

1 Article

# 2 Ice Forecasting in the Next-Generation Great Lakes 3 Operational Forecast System (GLOFS)

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17 **Abstract:** Ice Cover in the Great Lakes has significant impacts on regional weather, economy, lake  
18 ecology, and human safety. However, forecast guidance for the lakes is largely focused on the ice-  
19 free season and associated state variables (currents, water temperatures, etc.) A coupled lake-ice  
20 model is proposed with potential to provide valuable information to stakeholders and society at  
21 large about the current and near-future state of Great Lakes Ice. The model is run for three of the  
22 five Great Lakes for prior years and the modeled ice cover is compared to observations via several  
23 skill metrics. Model hindcasts of ice conditions reveal reasonable simulation of year-to-year  
24 variability of ice extent, ice season duration, and spatial distribution, though some years appear to  
25 be prone to higher error. This modeling framework will serve as the basis for NOAA's next-  
26 generation Great Lakes Operational Forecast System (GLOFS); a set of 3-D lake circulation  
27 forecast modeling systems which provides forecast guidance out to 120 hours.

28 **Keywords:** ice modeling, operational forecast, FVCOM, CICE, hydrodynamic modeling, Great  
29 Lakes  
30

## 31 1. Introduction

32 Ice formation in the Great Lakes occurs each year during the winter season, where typical ice  
33 onset occurs in early December and ice-off dates come in late spring (April or May; [1,2,3]).  
34 However, there is a high degree of interannual and inter-lake variability in ice cover driven by  
35 atmospheric conditions and lake characteristics, with the maximum extent of ice occurring near late  
36 January or early February ([4,5] Table 1). Only under rare occasions do the lakes experience  
37 complete or nearly-complete freeze-over due to their depth and large thermal heat content, with  
38 Lake Erie being the exception, experiencing annual maximum ice cover near 82% [1,2,3]. As such,  
39 ice first forms near the shorelines and in protected or shallow bays, followed by progressive growth  
40 toward the offshore. Though observations are sparse in space and time, ice thickness shows a high  
41 degree of variability, ranging from a few centimeters to over a meter [6,7,8].

42 Ice cover plays a major role in winter lake processes. Presence of ice cover inhibits latent and  
43 sensible heat fluxes from the lake to the atmosphere which impact lake surface temperatures, water  
44 levels, and hydrometeorological events [9,10,11]. Ice cover also alters air-water momentum transfer,  
45 which influences currents and waves. Ecological impacts can be observed due to ice conditions,

46 where for example, the timing of spring phytoplankton blooms are impacted by water temperatures  
 47 and ice-off timing [12]. Additionally, ice formation has a direct influence on search and rescue  
 48 operations, spill response efforts, and commercial navigation.

49 **Table 1.** Average annual maximum ice cover for the period 1973 – 2018.

	Superior	Michigan	Huron	Erie	Ontario	Basin
<b>Average Max. ice cover (%)</b>	60.91	39.64	64.60	82.19	29.77	54.28

50 The Great Lakes are home to a \$77 billion commercial shipping industry and several major  
 51 ports serving the United States and Canada as well as global trade [13; Fig. 1]. With the greatest  
 52 concentration and thickness of ice focused at the coastline and bays, **as well as ice jams in the**  
 53 **connecting channels**, shipping ports are often inaccessible to most vessels, and thus the shipping  
 54 season is largely restricted to the ice-free period in the lakes (April – December) or when aid can be  
 55 provided by US and Canadian ice-cutting vessels. However, for the vessels that continue to operate  
 56 during ice-covered periods, accurate information on ice extent, concentration, and thickness is  
 57 crucial to ensure safe navigation. Currently, the only available information on ice conditions comes  
 58 from the US and Canadian Ice Centers, which coordinate to produce a daily Great Lakes Ice  
 59 Analysis product. These ice charts are based on remotely-sensed data from satellites or flyovers and  
 60 provide an estimate of ice concentration and distribution based on observed data, which could be  
 61 hours or days old. However, due to the dynamic nature of ice in the Great Lakes, the ice field can  
 62 vary dramatically over several hours or a few days due to wind conditions or changes in air  
 63 temperature [8]. Therefore, observed ice conditions may not be sufficient to provide decision  
 64 makers with the information necessary to operate safely or effectively over the course of a few days.  
 65 Yet, currently there exists no operational forecast guidance for ice concentration in the Great Lakes.



66  
 67 **Fig. 1:** The Great Lakes domain, including Lakes Erie, Michigan, and Huron.

68 In the US, marine forecast guidance in the Great Lakes for currents, water temperatures, and  
 69 water level fluctuations, is provided by the National Oceanic and Atmospheric Administration’s  
 70 (NOAA) Great Lakes Operational Forecast System (GLOFS; [14,15,16]). GLOFS is a set of three-  
 71 dimensional hydrodynamic computer models that covers each of the Great Lakes and has been  
 72 operated by the National Ocean Service (NOS) since 2005. Real-time nowcast and forecast  
 73 predictions of lake conditions from GLOFS provide decision support for commercial navigation,  
 74 search and rescue operations, recreational use, spill response, drinking water safety, and lake  
 75 management. The first generation of GLOFS was developed as a result of the collaboration between

76 the NOAA Great Lakes Environmental Research Laboratory (GLERL) and Ohio State University  
77 (OSU), in which the hydrodynamic models were developed using a version of the Princeton Ocean  
78 Model (POM; [17]) adapted for the Great Lakes [18]. Although the first implementation of GLOFS  
79 did not include ice products, recent work has shown that coupling an ice model to Great Lakes  
80 POM models can provide accurate predictions of winter lake conditions [5].

81 An upgrade to GLOFS is underway to make a number of model improvements including an  
82 increase in model resolution in important regions, expansion of modeling domains, tracking of  
83 hydrologic water level changes, and providing support for the development of ecological forecast  
84 products in the Great Lakes. This next-generation GLOFS is being developed using the Finite  
85 Volume Community Ocean Model (FVCOM, [19]), which includes an internally-coupled  
86 unstructured grid version of the Los Alamos Sea Ice model (CICE, [20]). Recent work in two-way  
87 coupling between the lakes and a regional climate model has demonstrated the capability of CICE  
88 in the Great Lakes using evaluation of lake-averaged ice and temperature conditions [21]. However,  
89 this effort has not yet been extended and tested in an operational framework, in which a thorough  
90 spatio-temporal analysis of ice concentration has been carried out. Therefore, the goal of this study  
91 is to implement FVCOM-CICE into the next-generation GLOFS and assess the model's ability to  
92 resolve the spatial-temporal distribution of ice concentration in order to meet stakeholder  
93 requirements.

## 94 2. Methods

### 95 2.1. Hydrodynamic modeling

96 The next-generation GLOFS is based on FVCOM [19], a three-dimensional, unstructured, free-  
97 surface, primitive equation, sigma-coordinate oceanographic model that solves the integral form of  
98 the governing equations. FVCOM has been applied in several studies of the coastal ocean, including  
99 successful application to operational forecasting in the Great Lakes [22,23,24,25,26,27]. In this work,  
100 the existing FVCOM-based GLOFS models for Lake Erie, Huron, and Michigan will be used to  
101 assess performance of the hydrodynamic model in regard to winter conditions and ice formation  
102 using CICE. These implementations of FVCOM are based on the Lake Erie Operational Forecast  
103 System (LEOFS, [14]) and the Lake Michigan-Huron Operational Forecast System (LMHOFS, [25]),  
104 which combines Lakes Michigan and Huron into a single model since they form a single hydrologic  
105 system. Horizontal grid resolution in each model ranges from roughly 200 m near the shoreline to  
106 2500 m offshore, with 21 vertical sigma layers evenly distributed throughout the water column. As  
107 a result, the LEOFS model contains roughly 12,000 triangular elements, and the LMHOFS model is  
108 significantly larger with roughly 170,000 elements. Horizontal and vertical diffusion are handled by  
109 the Smagorinsky parameterization [28] and Mellor-Yamada level-2.5 turbulence closure scheme  
110 [29], respectively. The air-water drag coefficient is calculated as a function of wind speed [30].  
111 Latent and sensible heat fluxes are calculated from the Coupled Ocean-Atmosphere Response  
112 Experiment (COARE, [31,32,33]) algorithm for LMHOFS and from the SOLAR algorithm for LEOFS  
113 [34]. In both cases, the SOLAR algorithm is used to precompute the shortwave and longwave  
114 radiation, based on prescribed cloud cover and satellite-derived surface water temperatures.  
115 **Modeled depths are taken from 3 arc-second bathymetry data from the NOAA National Centers for  
116 Environmental Information (NCEI).**

117 Simulations without the ice model will be also conducted to be compared with simulations  
118 with the ice model in order to assess the impact of including the ice model on modeled water  
119 temperatures. In the non-ice simulations, no ice forms even when the surface water is super-cooled.  
120 The water temperature in the model is floored at -2.0 °C to avoid continual artificial cooling due to  
121 the water surface continuously exposed to the cold air above.

