Supplemental Information

Influence of invasive quagga mussels, phosphorus loads, and climate on spatial and temporal patterns of productivity in Lake Michigan: A biophysical modeling study

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Hydrodynamic model skill assessment

The FVCOM hydrodynamic simulations showed similar skill to previously-published Lake Michigan hydrodynamic models in simulation of surface and sub-surface temperature. The same model was previously shown to simulate currents observed during the 1998 NOAA EEGLE study with similar skill to previously-published models (Rowe et al., 2015a). In 2000, 2005, and 2010 simulations, surface temperature had a RMSD < 1.41 and absolute BD < 0.46 ºC in comparison to buoy surface temperature and satellite-derived lake-wide mean temperature (Fig. S2, Table S1). In comparison to vertically-resolved temperature measured at 12 offshore stations in the USEPA spring and summer surveys (Fig. 1), RMSD was < 1.3 ºC with absolute BD < 0.3 ºC for 2000, 2005, and 2010 (Table S3). Simulation of vertically-resolved temperature at the Muskegon nearshore-offshore transect was more complex than for the offshore stations, especially at the 45-m station, because of the oscillating thermocline position caused by upwelling-downwelling dynamics. The model simulated temperature at the Muskegon transect with reasonable accuracy (BD < 0.8, RMSD < 2.1 ºC, Table S4. Fig. S3). As a point of comparison, Beletsky et al. (2006) reported RMSD of 1-1.5 ºC for surface temperature and 0.3-2.9 ºC for sub-surface temperature in a 2-km grid Princeton Ocean Model (POM) simulation of Lake Michigan. The POM simulation had comparable skill to the values reported here, although both models suffered from a shallow-biased surface mixed layer and diffuse thermocline. Beletsky et al. (2006) focused on sub-surface thermal structure at the mid-lake buoys, and did not evaluate skill at nearshore locations such as the Muskegon 45 and 15-m stations that are affected by upwelling-downwelling in summer.

Biological model skill assessment

The model simulated major spatial and temporal patterns in chlorophyll-a concentration. In 2000, the model simulated the seasonal patterns of monthly mean satellite-derived surface chlorophyll-a (BD = 0.05 μg L^{-1}, RMSD = 0.24 μg L^{-1}, r = 0.57) and K_{dPAR} (BD = -0.01 m^{-1}, RMSD = 0.02 m^{-1}, r = 0.48), showing maxima in spring and fall with a minimum in mid-summer (Fig. 5a,d). Reduced chlorophyll-a and light attenuation in 2005 and 2010, compared to 2000, were simulated (Fig. 5b,c,e,f, Table S2); however simulated Feb-Apr chlorophyll-a was biased high and the unusually high chlorophyll-a maximum in Sep-Oct 2010 was not simulated, resulting in slightly worse skill statistics for 2005 and 2010 in comparison to satellite-derived chlorophyll-a. Correlation to vertically–resolved chlorophyll-a concentration measured by USEPA in 2000 was relatively high (BD = -0.19 μg L^{-1}, RMSD = 0.47 μg L^{-1}, r = 0.72) because the model simulated the deep chlorophyll-a layer, which accounts for much of the variance in chlorophyll-a during the summer offshore. Skill statistics declined slightly in 2005 and 2010 (Table S3, abs. BD < 0.5 μg L^{-1}, RMSD < 0.8 μg L^{-1}, r > 0.59). At the Muskegon transect in 2000, the model simulated major patterns in chlorophyll-a concentration, including surface maxima in spring and fall, a deep chlorophyll-a layer during summer stratification, and higher chlorophyll-a concentrations nearshore (15-m station) than offshore (Fig. 6, Table S4; abs. BD < 0.4, RMSD 1.0 μg L^{-1}, r > 0.52). Reduced chlorophyll-a concentration during deep mixing periods relative to 2000 was simulated in 2005 and 2010, although simulated Apr-May chlorophyll-a was biased high (Fig. 6c,f,i); skill statistics for 2010 were similar to 2000 (Table S4).

