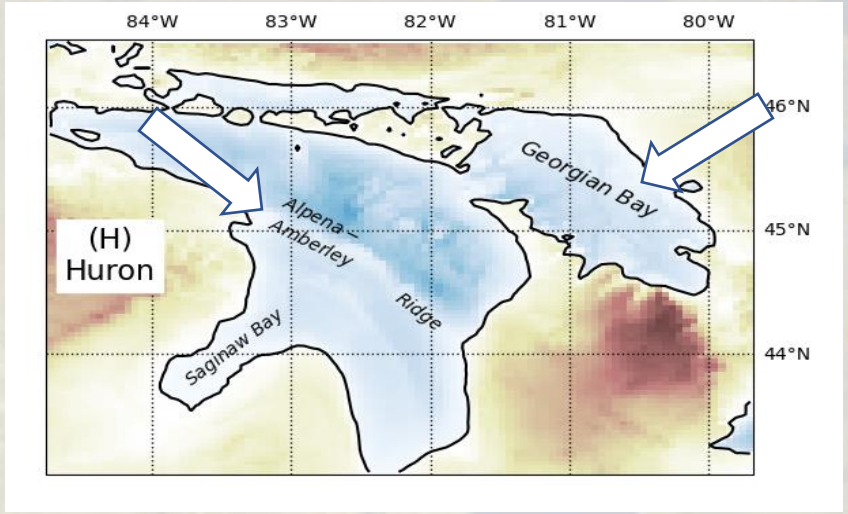


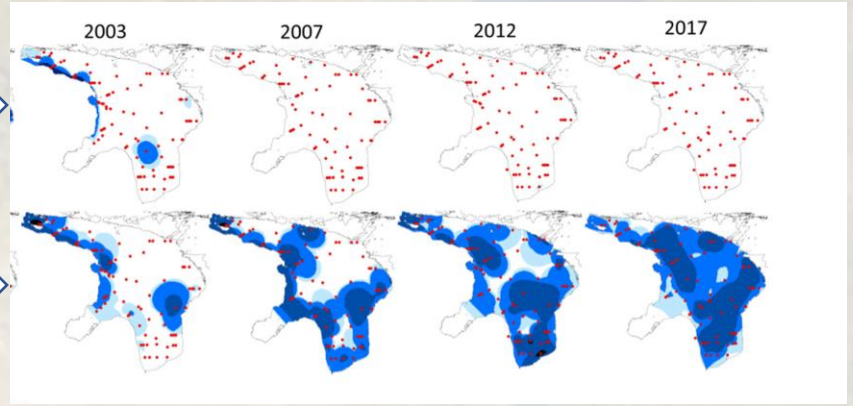




In Lake Huron, Chl-a changed to new regime:

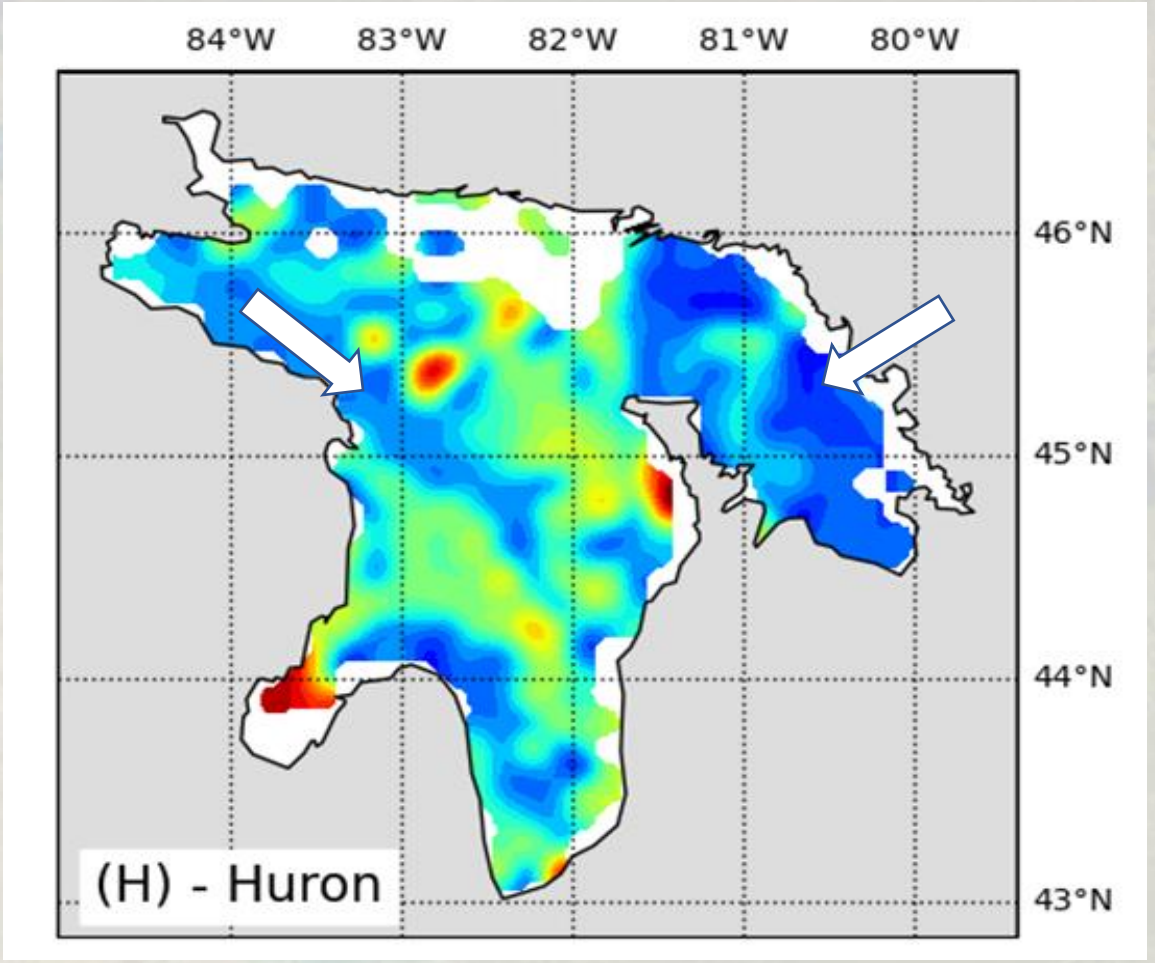
- 2002-2005 in the Georgian Bay, in the southern and northwestern parts and along Alpena-Amberley Ridge
- about 2012 in open parts of the lake