### 122 2.2. Ice modeling

123 An unstructured grid version of the Los Alamos Sea Ice model (CICE; [20,35]) has been  
124 included and coupled within FVCOM. The CICE model includes components for ice

125 thermodynamics and ice dynamics, using elastic-viscous-plastic rheology for internal stress [36],  
 126 and produces two-dimensional fields of ice concentration, thickness, and velocity. A multi-category  
 127 ice thickness distribution (ITD) model is employed in CICE to resolve mechanical deformation as  
 128 well as growth and decay [37]. For the Lake Erie and Lake Michigan-Huron models, five categories  
 129 of ice thickness are defined (5, 25, 65, 125, and 205 cm). The ice surface albedo depends on surface  
 130 temperature and thickness of ice, as well as the visible and infrared spectral bands of the incoming  
 131 solar radiation [38]. At ice-covered cells, the net momentum transfer is calculated as a weighted  
 132 average of the air-water and ice-water stresses by areal fraction of ice. The air-ice drag coefficient  
 133  $C_{D_{ai}}$  is a function of wind speed  $U$ , given as  $C_{D_{ai}} = (1.43 + 0.052U) \cdot 10^{-3}$  and the ice-water drag  
 134 coefficient is  $5.5 \cdot 10^{-3}$  [39]. Similarly, the net heat transfer is calculated as a weighted average of the  
 135 air-water and ice-water heat fluxes. The ice-water heat fluxes are calculated based on the bulk  
 136 transfer formula [40].

### 137 2.3. Simulation period

138 Two periods of simulation with three overlapping years are covered in this study. In the Lake  
 139 Erie simulation, the model was run for the years 2005 – 2017 using a continuous run (hotstarted)  
 140 from January 1, 2005. Initial conditions at the start of 2005 were provided by a spin-up simulation in  
 141 2004, in which conditions on January 1, 2004 were coldstarted with a uniform temperature of 4°C,  
 142 zero currents, and uniform lake level. Due to computational expense, the Lake Michigan-Huron  
 143 model (LMHOFS) was simulated for the years 2015 – 2017, with a spin-up year in 2014. On January  
 144 1, 2014, the LMHOFS model was initialized with satellite-derived surface water temperatures from  
 145 the Great Lakes Surface Environmental Analysis (GLSEA) [41] for the top 50 meters with a uniform  
 146 4°C temperature at depths below 50 meters. Similar to the Lake Erie case, the spin-up year was  
 147 coldstarted with zero currents and a uniform (resting) lake level. For both the Lake Erie and Lake  
 148 Michigan-Huron models, simulations are carried out with and without the ice model.

149 For years 2005 – 2014, hourly atmospheric forcing conditions are provided from the Great  
 150 Lakes Coastal Forecasting System (GLCFS; [18]), in which observations from coastal and offshore  
 151 meteorological stations are corrected for over-water conditions and interpolated, along with  
 152 available in-lake buoys, to the model grid [42]. This method of interpolated forcing conditions has  
 153 been the operational source of meteorological forcing for the GLOFS since its implementation.  
 154 However, starting in 2015, model output is available from the High-Resolution Rapid Refresh  
 155 (HRRR), a 3-km data-assimilated implementation of the Weather Research and Forecasting (WRF)  
 156 model [43]. In the upgrade of GLOFS, atmospheric forcing conditions are now being provided by  
 157 the HRRR in operations, and thus for the simulations presented here for the period 2015-2017, both  
 158 models are driven by HRRR model output. Although not as pertinent to this analysis, lateral  
 159 boundary conditions are provided for inflows and outflows to the lakes, details of which can be  
 160 found in previous work [14,25].