We also evaluated model skill in simulating water quality variables and zooplankton. Simulated particulate organic carbon, dissolved and total phosphorus fell generally within the range of observations (relative bias -3 to 15% USEPA, Table S3; -50 to 18% NOAA, Table S4), although correlation was less than for chlorophyll-a concentrations. Zooplankton biomass in 2000 was within the range of observations at station M110, although the seasonal maximum in mid-summer was under-predicted by the model (Fig. S4a). Reduced summer zooplankton biomass was simulated in 2010 vs. 2000, consistent with observations (Fig. S4c). Zooplankton observations were not available in 2005.

Model skill in simulating the spatial distribution of chlorophyll-a

The model simulated major features of the spatial distribution of chlorophyll-a in Lake Michigan, as observed in satellite-derived and field observations (Fig. S5). A circular pattern of low chlorophyll-a in the center of southern Lake Michigan surrounded by higher chlorophyll-a in mid-depth regions, which has been referred to as the "doughnut"-shaped phytoplankton bloom (Kerfoot et al., 2008), was observed in March and April prior to the quagga mussel invasion. The 2000 simulation reproduced this pattern, showing low chlorophyll-a in the centers of the deep north and south basins (> 100 m) with higher chlorophyll-a in mid-depth regions (Fig. S5a). In April 2005 and 2010, post-quagga mussel invasion, the doughnut pattern in the southern basin was not simulated, consistent with observations (Fig. S5b,c).

During the summer stratified period in July and August, low surface chlorophyll-a concentration was observed offshore, with plumes of higher chlorophyll-a concentration extending from the shore. The model reproduced this pattern, and even the locations of some of these chlorophyll-a plumes (Fig. S5d, Jul 2000 east shore; S5e Jul 2005 near Green Bay; S5f; Aug 2010 west shore), although the modeled plumes were more diffuse than the satellite-derived plumes. Animations of model surface chlorophyll-a, and model state variables, are included in Supplemental Information to illustrate the dynamics of these nearshore chlorophyll-a plumes, a process that is difficult to visualize by field observations or through infrequent cloud-free satellite images.

Surface chlorophyll-a concentration increased from September to October or November (Fig. 6; Fig. S5g,h,i) and became more uniform, consistent with observations. Bands of reduced chlorophyll-a concentration in 2005 and 2010, relative to 2000, were observed and simulated in April and November, but not in July and August.

Animation files

Animation files show the 12-month "baseline" simulations (Table 1) for 2000, 2005, and 2010. The animation files may be downloaded from the journal website, or may be conveniently viewed at https://deepblue.lib.umich.edu/handle/2027.42/136202

Temperature_1_animation.wmv: Surface temperature

Chlorophylla_1_animation.wmv: Surface chlorophyll-*a*

DissolvedP_1_animation.wmv: Surface total dissolved phosphorus

Detritus_1_animation.wmv: Surface detritus concentration (particulate organic carbon, excluding phytoplankton and zooplankton).

Zooplankton_1_animation.wmv: Surface zooplankton carbon concentration

DreissenidRation_1_animation.wmv: Rate of food assimilation by mussels, given by $f_a F_A P$ in Eq. 2, expressed as mg phytoplankton carbon per mg mussel biomass carbon per day $\times$ 100%.

DreissenidBiomass_1_animation.wmv: Simulated mussel biomass in mg ash-free-dry-mass m^{-2}

Table S1. Skill statistics for simulation of surface temperature in comparison to NDBC buoys (Figure 1) and satellite-derived lake-wide mean temperature. Statistics are the bias deviation (BD, ºC), root-mean-square deviation (RMSD, ºC), Pearson correlation coefficient (r).

Year	Location	BD	RMSD	r
2000	North buoy	0.04	0.59	1.00
2000	South buoy	-0.01	0.63	0.99
2000	Lake-wide	-0.10	1.41	0.98
2005	North buoy	0.26	0.91	0.99
2005	South buoy	0.46	1.08	0.99
2005	Lake-wide	-0.30	0.87	0.99
2010	North buoy	-0.14	1.30	0.98
2010	South buoy	0.38	0.92	0.99
2010	Lake-wide	0.25	1.21	0.99

Table S2. Skill statistics for simulation of satellite-derived chlorophyll-*a* (μg L^{-1}) and K_{PAR} (m^{-1}) averaged lake-wide by month. Statistics are the bias deviation (BD, ºC), root-mean-square deviation (RMSD, ºC), Pearson correlation coefficient (r), observed and simulated standard deviation (SD).