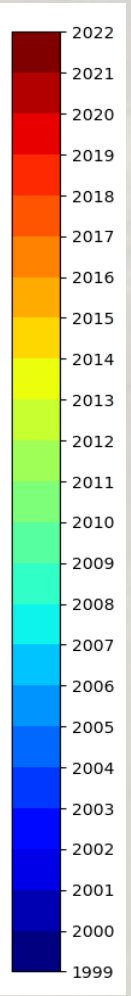




Zebra

Quagga





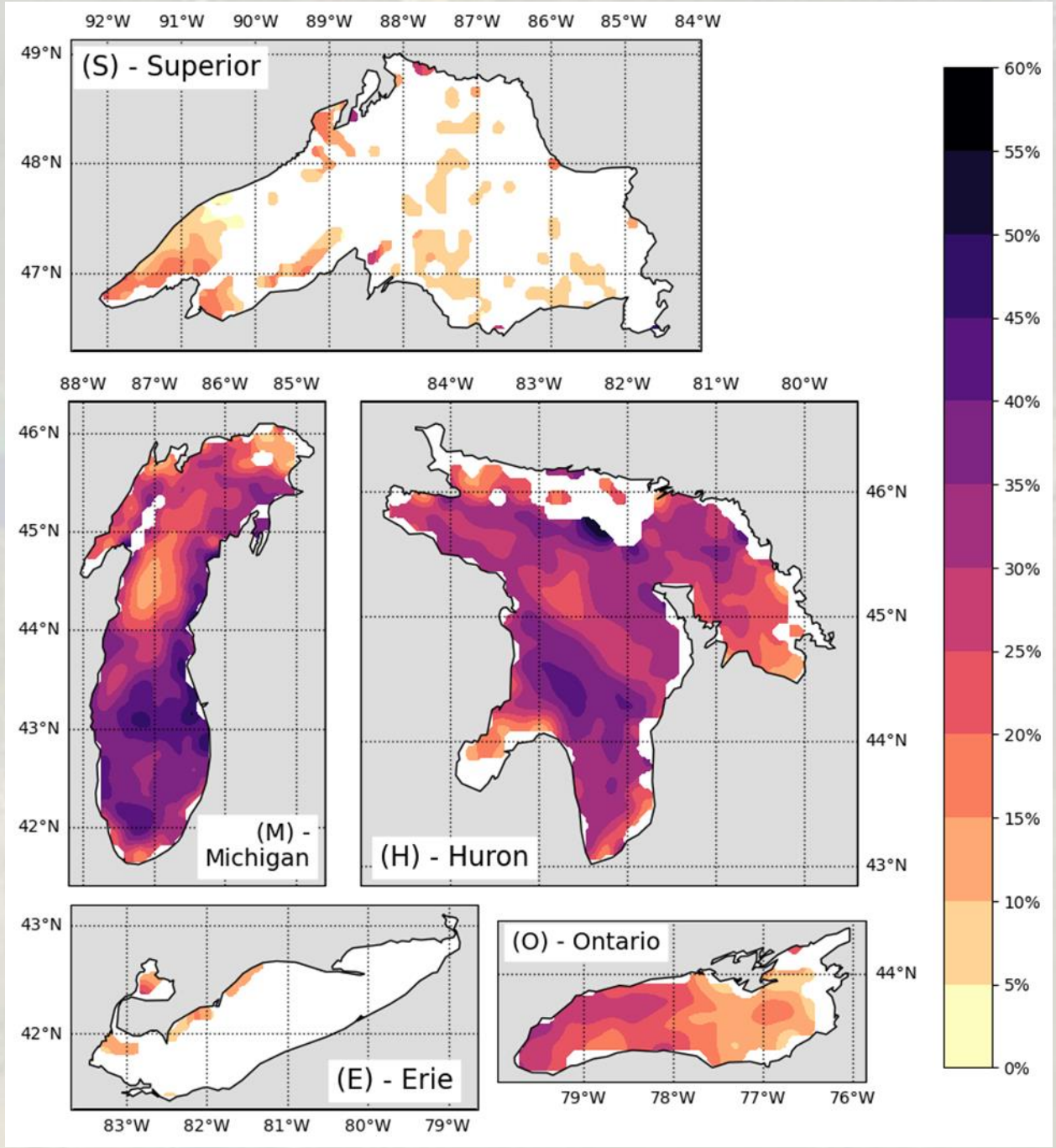
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How much Chl-a decreased since 1997?