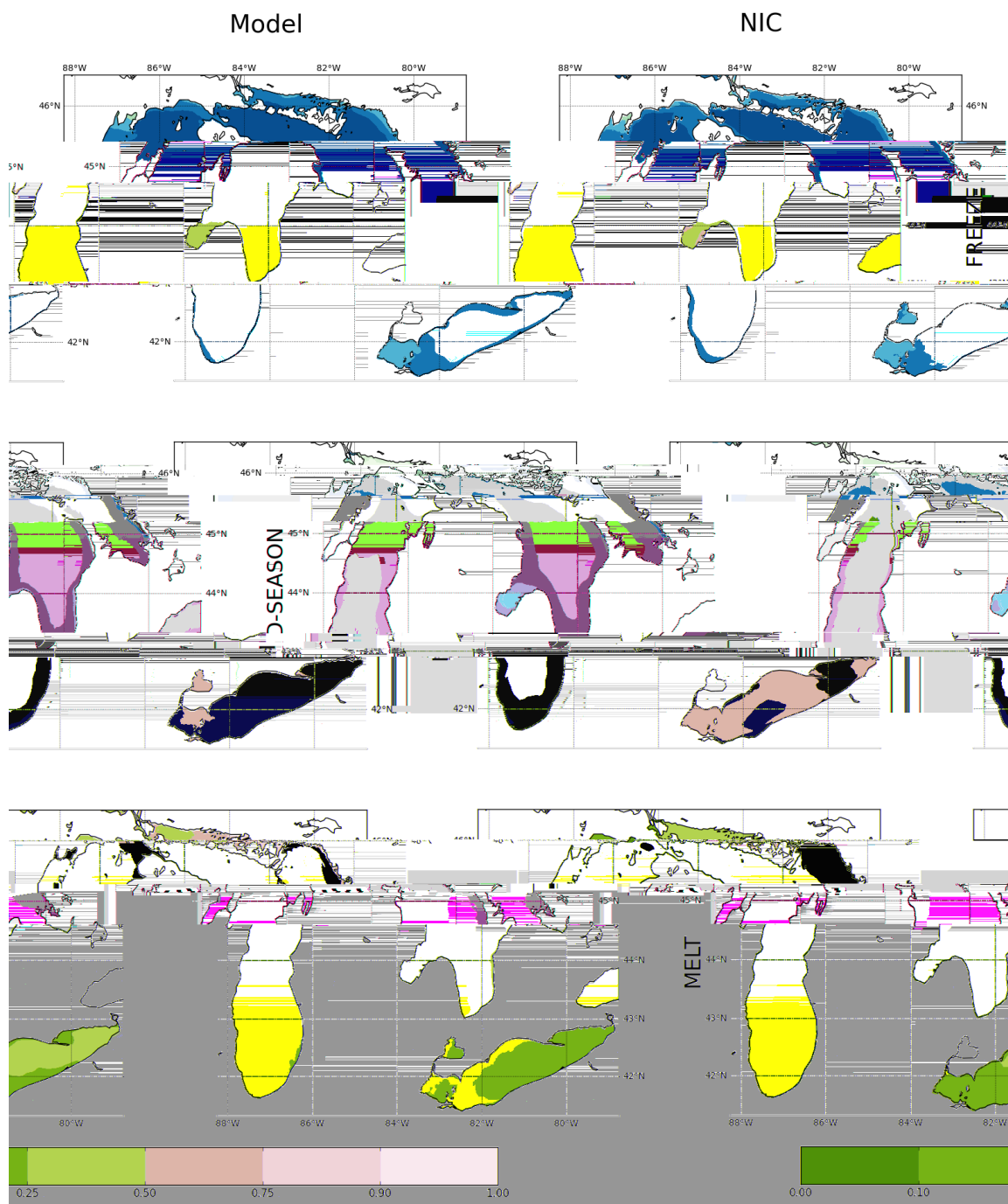
### 161 2.4. Model validation

162 To evaluate modeled ice concentration and spatial distribution, Great Lakes ice concentration  
 163 data is obtained from the US National Ice Center (NIC; [44]). Through a bi-national coordinated  
 164 effort between the US NIC and Canadian Ice Center, routine gridded ice analysis products are  
 165 produced from available data sources including Radarsat-2, Envisat, AVHRR, Geostationary  
 166 Operational and Environmental Satellites (GOES), and Moderate Resolution Imaging  
 167 Spectroradiometer (MODIS). Spatial resolution of the ice charts, hereafter referred to as NIC, is 2.55  
 168 km in 2005, and 1.8 km from 2006-2017. The resulting NIC data set defines ice concentration values  
 169 from 0 to 100% on 10% increments.

170 Assessment of model skill in simulating ice concentration is evaluated using root mean  
 171 squared error (RMSE, Eqn. 1) between the model and observed value

$$172 \text{RMSE} = \sqrt{\frac{\sum_{t=1}^T (i_{tm} - i_{to})^2}{T}} \quad (1)$$

173 where  $i_{tm}$  is modeled ice at time  $t$ ,  $i_{to}$  is observed ice from the NIC, and  $T$  is the total number of  
 174 records. RMSEs are calculated to assess skill in three categories: 1) lake-wide ice extent expressed as  
 175 a fraction, 2) spatially-computed RMSE of ice concentration in each model grid cell, and 3) spatially-  
 176 computed RMSE of binary ice cover in each model grid cell (presence/absence of ice). To perform  
 177 the spatial skill assessment (categories 2 and 3), the model output is interpolated onto the NIC grid

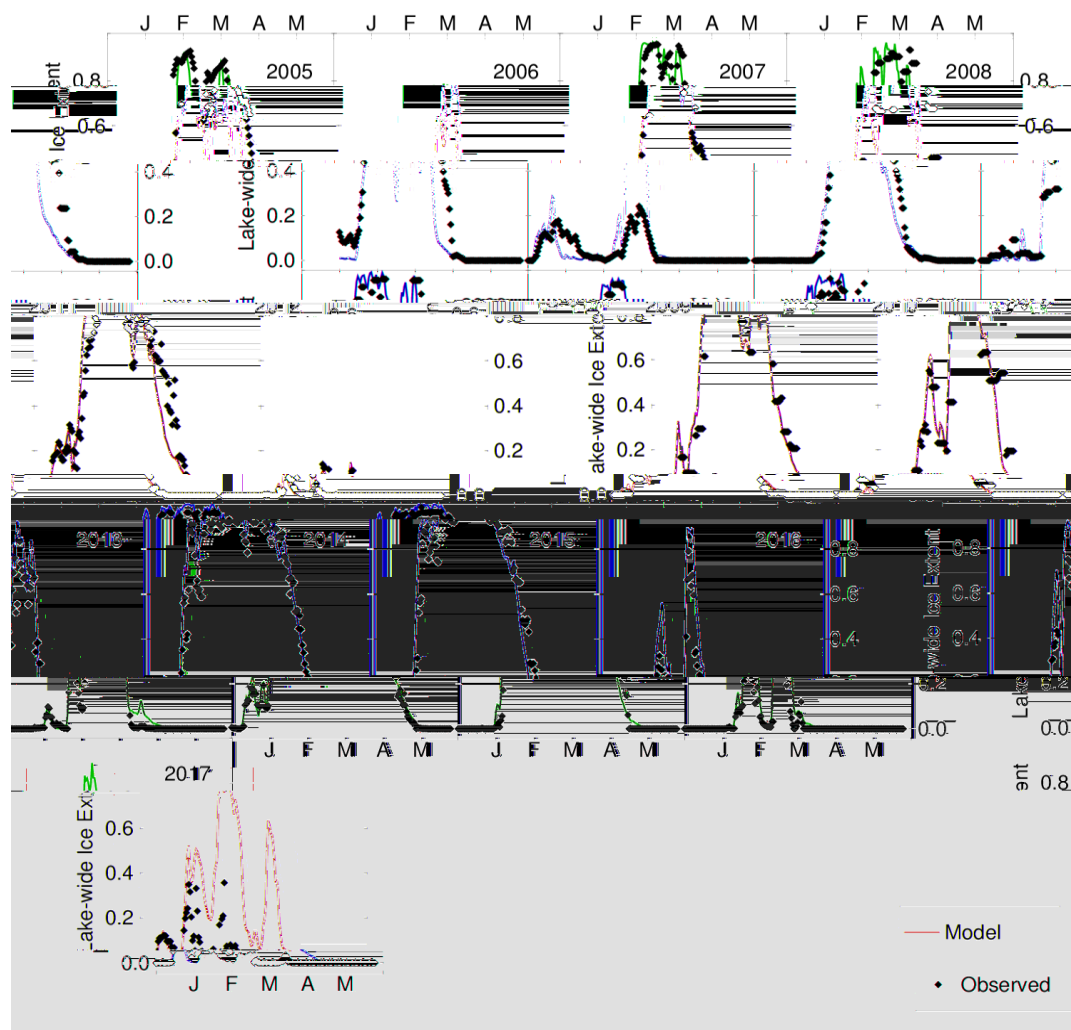


178 **Fig. 2:** Spatial pattern of ice concentration (0-1) for freezing (December 1 - January 15), mid-season (January  
 179 16 - March 15), and melting (March 15 – May 1) seasons. Averaging is performed for each season from 2015-  
 180 2017. Left column shows the model results from LEOFS and LMHOFS, and right column shows the NIC  
 181 analysis.  
 182 and the RMSEs between corresponding cells are computed. Since the NIC data is given in 10%  
 183 increments, for category 3, the modeled binary ice cover is defined as 1 when ice concentration in a

184 cell exceeds 10%, which is the threshold for ice presence in the NIC, and 0 otherwise. These RMSE  
 185 values are tabulated and plotted as time series. Additionally, to identify and address trends in ice  
 186 model performance, the spatial concentration RMSEs are evaluated as a function of time of year,  
 187 observed ice concentration, and modeled ice thickness. Based on category 1, modeled ice on/off  
 188 dates are plotted in order to evaluate the timing and length of the ice season for each lake. Based on  
 189 categories 2 and 3, the spatial distribution of error is averaged through time and plotted on a map  
 190 to identify any regions with consistently high/low error. In addition to ice assessment, observed  
 191 surface water temperatures from the GLSEA are compared to modeled (with and without including  
 192 the ice model) lake-wide average surface temperatures for the ice season (December through April).

193 **3. Results**

194 The Lake Erie and Lake Michigan-Huron models are simulated for the years 2005 – 2017 and  
 195 2015 – 2017, respectively, with and without the ice model enabled. In regard to the ice simulations  
 196 (averaged over the 2015-2017 period), the spatial pattern of ice cover is reasonably simulated in  
 197 comparison with the NIC analyses (Fig. 2), as represented by the development of nearshore ice in  
 198 freezing period, high ice cover and offshore open water region in the mid-season, and decay from  
 199 the south in the melting period.