Variable	Year	BD	RMSD	r	Obs. Mean	Obs. SD	Sim. SD
chlorophyll-*a*	2000	0.05	0.24	0.57	1.24	0.26	0.27
chlorophyll-*a*	2005	0.14	0.28	0.50	0.88	0.16	0.29
chlorophyll-*a*	2010	0.03	0.38	0.34	0.95	0.39	0.27
K_{PAR}	2000	-0.01	0.02	0.48	0.14	0.02	0.01
K_{PAR}	2005	0.00	0.01	0.60	0.12	0.01	0.01
K_{PAR}	2010	-0.02	0.04	0.45	0.13	0.04	0.01

Table S3. Skill statistics for simulation of vertically-resolved temperature (ºC), chlorophyll-*a* (μg L^{-1}), total and dissolved phosphorus (TP, DP, μg L^{-1}) for USEPA spring and summer surveys at offshore stations (Figure 1). Statistics are as defined in Table S2.

Variable	Year	BD	RMSD	r	Obs. Mean	Obs. SD	Sim. SD
Temperature	2000	-0.3	1.3	0.99	8.8	7.3	6.7
Temperature	2005	0.1	1.2	0.99	7.0	7.3	7.3
Temperature	2010	0.0	1.0	0.99	6.7	7.1	6.9
chlorophyll-*a*	2000	-0.2	0.5	0.72	1.0	0.6	0.6
chlorophyll-*a*	2005	-0.5	0.8	0.60	1.1	0.8	0.6
chlorophyll-*a*	2010	-0.1	0.5	0.59	0.7	0.4	0.5
TP	2000	0.6	2.2	0.12	4.5	2.1	0.6
TP	2005	0.5	1.4	0.27	3.3	1.3	0.5
TP	2010	0.4	1.2	0.04	3.0	1.1	0.6
DP	2000	0.0	1.3	0.52	2.3	1.5	0.5
DP	2005	0.1	0.8	0.41	1.8	0.8	0.4
DP	2010	-0.1	0.8	0.19	1.9	0.8	0.3

Table S4. Skill statistics for simulation of vertically-resolved temperature (ºC), chlorophyll-*a* (μg L^{-1}), total and dissolved phosphorus (TP, DP, μg L^{-1}), and particulate organic carbon (POC, μg L^{-1}) for 2000 and 2010 (data not available in 2005) at the NOAA Muskegon transect 15, 45, and 110-m stations (Figure 1). Statistics are as defined in Table S2.

Variable	Year	BD	RMSD	r	Obs. Mean	Obs. SD	Sim. SD
Temperature	2000	0.8	2.0	0.95	7.5	5.7	5.2
Temperature	2010	0.3	2.1	0.95	9.4	6.4	5.6
chlorophyll-*a*	2000	-0.3	1.0	0.52	1.8	0.9	1.0
chlorophyll-*a*	2010	-0.4	1.0	0.58	1.5	1.0	0.9
TP	2000	0.9	2.3	0.14	5.5	1.4	1.7
TP	2010	-1.4	2.2	0.42	5.5	1.8	1.2
DP	2000	0.1	0.7	0.27	1.8	0.7	0.4
DP	2010	-1.6	2.0	-0.16	3.3	1.1	0.3
POC	2000	44.9	136.6	0.13	244.5	88.4	107.6
POC	2010	-26.3	81.8	0.47	176.2	82.3	66.7

