



Supplemental Material for Recurrently Hypoxic: Bottom Water Oxygen Depletion Is Linked to Temperature and Precipitation in a Great Lakes Estuary

Table S1. Table of Muskegon River discharge and temperature values averaged from January–July 2011–2021, timetable prior to the onset of hypoxic. In 2020 data acquisition was incomplete due to Covid-related issues and was not included in the estimation of the hypoxia severity index. Thus, data for 2020 is not shown.

Date	Discharge (m ³ /s)	River Temperature (°C)
2011	76.5	6.9
2012	71.3	8.7
2013	93	6.6
2014	84.6	6.5
2015	67	6.9
2016	85.1	7.5
2017	89.8	7.8
2018	82.3	7.3
2019	93.6	6.5
2021	50	7.9

Table S2. The onset and disruption of stratification. 2020 was removed due to the lack of data during the Covid-year.

Year	Onset of Stratification	Breakdown of Stratification
2011	June 9th	September 17th
2012	May 21st	September 13th
2013	June 24th	September 17th
2014	May 30th	September 10th
2015	July 4th	September 9th
2016	May 25th	September 24th
2017	June 13th	October 5th
2018	May 26th	September 27th
2019	June 28th	September 4th
2021	May 20th	September 7th

Table S3. Chronologically ordered table illustrating the number of days where hypoxia was detected at a mild or severe level of hypoxia or near anoxia. 2018 was missing a large portion of data and showed signs of severe hypoxia including high strength of stratification values.

Year	Mild Hypoxia 8m	Severe Hypoxia 8m	Near Anoxia 8m	Mild Hypoxia 11m	Severe Hypoxia 11m	Near Anoxia 11m	Hypoxic Severity Index
2011	17	40	8	35	34	16	63.38
2012	31	7	0	6	39	19	91.27
2013	33	21	0	52	40	0	42.32
2014	18	0	0	41	13	0	26.13
2015	12	0	0	23	15	2	20.95
2016	22	14	2	27	42	6	56.96
2017	8	7	0	36	36	1	44.96
2018	16	22	0	8	26	9	51.52
2019	25	1	0	45	16	2	25.86
2021	24	14	0	13	32	28	97.06

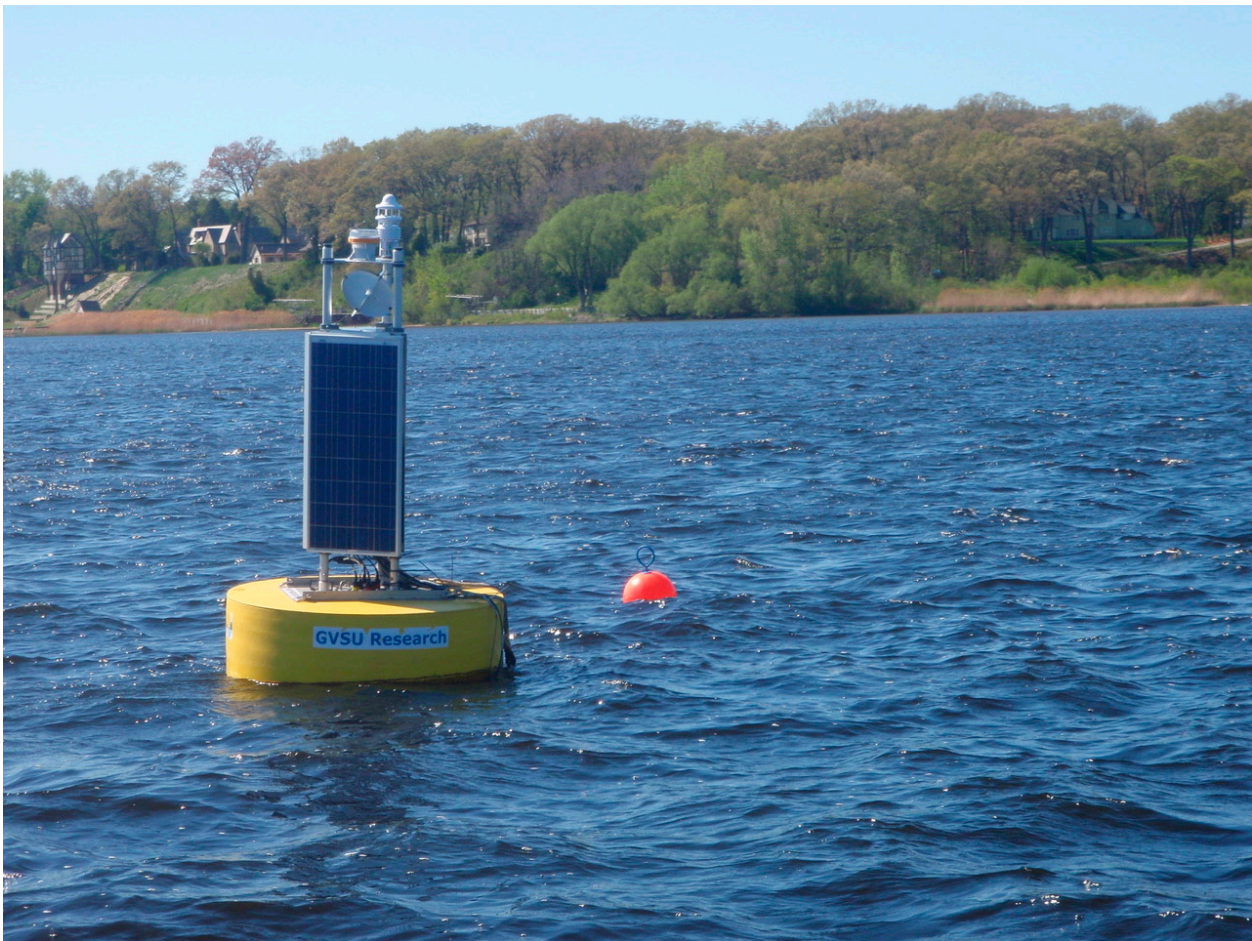
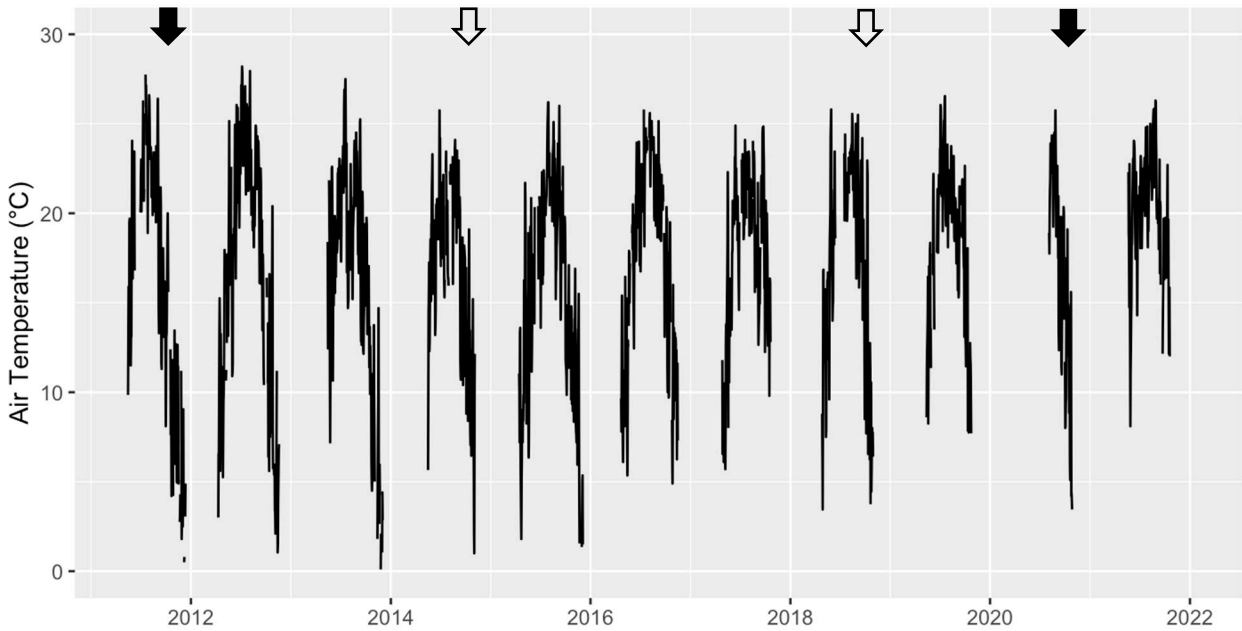