200  
 201 **Fig. 3:** Simulated lake-wide average ice extent for Lake Erie (green line) and the ice extent from the NIC  
 202 (black dots).  
 203

204 3.1. Erie Ice Skill Statistics

205 For Lake Erie, the simulation period covers low-, intermediate-, and high-ice years, revealing  
 206 model performance under a wide array of conditions (Fig. 3). In a majority of years, the model  
 207 successfully follows the lake-wide ice extent as produced by the NIC each year, capturing the initial  
 208 formation of ice, annual maximum ice, and the ice-off timing, with a few exceptions. The largest  
 209 divergence between the modeled lake extent and that reported by the NIC occurs during a late-  
 210 March pulse in 2006 and again in 2017, where the model significantly overpredicts late season ice.  
 211 In years 2005, 2007, and 2008, and to a lesser extent in 2001, the model also shows a tendency to  
 212 melt more rapidly in the spring than the NIC. However, in each of these cases, both the model and  
 213 the NIC showed a decreasing trend in lake-ice leading to the ice-off date. During extreme high- or  
 214 low-ice years, the model also performs well, where RMSE in the low-ice year of 2012 is 0.01 (Table  
 215 2), and in the high-ice years of 2014 and 2015, RMSEs are 0.07 and 0.08, respectively (Table 2).

216 **Table 2.** Seasonal mean RMSEs [0-1] of simulated lake-wide ice area, ice concentration at pixels, and  
 217 binary ice cover at pixels. The lake-wide RMSEs are normalized by an area of each lake. The  
 218 seasonal means are calculated from December 1 in the previous year to May 31.

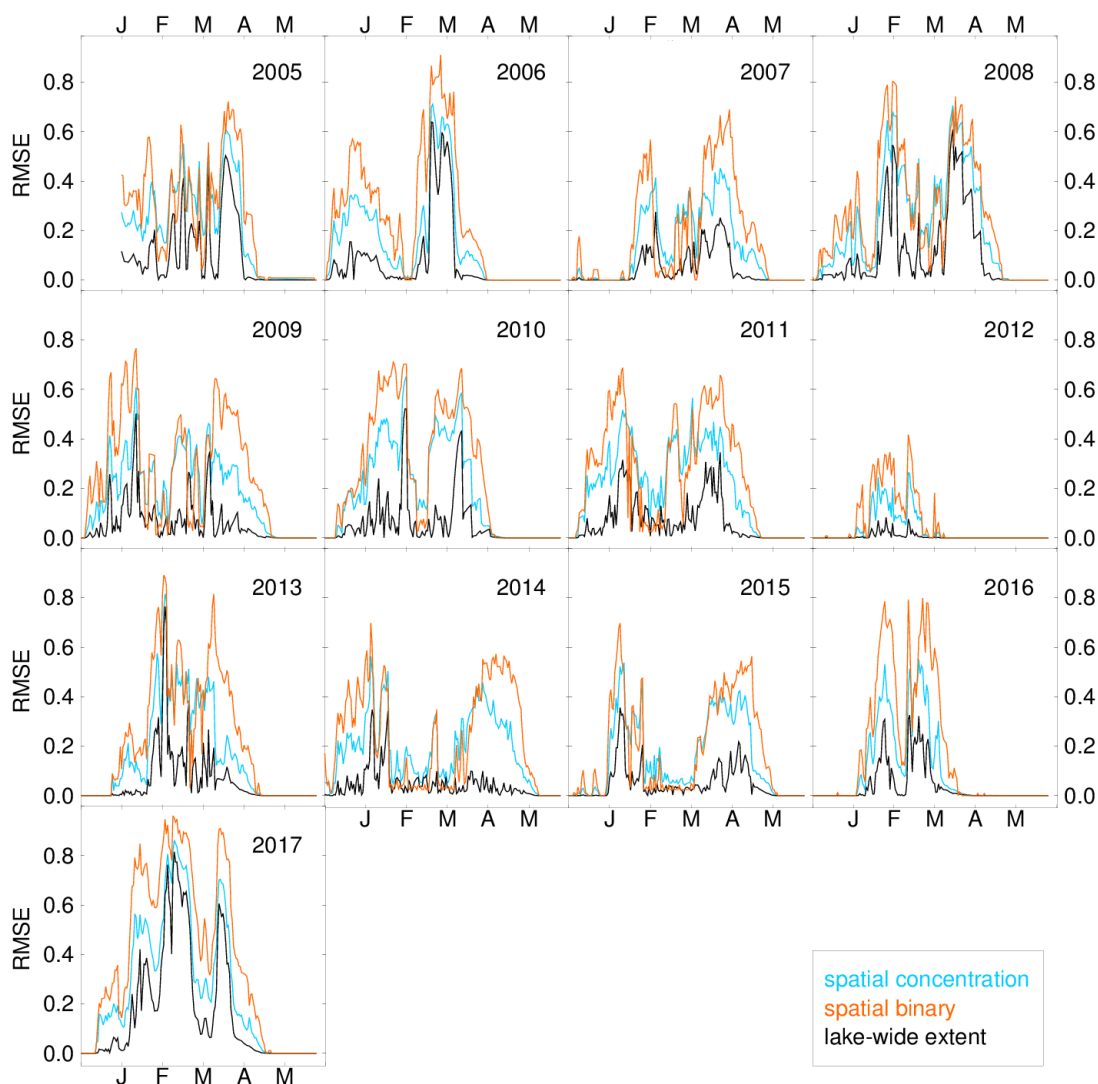
Year	Erie			Michigan			Huron		
	lake wide	spatial		lake wide	spatial		lake wide	spatial	
		concentration	binary		concentration	binary		concentration	binary
2005	0.17 <sup>1</sup>	0.21 <sup>1</sup>	0.25 <sup>1</sup>						
2006	0.17	0.15	0.24						
2007	0.08	0.13	0.17						
2008	0.19	0.22	0.26						
2009	0.10	0.18	0.25						
2010	0.12	0.19	0.26						
2011	0.11	0.21	0.25						
2012	0.01	0.03	0.06						
2013	0.13	0.16	0.23						
2014	0.07	0.18	0.23						
2015	0.08	0.15	0.18	0.09 <sup>1</sup>	0.20 <sup>1</sup>	0.31 <sup>1</sup>	0.13 <sup>1</sup>	0.26 <sup>1</sup>	0.34 <sup>1</sup>
2016	0.09	0.10	0.17	0.01	0.07	0.11	0.03	0.12	0.18
2017	0.28	0.26	0.38	0.04	0.10	0.15	0.05	0.14	0.21
mean	0.12	0.17	0.23	0.05	0.12	0.19	0.07	0.17	0.24

219 <sup>1</sup> Averaging period for the initial year (2005 for LEOFS and 2015 for LMHOFS) is from January 1 to  
 220 May 31.

221 The overall lake-wide extent RMSE for Lake Erie is 0.12 (Table 2), however most of the error, or  
 222 difference between the model and the NIC, is found during the periods of rapid ice formation and  
 223 ice melting, resulting in an “M-shape” in the time series of RMSE (Fig. 4). The overall RMSE is  
 224 higher for spatial concentration (0.17) and higher still for spatial binary (0.23), though the trends  
 225 between all three RMSE’s are fairly consistent through time (Fig. 4). In a few cases, e.g. April-May  
 226 2014, the lake-wide error is very low compared to the spatial errors. This indicates that although  
 227 the model reproduced realistic lake-wide ice extent, the distribution of ice did not agree well with  
 228 observations, which further motivates the need for spatial skill analyses.

229 When evaluating spatial concentration RMSE as a function of month (Fig. 5a), interestingly, the  
 230 M-shape pattern that exists in Fig. 4 disappears. This is likely because the timing of maximum ice  
 231 cover shifts from year to year. Thus, in the long-term mean, such patterns are smoothed out, and  
 232 the larger RMSEs occur during the peak ice months, January through March. In Figure 5b, the  
 233 model shows the lowest median RMSE for the 0-5% category, indicating that the model performs  
 234 relatively well over open water or regions with low ice concentration. The data frequency is the  
 235 highest for 0-5% ice concentration and much lower in the other categories, showing a slight increase  
 236 toward the higher ice concentration categories. Such distribution is well captured by the model.  
 237 When RMSEs are evaluated as a function of modeled ice thickness (Fig. 5c), the median RMSE is  
 238 slightly higher at the thinnest ice thickness range (0-5 cm), and then fairly comparable across the

239 other ice thickness categories. The data frequency shows that the modeled ice thickness is the most  
 240 common for the 35-65 cm range, and least common for ice thicker than 135 cm. Due to the limited  
 241 availability of observational ice thickness data, no validation is possible at the time of this writing.