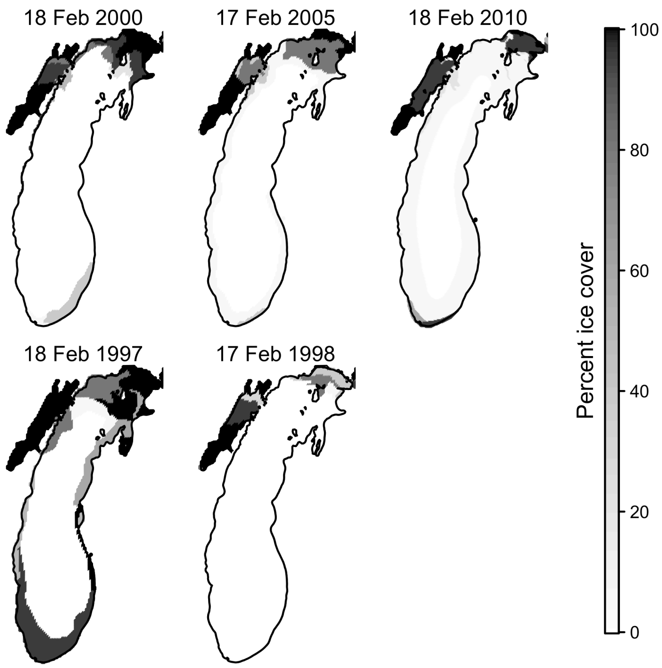

Figure S1. Satellite-derived ice concentration maps near the date of maximum ice cover of the model years. (data source, http://www.glerl.noaa.gov/data/ice/, accessed May 2016).