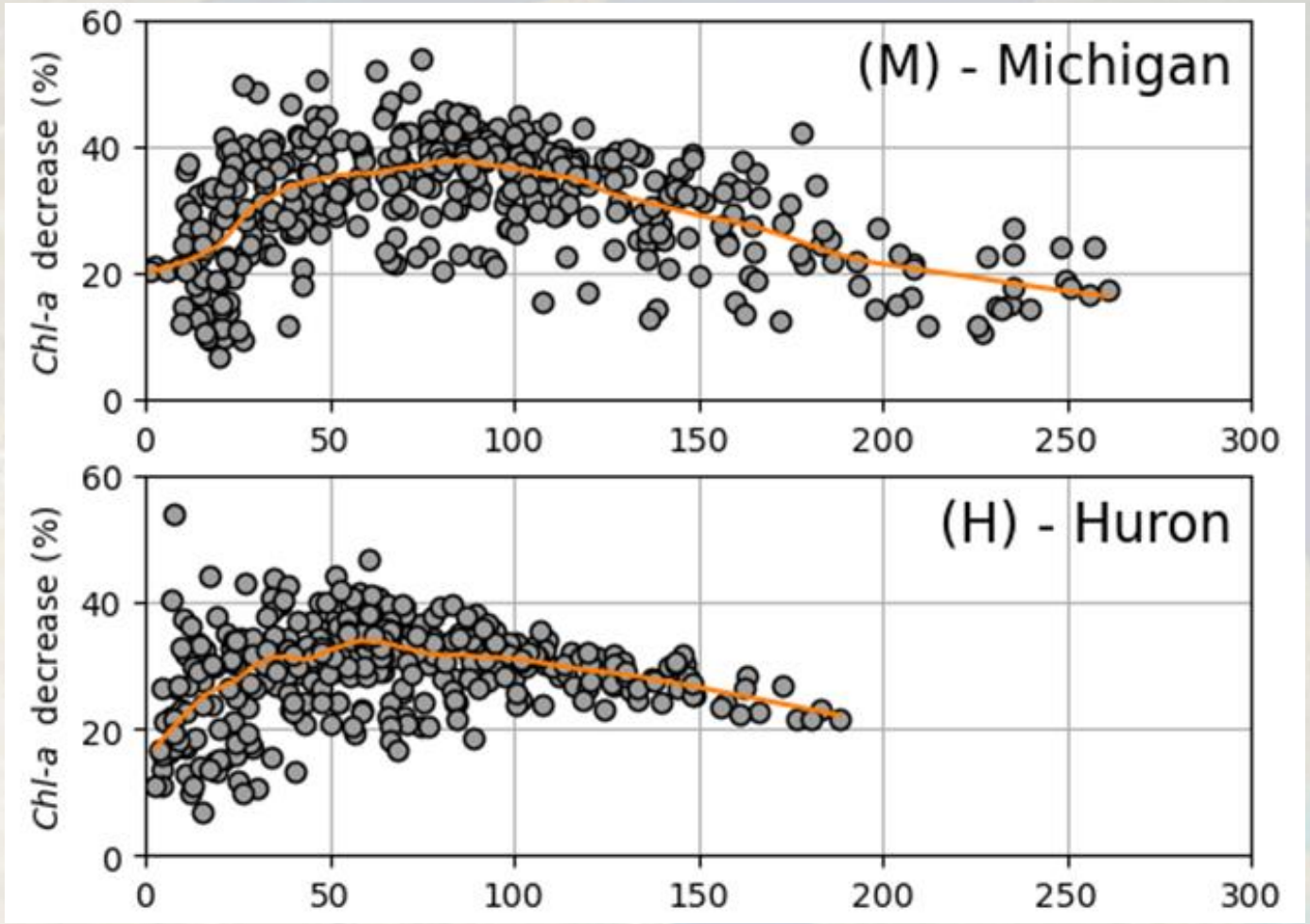
- 40-50% in southern lake Michigan and southern lake Huron
- 20-30% in western lake Ontario, northern parts of Michigan and Huron
- 10-20% in eastern Ontario and Superior

In the regions where new regime was established earlier, the magnitude of decrease was lower. Supposedly, because we are missing the period of regime transformation before 1997