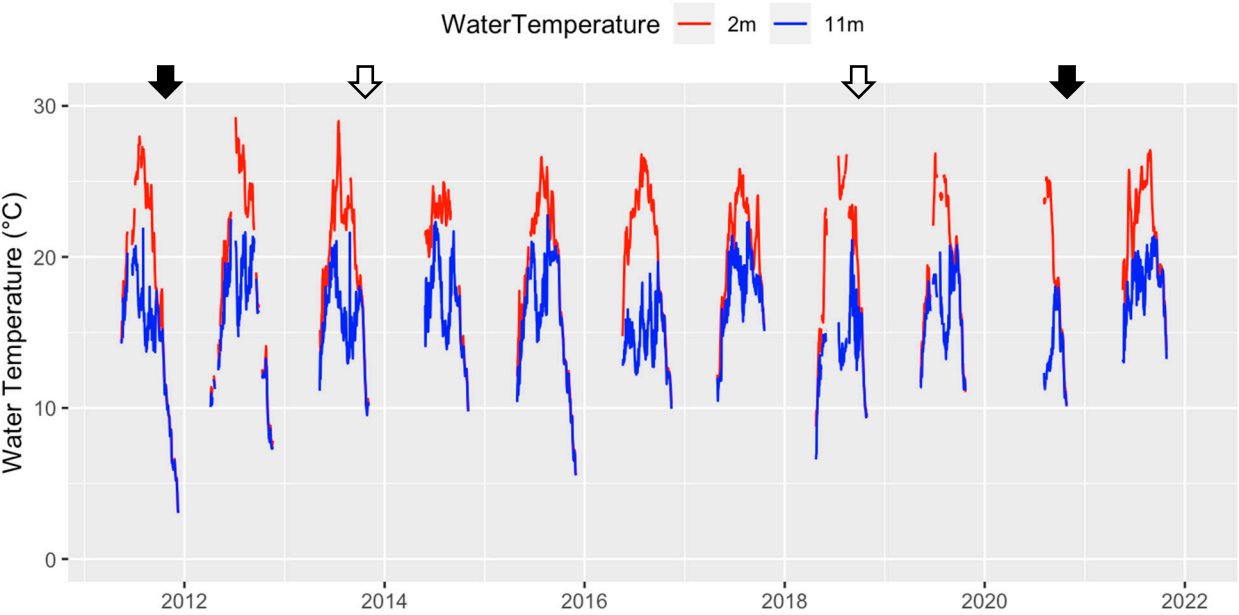
Figure S1. Muskegon Lake Observatory gathering time-series meteorological and water quality data in Muskegon Lake, MI.