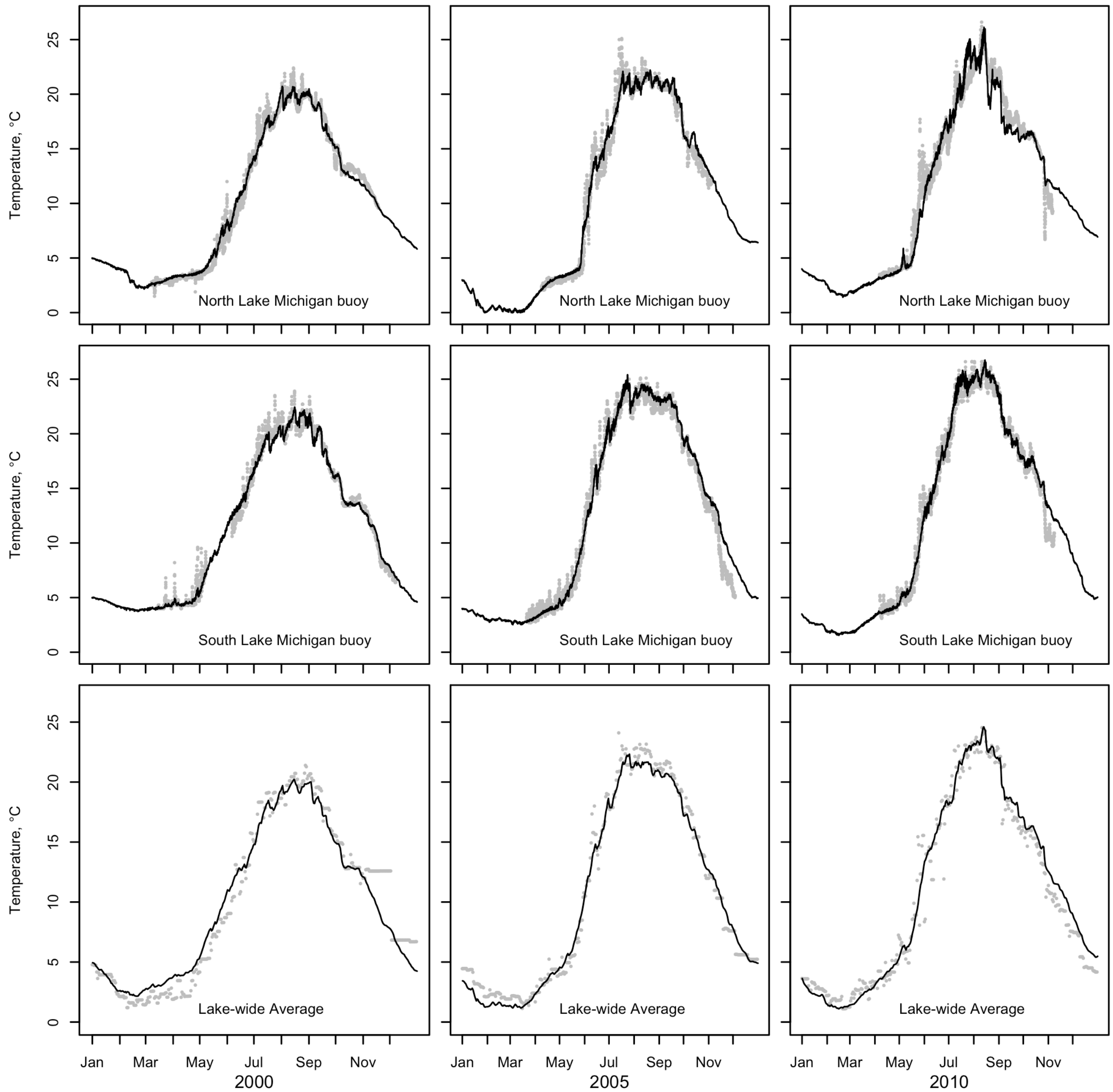

Figure S2. Simulated (lines) and observed (points) water surface temperature at NDBC buoys (Figure 1) and lake-wide mean satellite-derived surface temperature.