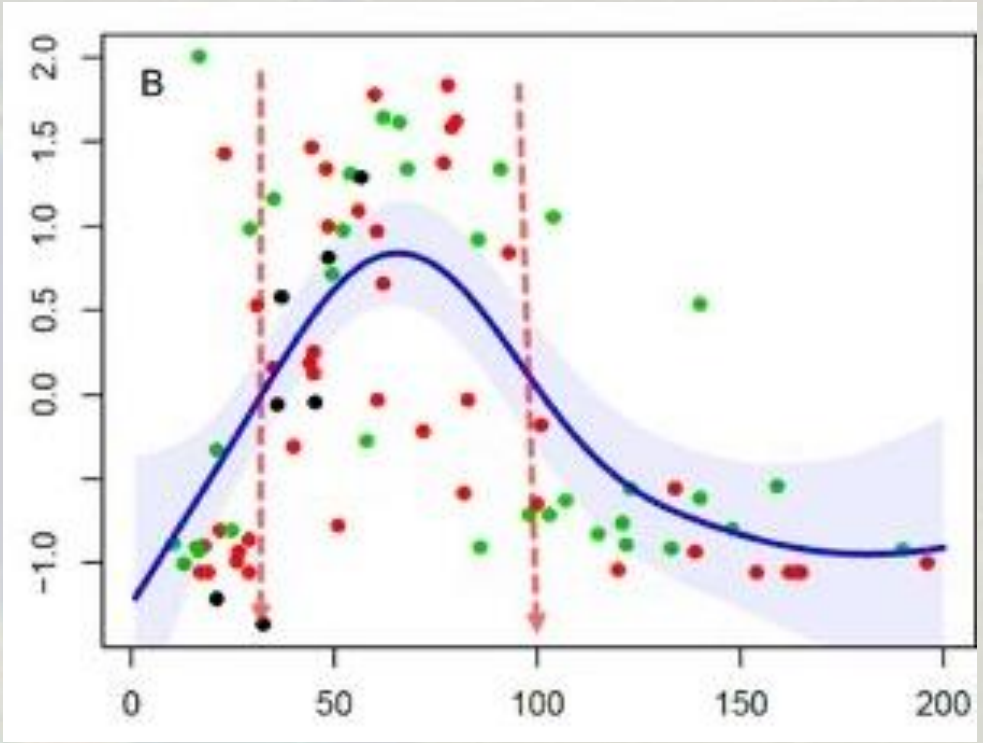


Maximum effect of *Dreissena* invasion within depth range 30-100 m

Magnitude of transformation (Chl-a decrease in %)



Dreissena percent coverage along depth gradient[a]