242  
 243 **Fig. 4:** Time series of ice simulation errors between the Lake Erie model and the NIC based on the three  
 244 methods: Pixel-to-pixel RMSE based on ice concentration (cyan), pixel-to-pixel RMSE based on binary ice  
 245 cover (orange), and lake-wide absolute error (black). Note that lake-wide absolute error shows only the  
 246 magnitude of error (i.e. does not show the sign of model bias).

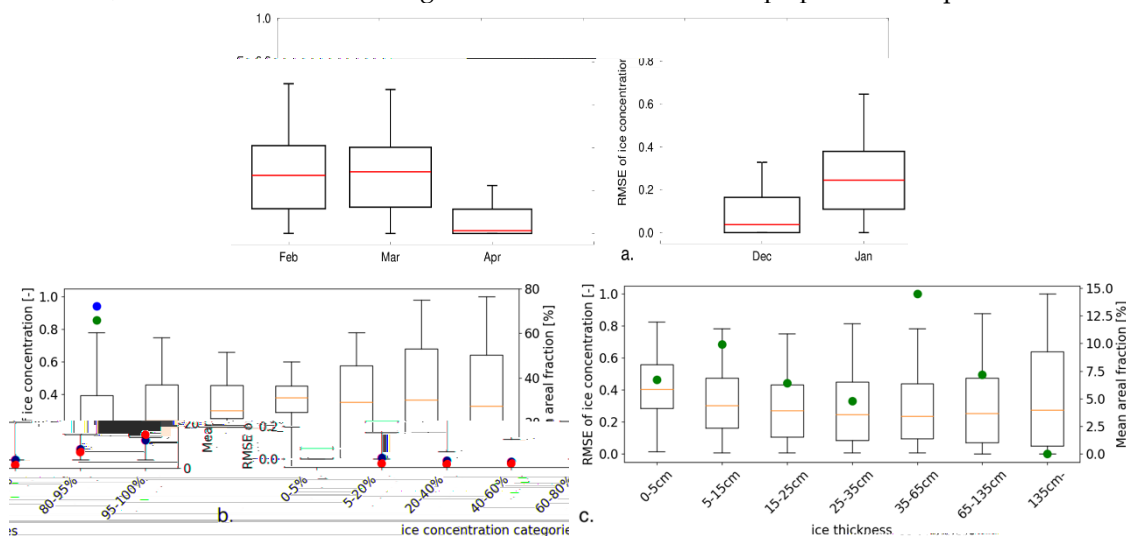
247 *3.2 Michigan-Huron Ice Skill Statistics*

248 For the Lake Michigan-Huron model, the results are similar to those seen for Lake Erie, even  
 249 with a shorter simulation period. However, unlike Lake Erie, ice formation is primarily constrained  
 250 to the shallow bays and coastal areas during freezing, peak ice, and melting periods (Fig. 2). Time  
 251 series of ice extent shows a reasonable agreement between simulated and NIC peak ice for all three  
 252 years (Fig. 6). In the heavy-ice year of 2015, the peak ice in Lake Michigan is slightly overpredicted,  
 253 however ice melting is captured, resulting in a mean RMSE of 0.09 (Table 2). In Lake Huron, the  
 254 opposite is true, where peak ice matches well with NIC, but the model experiences a slower decline  
 255 in ice melting, contrary to the melting trend in Lake Erie, and results in a slightly higher RMSE  
 256 (0.13, Table 2). In 2016 and 2017, both intermediate- to low-ice years, simulated lake-wide ice extent



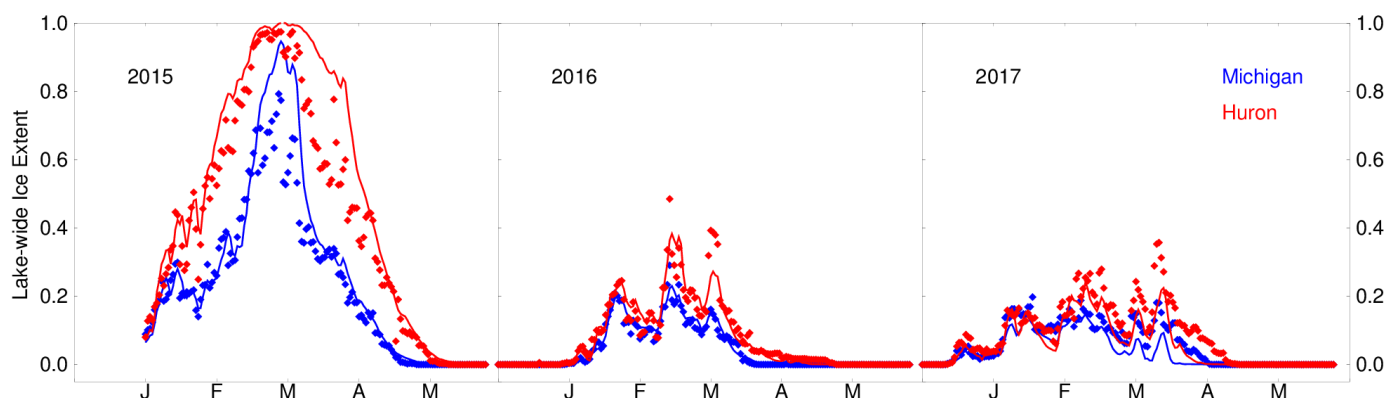
257 follows the NIC more closely with the exception of the very end of the 2017 season. Unlike the Lake  
 258 Erie results, the error time series in Fig. 7 does not show the M-shape pattern except for Lake Huron

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261

262 **Figure 5.** Ranges of spatial concentration RMSE as functions of (a) months, (b) observed ice  
 263 concentration, and (c) modeled ice thickness for the LEOFS 2005-2017 simulation results. A box  
 264 extends from the lower and upper 25% of the RMSEs. A horizontal line within each box denotes the  
 265 median value. The whiskers show the range of RMSE, extending from the box toward farthest data  
 266 points within the interquartile range (i.e. length of the box) from the upper and lower bounds of the  
 267 box. In (b) and (c), solid circles show mean areal fractions for observation (blue) and model (green),  
 268 representing data frequency for each category. For (c), open water cells are excluded.



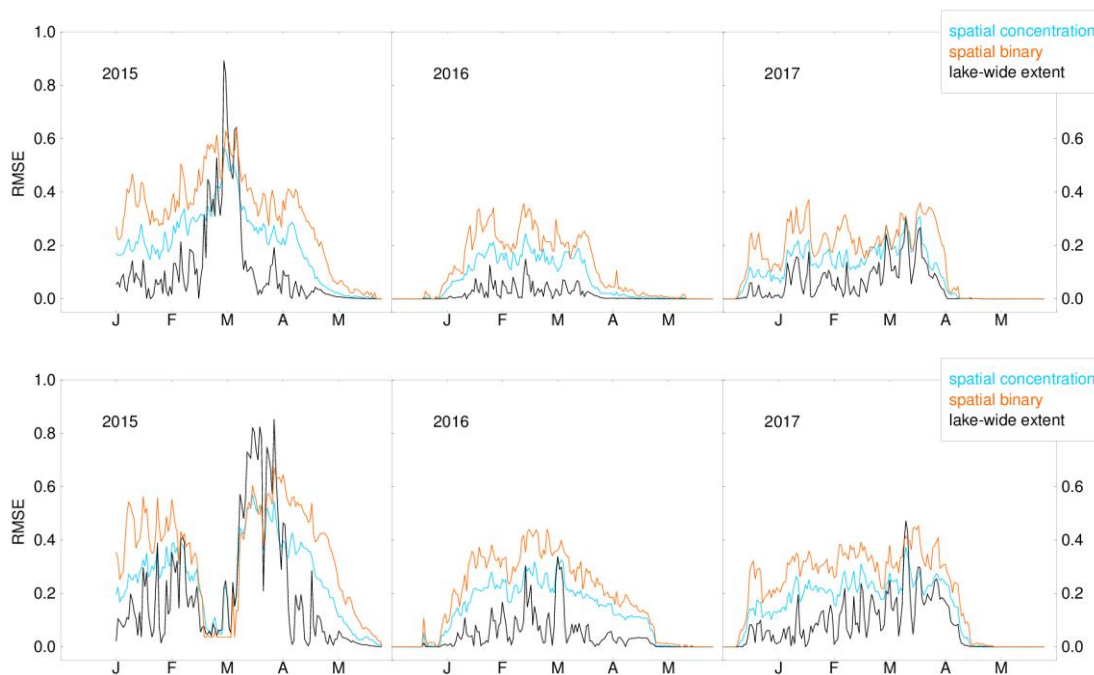
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271 **Fig. 6.** Lake-wide average ice extent for Lake Michigan (blue) and Lake Huron (red). The model ice  
 272 extent (solid lines) is compared to the NIC (diamonds).