(A)



(B)

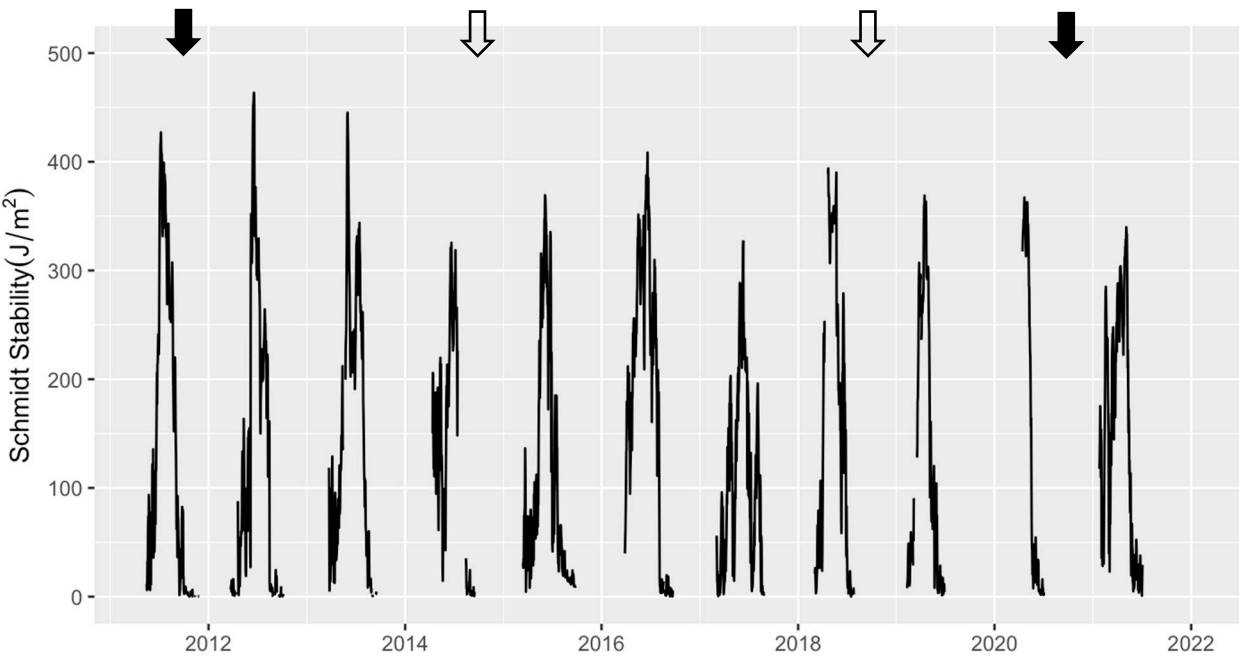
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(C)