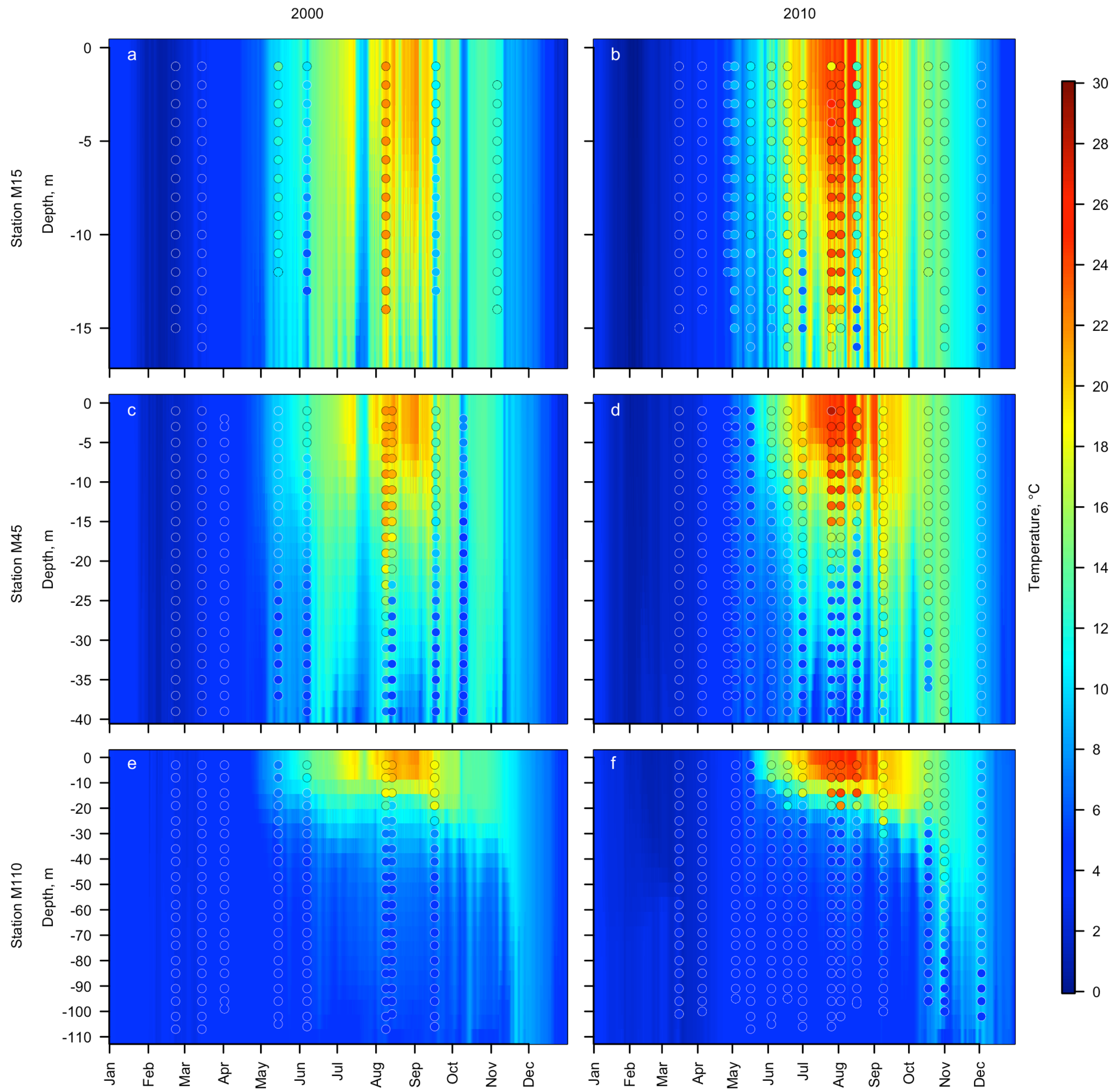

Figure S3. Comparison of simulated to observed (symbols) water temperature at the Muskegon transect stations (Figure 1). Note the variable thermocline position and surface temperature at the 15 and 45-m stations caused by coastal upwelling-downwelling dynamics.

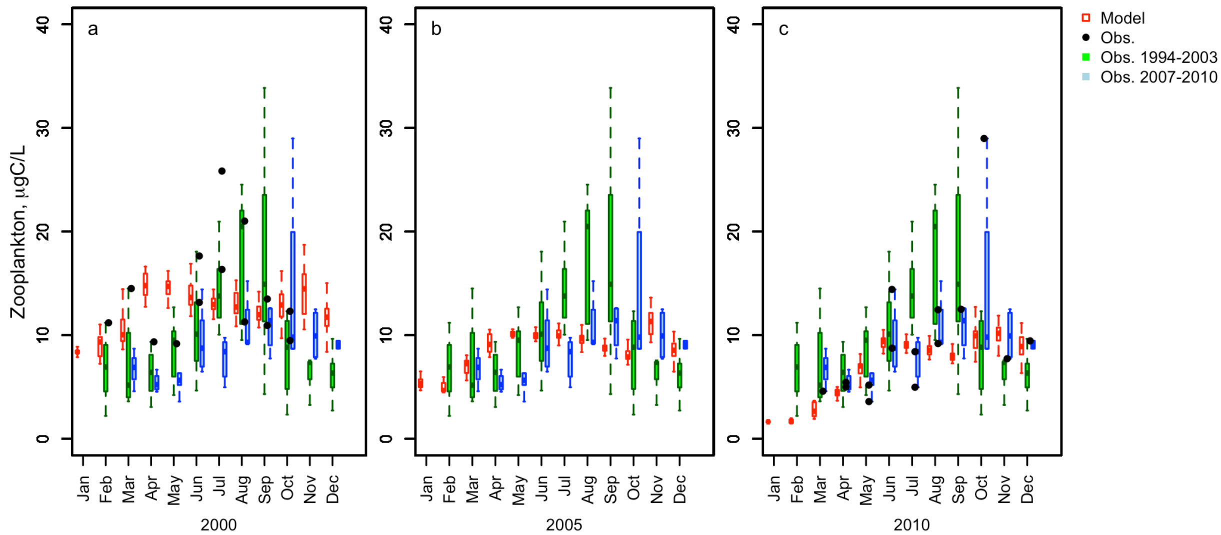

Figure S4. Simulated and observed column mean zooplankton biomass at the Muskegon 110-m station (Vanderploeg et al., 2012; Pothoven and Fahnenstiel, 2015; Pothoven unpubl.)