273 in 2015. This is likely because ice cover is not restricted by the coastlines for Michigan and Huron,  
 274 except for under conditions with unusually high ice cover (e.g. Huron in 2015).

275 Overall lake-wide RMSE between the model and NIC are 0.05 for Lake Michigan and 0.07 for  
 276 Lake Huron, respectively. Similar to Erie, the spatial RMSE is higher for concentration, 0.12 and  
 277 0.17 for Michigan and Huron, and higher still for binary with 0.19 and 0.24. The RMSE trends as  
 278 functions of time, thickness and concentration for Lakes Michigan and Huron (Figs. 8, 9) are also  
 279 similar to that of Erie. Again, the lowest median RMSE occurs at 0-5% ice concentration, and the  
 280 median RMSE's are largest for the thinnest ice (0-5 cm).

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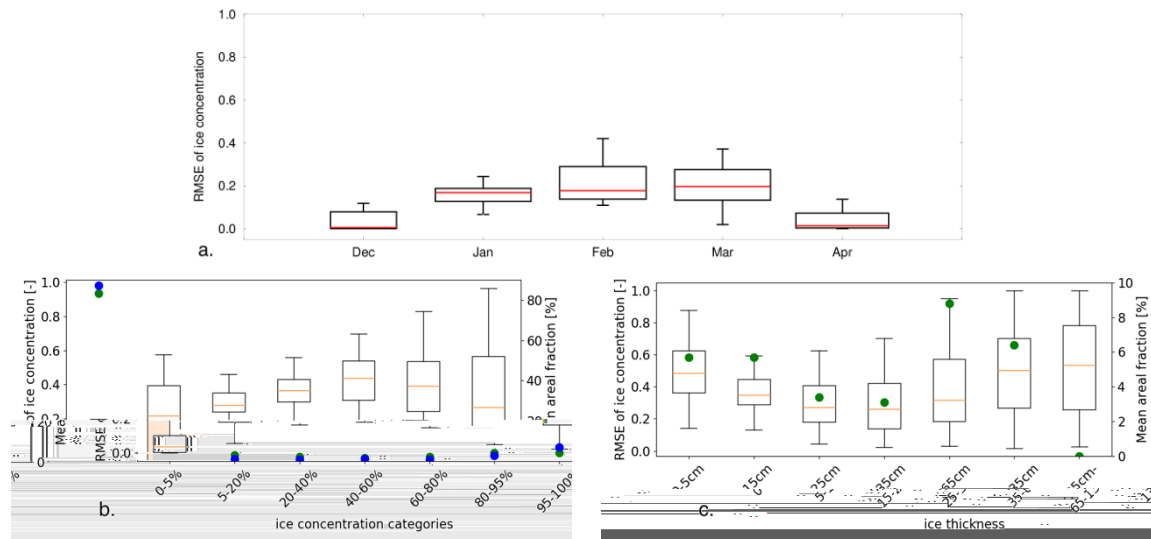
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**Fig. 7.** Time series of ice simulation errors between the Lake Michigan-Huron model and the NIC based on the three methods for (top) Lake Michigan and (bottom) Lake Huron: Pixel-to-pixel RMSE based on ice concentration (cyan), pixel-to-pixel RMSE based on binary ice cover (orange), and lake-wide absolute error (black). Note that lake-wide absolute error shows only the magnitude of error (i.e. does not show the sign of model bias).



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**Figure 8.** Ranges of spatial concentration RMSE as functions of month (a), ice concentration (b) and ice thickness (c) for Lake Michigan from the LMHOFS 2015-2017 simulation results. See the caption of Fig. 5 for the explanation of the box, whiskers, and solid circles. For (c), open water cells are excluded.

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### 3.3 Ice Duration and Spatial Maps

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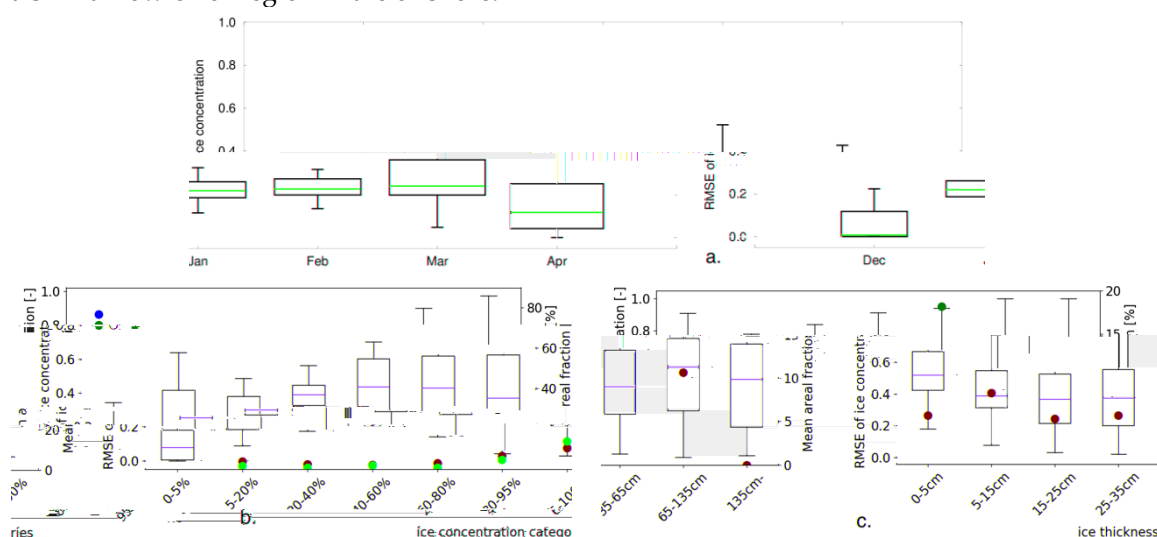
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Based on the lake-wide extent analyzed above, ice on and off dates by the models are compared with the NIC in all simulation years (Fig. 10). For Erie, 10 of the 13 simulated years show very good agreement with observed ice onset (within 5 days), and 5 of 13 years show extremely good agreement (within 1 day). Erie ice-off dates show a similar trend (9/13 are within 1 week and 5/13 are within 1 day). However, 2005 and 2017 show notably low skill for Erie. In 2017,

298 the ice-on date by the Lake Erie model matched the NIC within one day but the ice-off date was 46  
 299 days later than the NIC. The Lake Michigan and Huron model performs well in producing accurate  
 300 ice-on dates (Lake Michigan: all within 3 days, Lake Huron: all within 1 day), but show varied  
 301 results in producing ice-off dates. Note that in 2017, Michigan and Huron’s modeled ice season  
 302 ended much too soon, despite the opposite being true for Erie.