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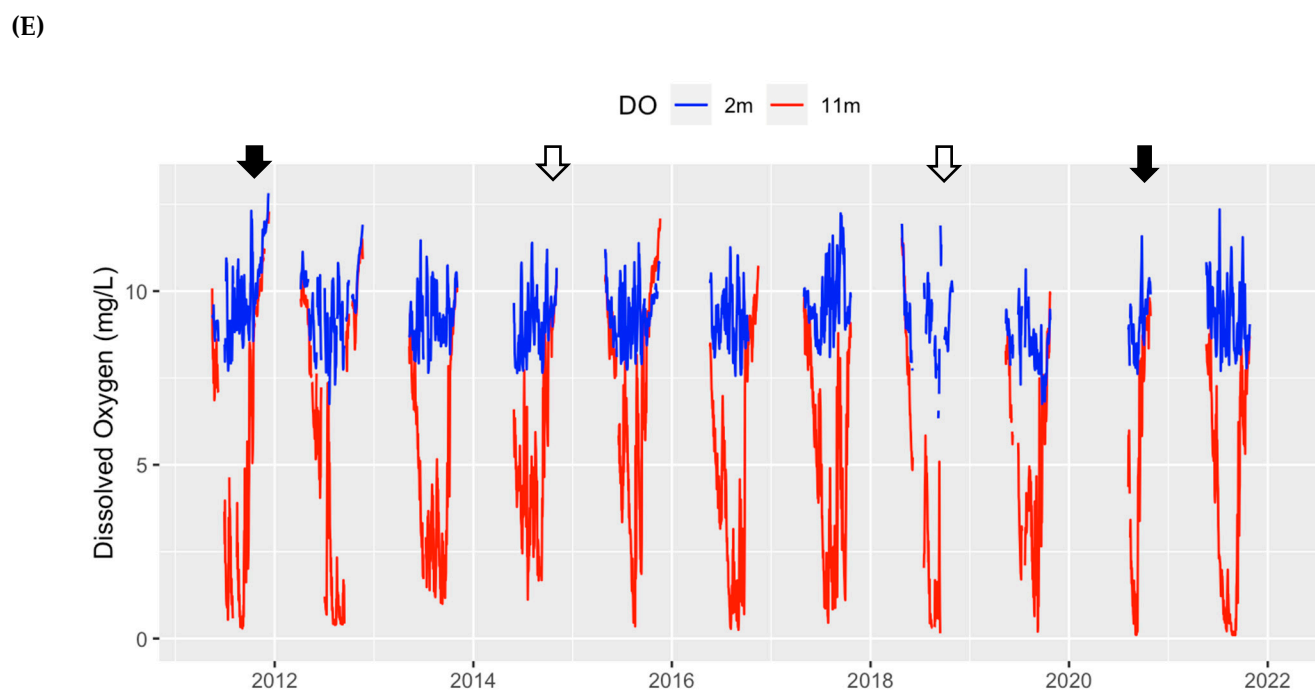
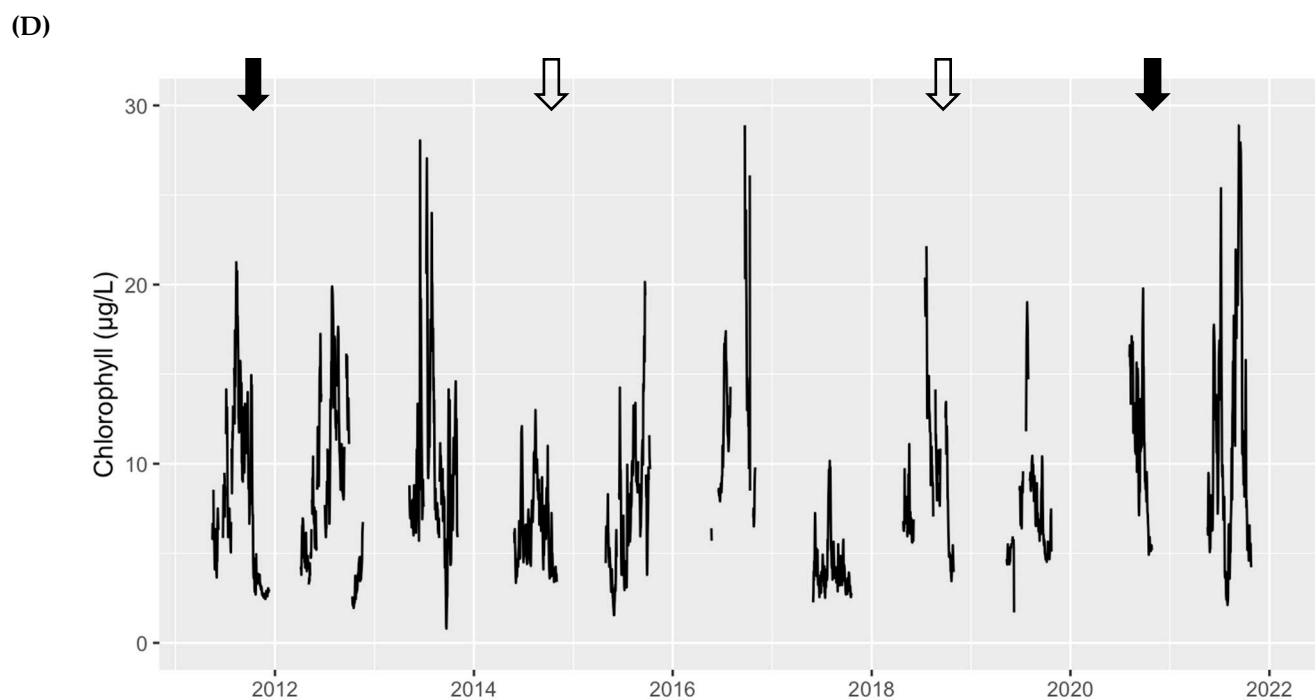
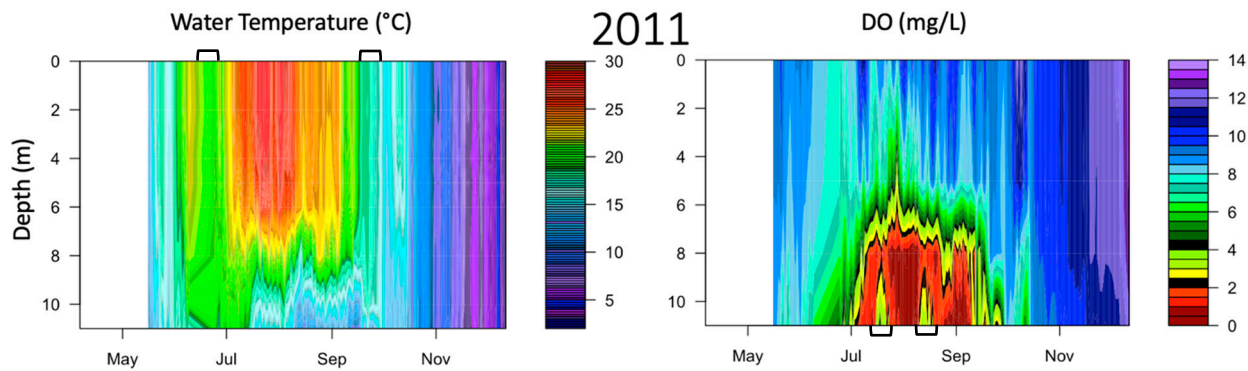
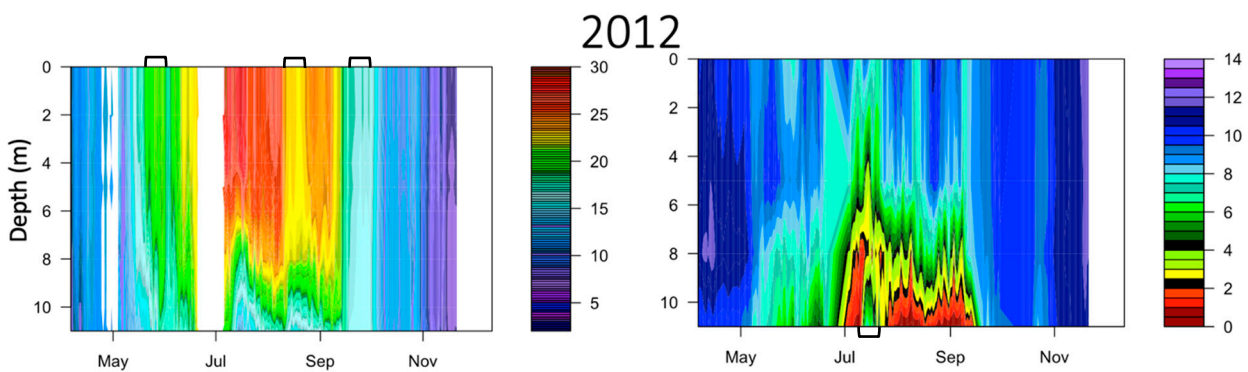


Figure S2. Time-series graphs of (A) air temperature, (B) surface water temperature, (C) Schmidt Stability, (D) surface chlorophyll-a at 2 m, and (E) DO at 2 m and 11 m from 2011–2021. Filled arrows represent the two most severely hypoxic years while empty arrows represent the two least severely hypoxic years.