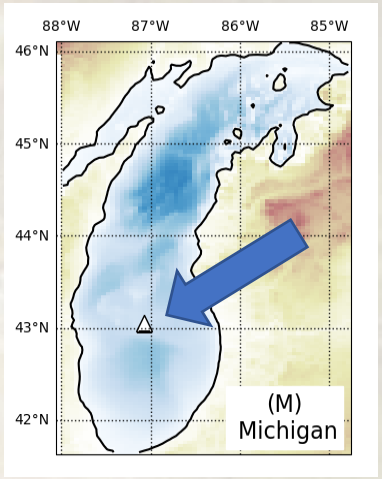


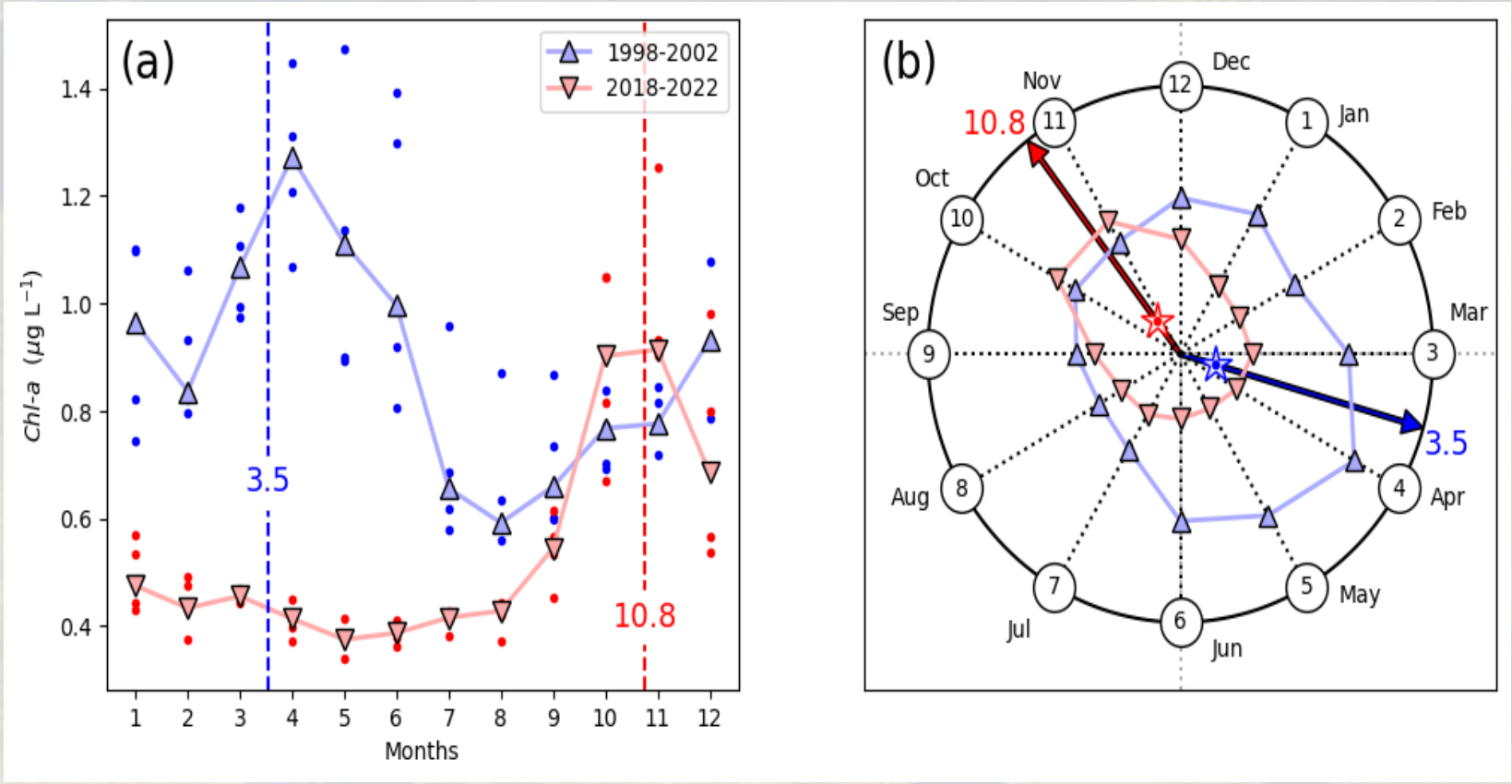
[a]Karatayev, Burlakova, 2022. Hydrobiologia, doi:10.1007/s10750-022-04990-x

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Quantification of the timing of seasonal maximum





Monthly median chlorophyll concentrations (dots) and its five-year median in the center of southern Lake Michigan

In polar coordinates, the arrow pointing through the **centers of gravity** indicate the timing of seasonal maximum