303 Extending the analysis of spatial ice extent, time-averaged spatial error maps are shown in  
 304 Figure 11 for concentration RMSE. Lakes Michigan and Huron tend to show higher error in the  
 305 shallow, protected coastal regions and less error offshore. This is likely an artifact of the ice  
 306 formation pattern discussed earlier, as ice rarely extends to the offshore and thus error is inherently  
 307 lower (see Fig. 2). Erie’s spatial error, which is averaged over a much greater simulation period, is  
 308 nearly homogeneous. The two regions with increased error are the southern portion of the western  
 309 basin and the southern portion of the eastern basin, likely related to difficulties in simulating ice-  
 310 initiation and ice-melting in those regions, respectively. Unlike in Lakes Michigan and Huron, the  
 311 frequent offshore ice formation in Lake Erie, or absence of open-water conditions, does not produce  
 312 a similar low-error region in the offshore.



313 **Figure 9.** Ranges of spatial concentration RMSE as functions of month (a), ice concentration (b) and  
 314 ice thickness (c) for Lake Huron from the LMHOFS 2015-2017 simulation results. See the caption of  
 315 Fig. 5 for the explanation of the box, whiskers, and solid circles. For (c), open water cells are  
 316 excluded.

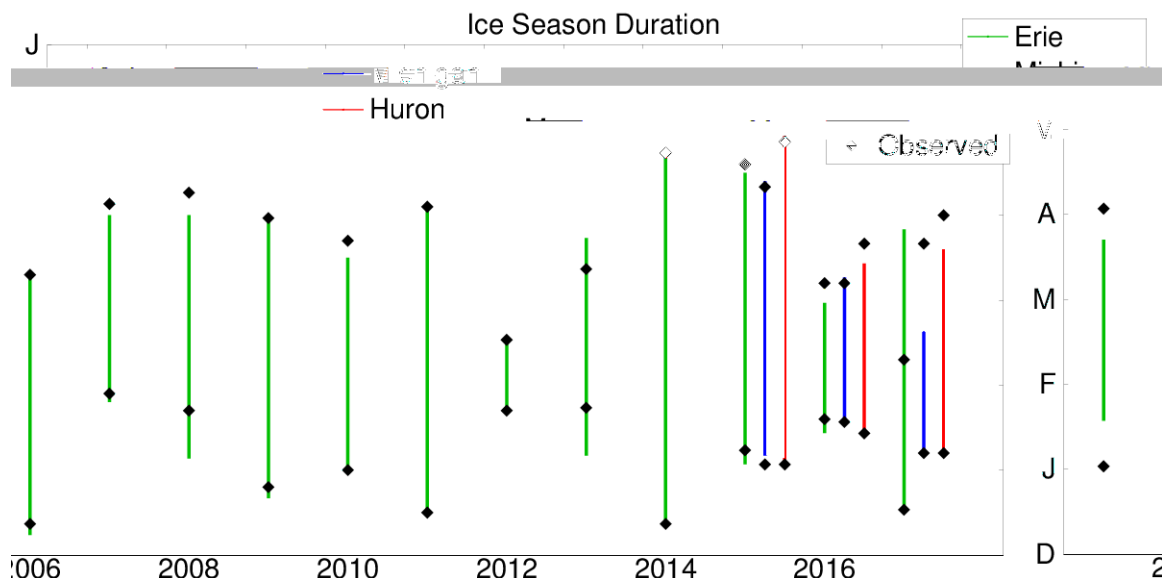
317  
 318 **Table 3.** Surface water temperature RMSE (°C) between model simulations and observed  
 319 temperatures from satellite-derived lake surface temperature from the GLSEA during winter  
 320 months (Dec – Apr).

	FVCOM-CICE	FVCOM (no-ice)
<b>Lake Erie GLSEA</b>	0.69	1.12
<b>Lake Michigan GLSEA</b>	0.66	0.87
<b>Lake Huron GLSEA</b>	0.68	0.94

321 **3.4 Water Temperatures**

322 Finally, in terms of the impact on water temperatures, the inclusion of the ice model improves  
 323 the winter water surface temperatures by eliminating a cold-water bias present in the non-ice  
 324 simulations (Table 3, Fig. 12). This can most likely be attributed to the presence of artificially-cooled  
 325 water in the non-ice simulation, where water temperatures can drop below freezing. Accordingly,  
 326 the difference between the with and without ice model simulations is evident during the months of  
 327 January, February, and March (Fig. 12). Slight differences between the two simulations are found in

328 April, especially for Lake Erie, which may be improvements made with the ice model simulations  
 329 where spring warm-up in surface water temperature is realistically delayed by remnant of ice cover  
 330 later in spring. The RMSE between the model water temperature and GLSEA improves by 0.43 °C  
 331 for Lake Erie and by 0.21 and 0.26 °C for Michigan and Huron, respectively, when the ice model is  
 332 activated (Table 3).



333

334 **Figure 10.** Modeled vs observed ice season duration for all simulated years. The duration is  
 335 defined as the period of time between ice onset (first day lake-wide extent exceeds 10%) and ice-off  
 336 (last day extent exceeds 10%). The y-axis shows the length and timing of the ice season by month.

337

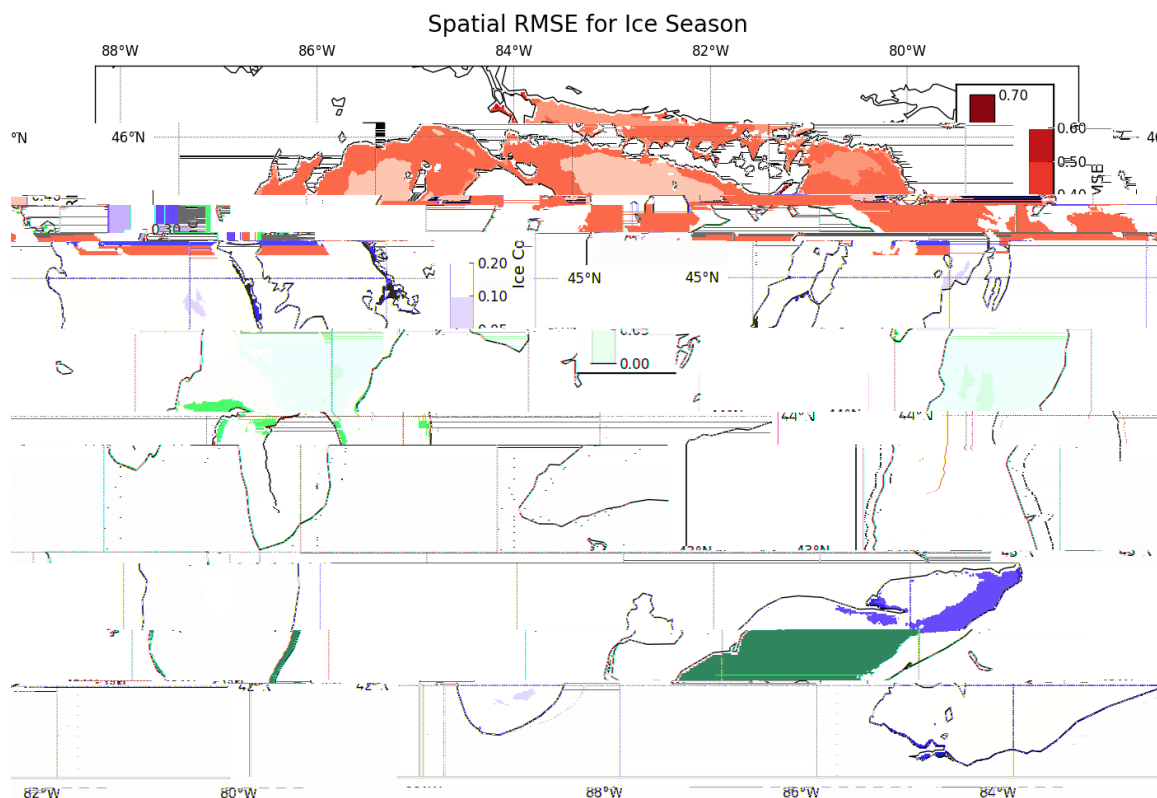
**Table 4:** Ice season length (in days) as defined in figure 10.