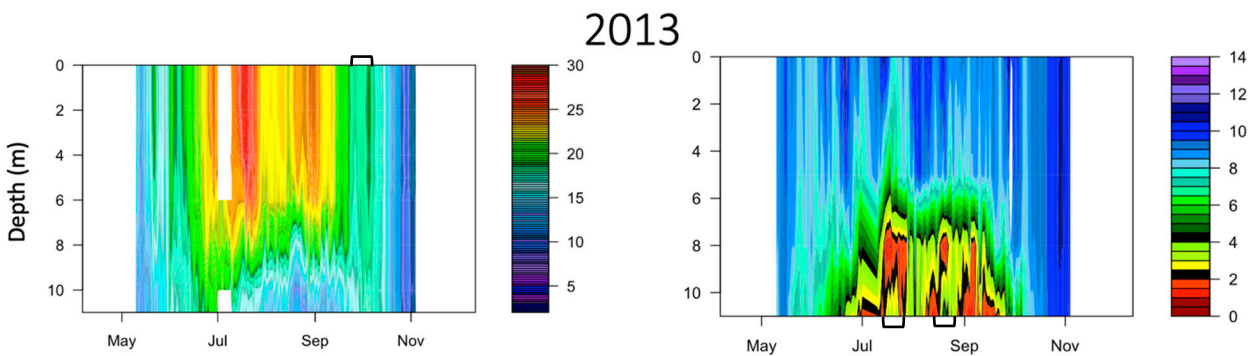
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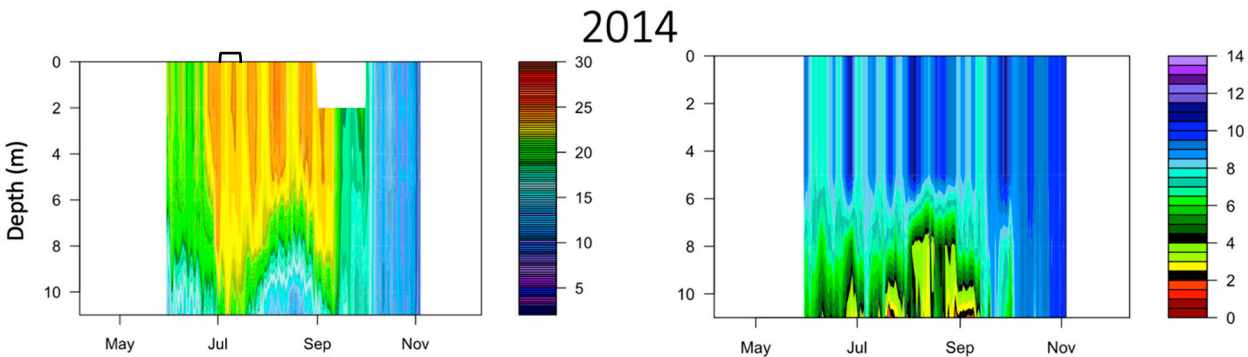
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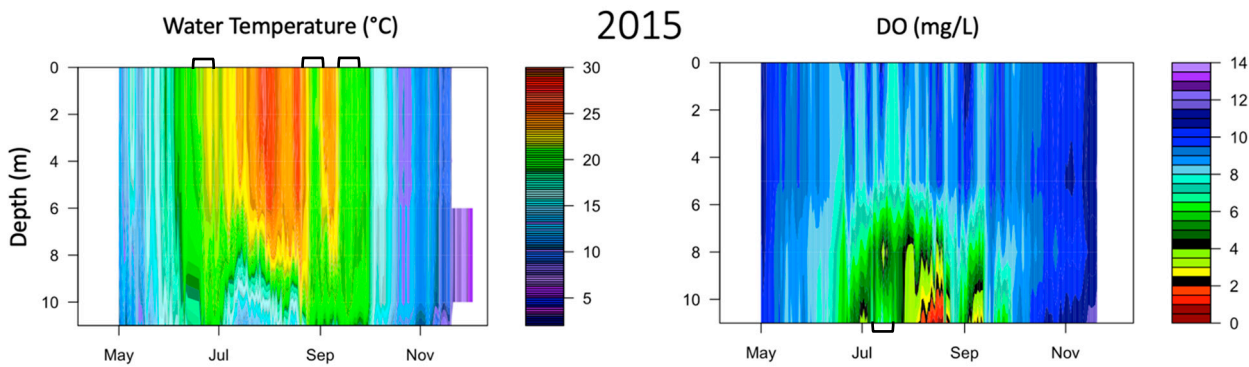
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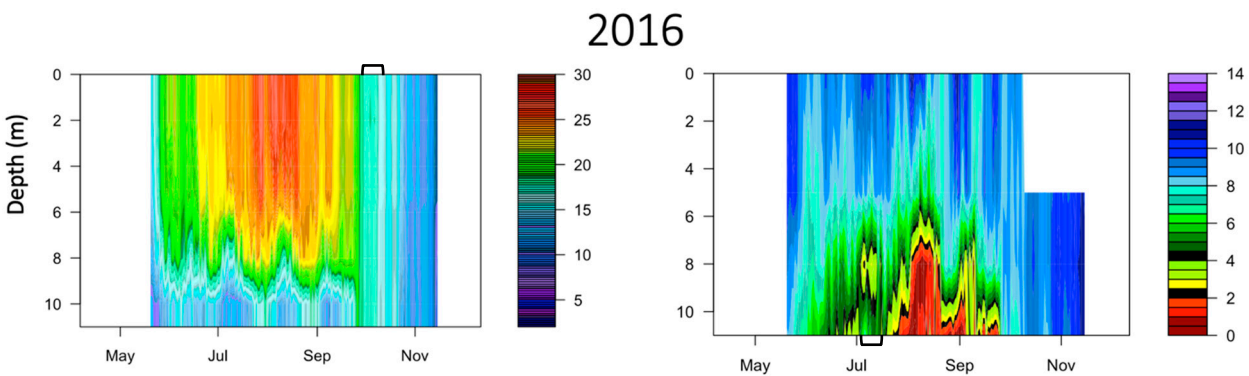