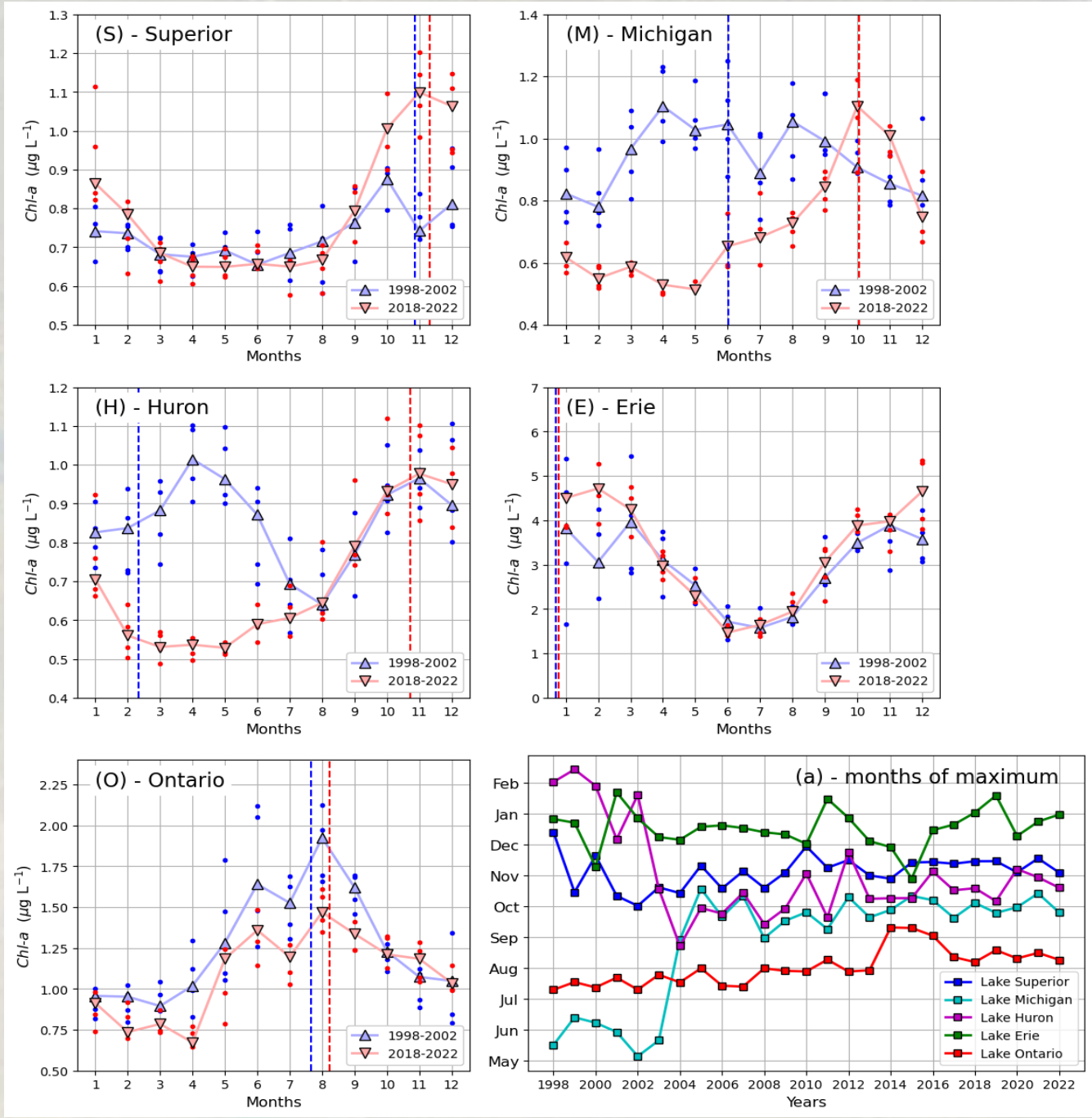
Median Chl-a in 5 lakes:

Seasonal cycles:
1998-2002 vs. 2018-2022

Seasonal maxima changed in two lakes

- Lakes **Michigan** – Chl-a maximum changed from **summer** to **fall**
- Lake **Huron** – Chl-a maximum changed from **spring** to **fall**
- Lake **Superior** – Chl-a maximum in **fall increased**
- Lake **Ontario** - Chl-a maximum in **summer decreased**

- In Lakes **Michigan** and **Huron**, the timings of maxima changed between **2002-2005**