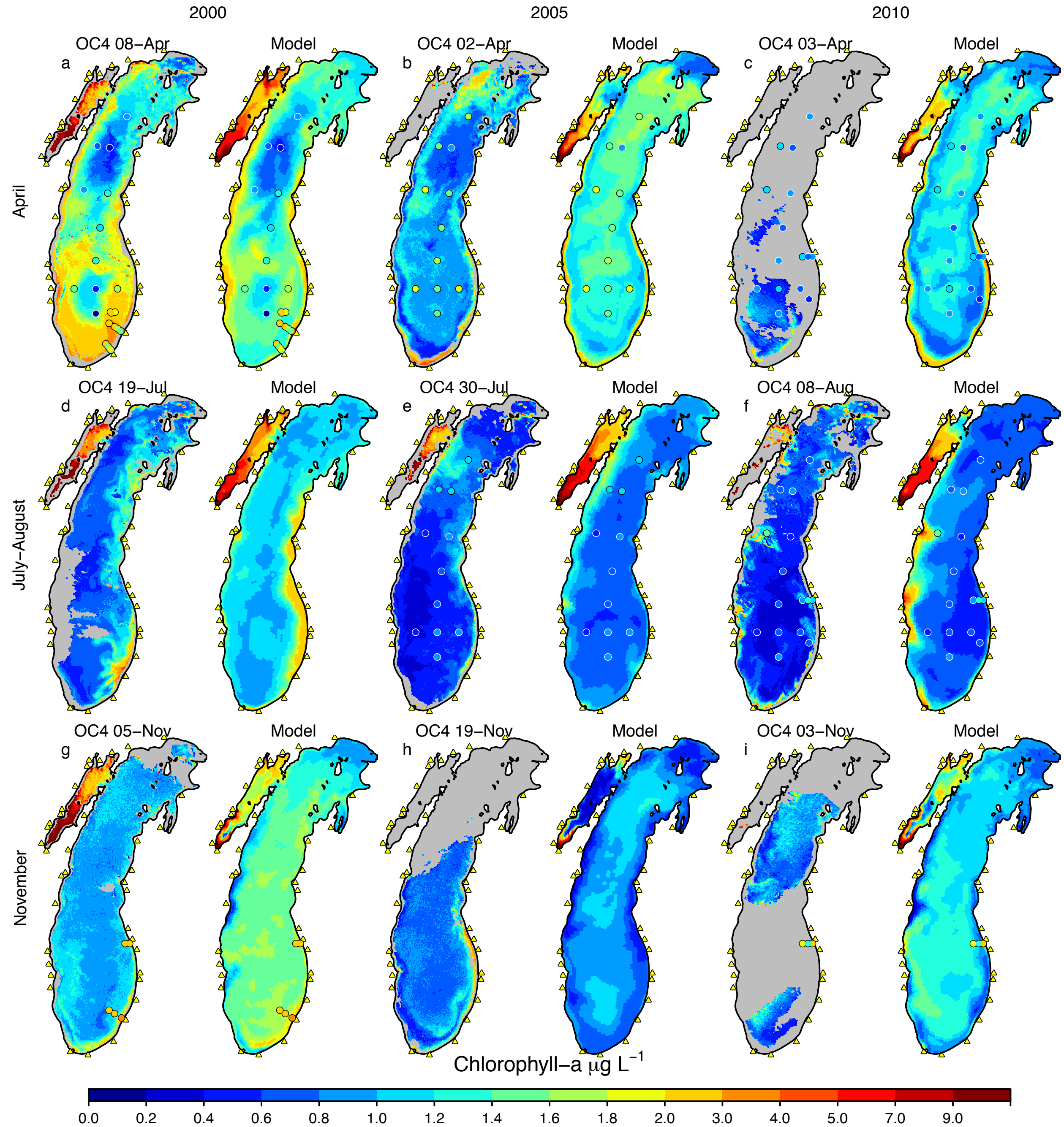

Figure S5. Comparison of modeled surface chlorophyll-a to satellite-derived (SeaWiFS OC4) and field-sampled (symbols) chlorophyll-a for dates in 2000, 2005, and 2010, selected to represent the seasons and for availability of observational data. All chlorophyll-a data are plotted on the same color scale. Locations of tributary phosphorus load input are indicated by yellow triangles.