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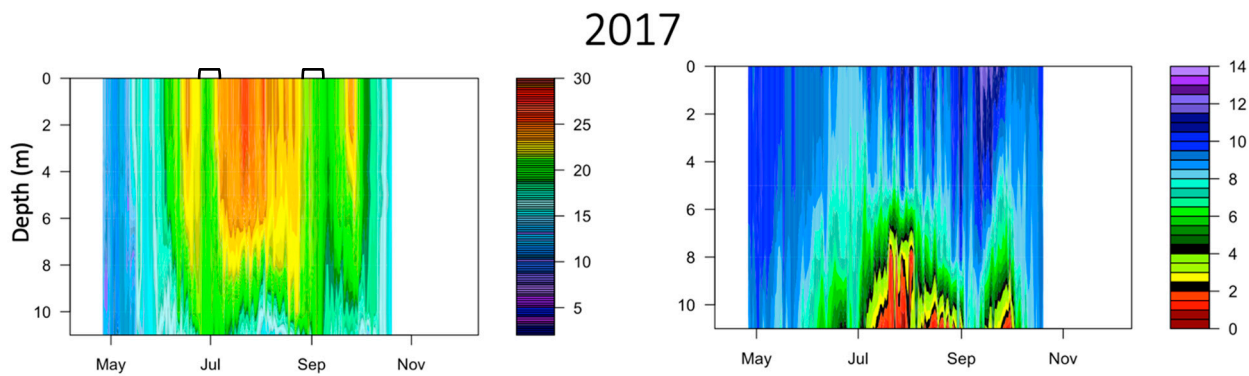
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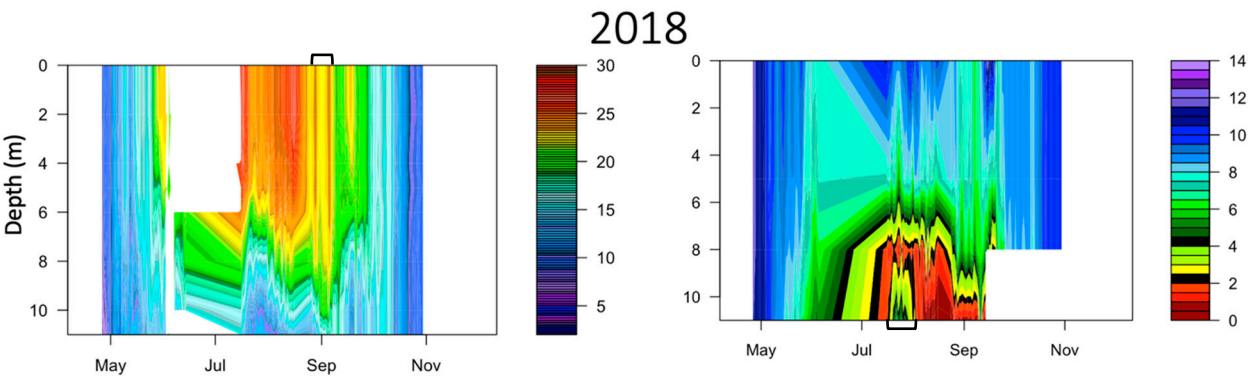
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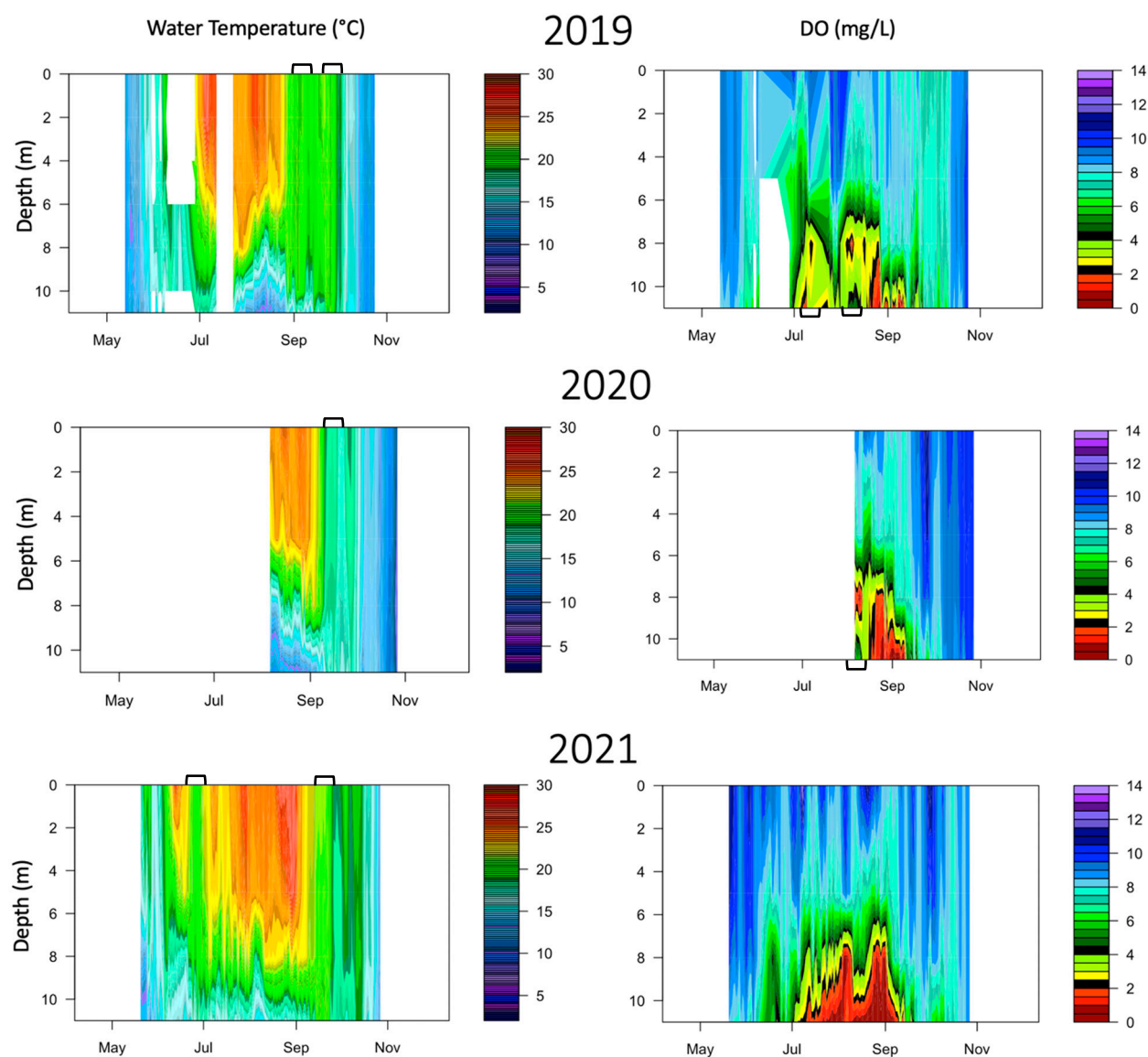
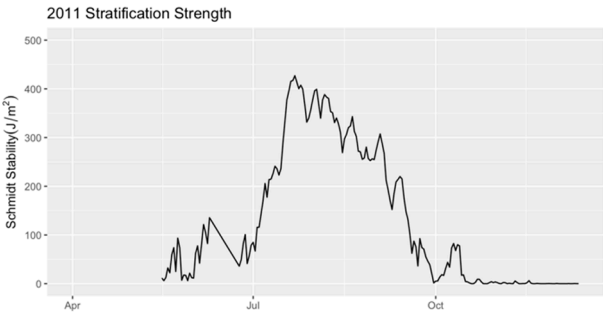
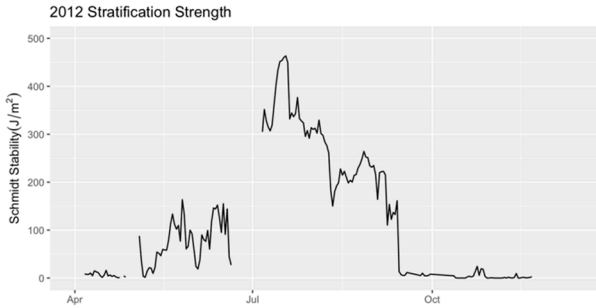