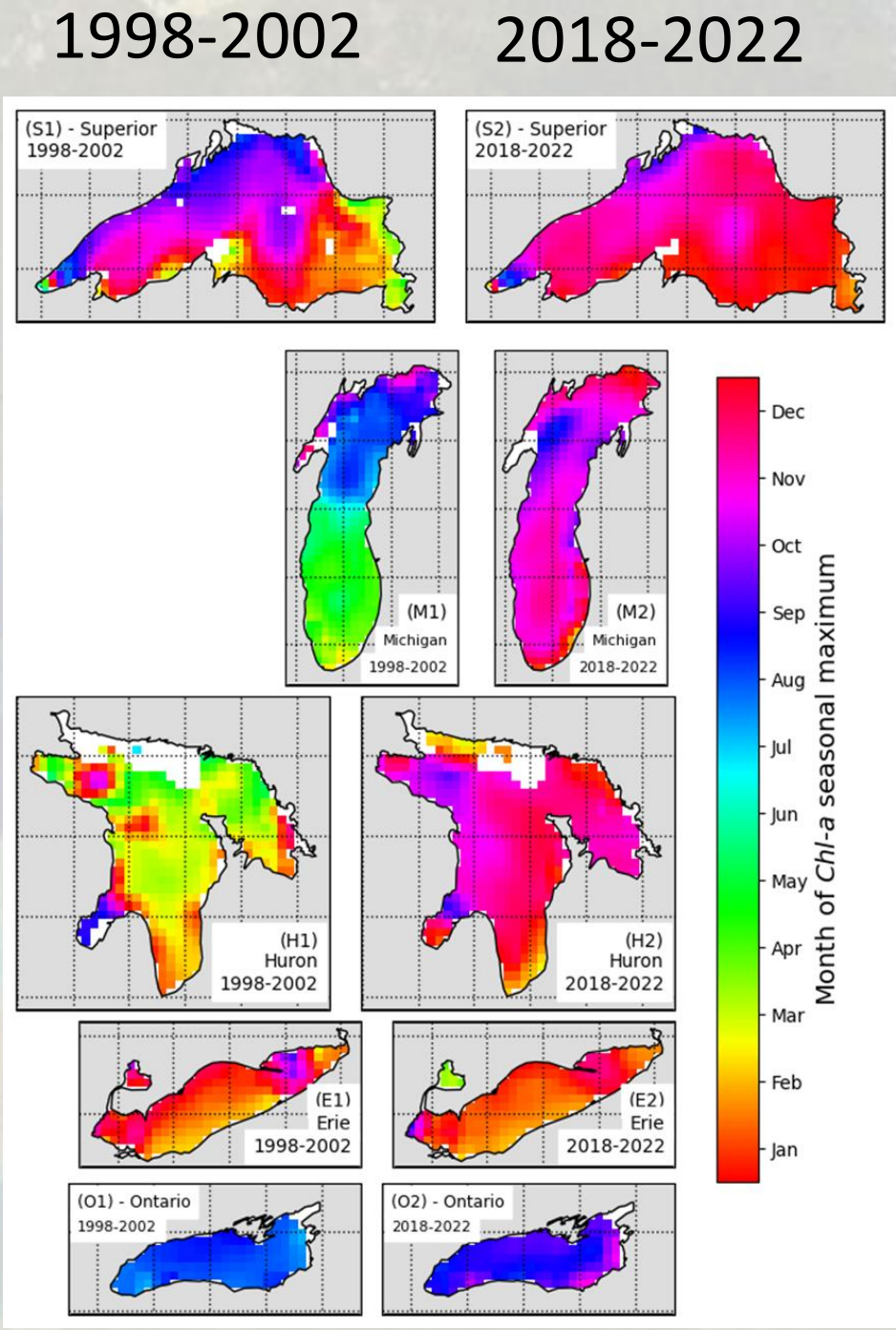
Timings of seasonal maximum were different in different parts of the lakes

1998-2002:

- Lake Michigan
  - Late summer in northern part
  - Spring in southern part
- Lake Huron
  - Spring in open part
  - Winter in nearshore part

2018-2022:

- Chl-a maximum in fall in lakes Superior, Michigan, Huron and Erie
- Summer maximum in lake Ontario



Conclusions:

- **OC-CCI** dataset is a **reliable source of data** for detection of regime shifts in different regions of the world, including the major lakes.
- The effect of inconsistencies resulting from the **biases** between different satellites/periods is **minor** compared to regime transformations observed in the Great Lakes.
- ***Dreissena* invasion** looks like a primary factor regulating regime transformation in LGL
- In two of the five lakes (deep, cold and oligotrophic **Lake Superior** and shallow eutrophic **Lake Erie**), the regime shift was either **small or completed before 1997**.
- Over most of **Lakes Michigan and Huron**, pelagic ecosystems stabilized at a new lower trophic regime from **2005–2015**.
- In a **few locations** (the central part of Lake Michigan, Saginaw Bay in Lake Huron, and most of Lake Ontario), regime transformation either occurred prior to the timeframe of this study or is ongoing and **may continue in the future**.

Thank you!
Questions?

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