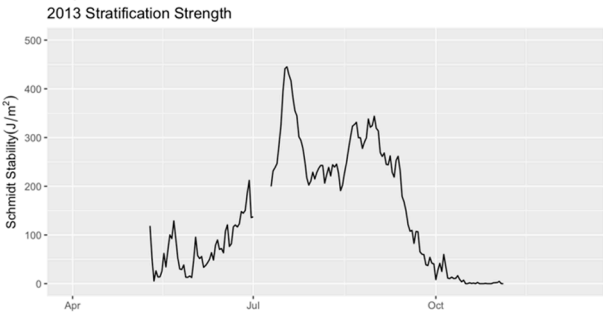
Figure S3. Time-series heat maps of 2011-2021 thermal stratification and dissolved oxygen from the Muskegon Lake Observatory (MLO) buoy. Each graph is scaled to the earliest deployment and the latest retrieval of the MLO leading to the lack of data when the buoy was not yet deployed in other years. Black lines were drawn at DO concentrations of 4 mg/L to signify mild hypoxia and 2 mg/L to signify severe hypoxia. Black brackets were drawn to highlight wind mixing events and cold, oxygenated upwelled water intrusions, respectively. Missing data throughout the heat maps are attributed to malfunctioning sensors and extreme biofouling.



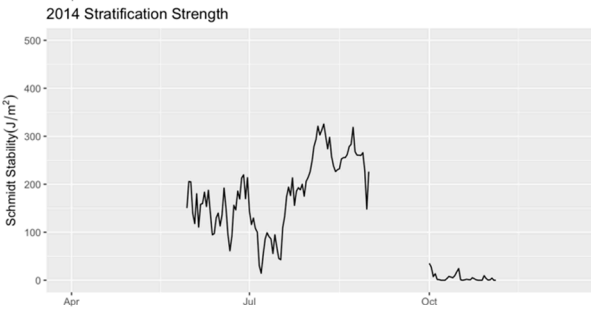
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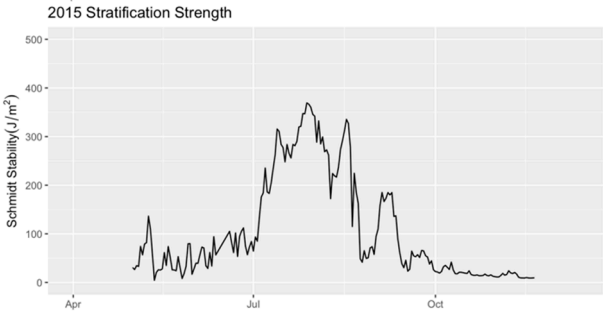
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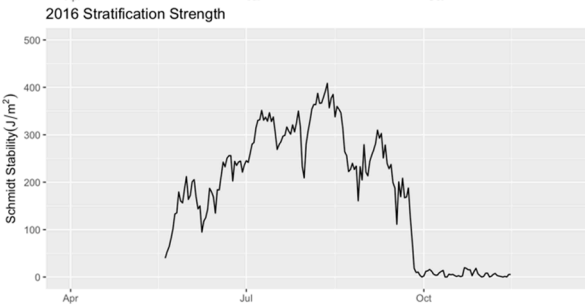
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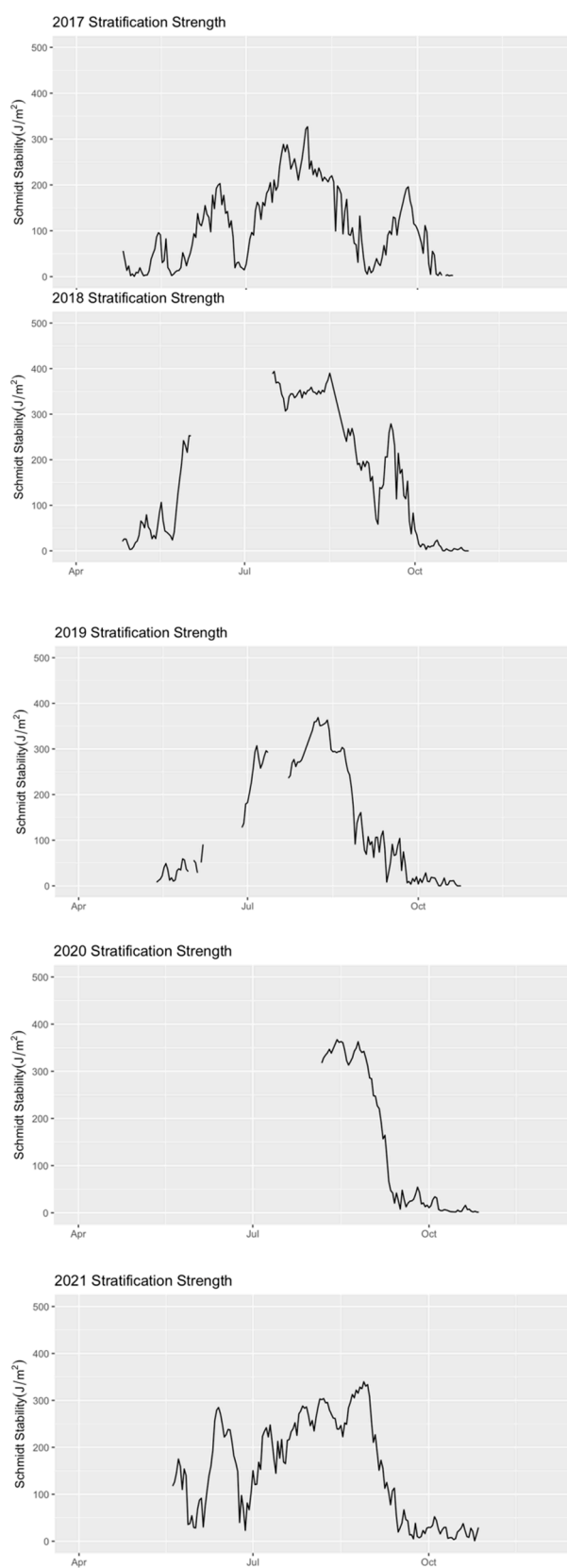


Figure S4. Schmidt stability time-series graphs from 2011-2021. Higher values correspond with stronger stratification while values at 0 signify a mixed estuary. The lack of data for 2020 was due to the late deployment of the Muskegon Lake Observatory buoy in light of Covid-19.

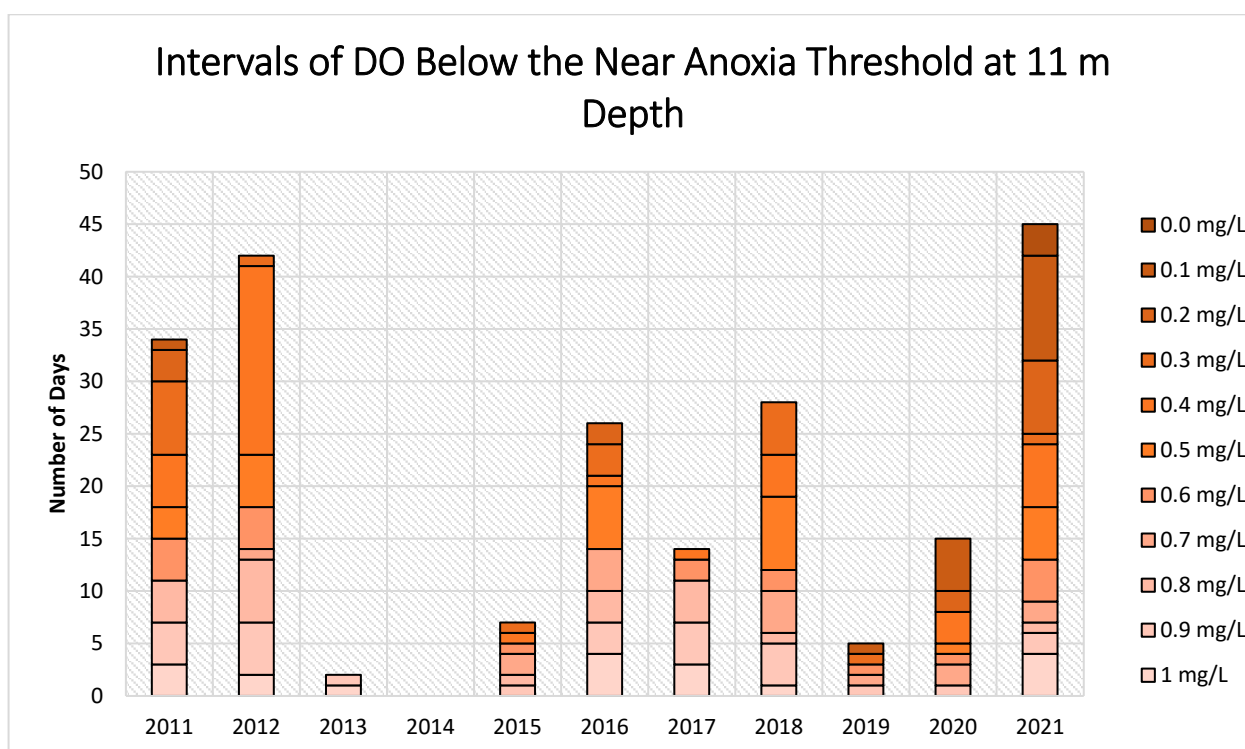


Figure S5. Histogram of DO intervals below the near anoxia threshold of 1 mg/L from 2011-2021. Each interval is on a scale of 0.1 mg/L. The histogram determines the number of days that daily averaged DO concentrations reached that interval at 11m depth.