Year	Erie		Michigan		Huron	
	NIC	Model	NIC	Model	NIC	Model
2005	91	64				
2006	88	92				
2007	67	66				
2008	77	86				
2009	95	100				
2010	81	76				
2011	108	107				
2012	25	24				
2013	49	77				
2014	131	131				
2015	101	103	98	97	114	115
2016	48	46	49	50	67	59
2017	53	98	74	42	84	71

338 **4. Discussion**

339 Ice conditions in the Great Lakes result from dynamic processes that yield significant spatio-  
 340 temporal variability, and most often resemble a continual marginal ice zone that is in constant flux  
 341 due to atmospheric conditions such as wind speed and direction and air temperature. As such,

342 having updated and accurate information on ice conditions is crucial to safe commercial navigation  
 343 and USCG operations. Historically, operational models of the Great Lakes have not included ice  
 344 conditions as part of the available forecast guidance, and thus decision makers are limited to recent  
 345 observational-based products such as ice charts produced by the National Ice Center (NIC). In the  
 346 work presented here, the Los Alamos Sea Ice model (CICE) has been included as part of the next-  
 347 generational GLOFS and a skill assessment is carried out for Lakes Erie, Michigan, and Huron in  
 348 regard to modeled ice cover as compared to the NIC.

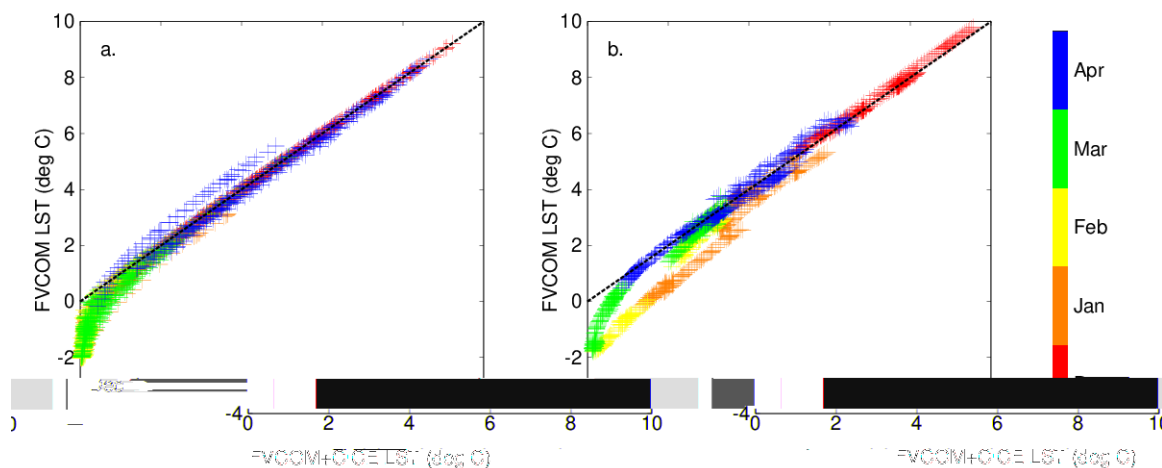


349  
 350 **Figure 11.** Spatial distribution of ice concentration RMSE averaged throughout the entire ice season  
 351 for all simulated years.

352 In general, the FVCOM-CICE model captures the dynamic nature of Great Lakes ice conditions  
 353 in low-, intermediate-, and high-ice years. The three periods early-season freezing or ice formation,  
 354 mid-season peak ice, and late-season ice melting are reproduced in both Erie and Michigan-Huron.  
 355 The M-shape of RMSE timeseries indicates relatively high errors in the freezing and melting  
 356 periods while errors are reduced in the peak period, when model simulations benefit from spatial  
 357 restrictions by the coastlines. This is evident for Erie in nearly all simulation years and for Huron in  
 358 2015. The RMSE timeseries are amplified when spatial distributions of ice are taken into account,  
 359 indicating limitation of evaluations based on the lake-wide values. The RMSE values for spatial  
 360 binary ice cover are almost always larger than the corresponding RMSEs for spatial ice  
 361 concentration. This is rather an artifact of the error calculation with binary ice cover: For example,  
 362 if modeled ice concentration is 9% at a cell where the NIC has 10%, the differences are only 1% for  
 363 actual ice concentration but 100% when treated as binary ice cover.

364 Ultimately, model success must be evaluated based on user requirements for ice concentration  
 365 accuracy. Interaction with key stakeholders, such as commercial ship captains and the USCG,  
 366 suggested that although there may be a wide range of requirements depending on conditions or the  
 367 specific stakeholder, areas of common interest were ice formation and ice-off dates, as well as open  
 368 versus ice-covered areas. With respect to these measures, the dates of predicted ice initiation and  
 369 termination were often within 4 days of the NIC (more than half of the Lake Erie simulation years  
 370 and all of the Lakes Michigan and Huron simulation years). Similarly, the model performed well in

371 predicting areas of open water, often found in Lakes Michigan and Huron, illustrated by the lowest  
 372 errors found at ice concentration from 0 to 5%. At ice concentrations above 5%, RMSEs were nearly  
 373 uniform and ranged from 20-40%. In addition, the data frequency is higher at high ice  
 374 concentrations (>80%), but relatively insignificant at medium ice concentrations (5-80%). These  
 375 results suggest that stakeholders may find confidence in the model’s ability to predict the binary  
 376 presence of ice, and thus enable them to plan a shipping route to avoid ice fields. However, if user  
 377 requirements are established that specifies criteria based on ice concentrations, and/or ice thickness,  
 378 beyond the presence/absence of ice, more work will be required to evaluate model performance  
 379 under these guidelines.



380  
 381 **Figure 12.** Lake surface temperature (LST) for Lake Erie (left) and Lake Michigan-Huron (right) for  
 382 simulations of FVCOM with and without CICE during the winter months.

383 Previous work has shown that the next-generation GLOFS, which is based on FVCOM, has  
 384 performed well for water temperatures in the non-ice period, as well as for currents and water level  
 385 fluctuations [14,25]. As illustrated, using a coupled FVCOM-CICE model produces an immediate  
 386 improvement to winter water temperatures, where the ability to form ice when freezing  
 387 temperatures are reached prevents the unrealistically low water temperatures produced in the  
 388 existing operational models. This result, in itself, marks an important improvement during the  
 389 winter season, where often forecast guidance has been limited by unrealistic physical treatment of  
 390 the lakes (i.e. artificially-cooled water).

391 Discrepancies between modeled and NIC ice concentration may be due to a multitude of  
 392 reasons. In terms of ice dynamics, some processes that are potentially important for nearshore ice  
 393 physics are currently not taken into account, such as land-fast ice and ice-wave interaction. Land-  
 394 fast ice may provide a stable ice zone along the shore resistant to wind disturbance. Surface waves  
 395 may break ice cover into smaller pieces that are more sensitive to heat fluxes from air and water  
 396 due to increased contact surface. In terms of ice thermodynamics, inclusion of realistic snow cover  
 397 on top of the ice would be an important step to the future improvement as it influences calculations  
 398 of ice albedo and thermal conductivity of the snow/ice medium. Another possible cause for  
 399 discrepancy could be related to the uncertainty in the meteorological forcing. Previous work has  
 400 shown that as much as 70% of ice cover variability in the Great Lakes can be explained by surface  
 401 air temperature alone [45]. As such, the model will show significant sensitivity to the surface air  
 402 temperature prescribed in the meteorological forcing.

403 Overall, the addition of an ice model to the existing operational hydrodynamic models can  
 404 make significant improvements to forecast guidance and support stakeholder needs in navigation,  
 405 hydropower, recreation, spill response, and other areas. As such, this work serves as the precursor  
 406 to the upgrade of the Great Lakes Operational Forecast System (GLOFS) and to the first-ever  
 407 operational ice forecast guidance in the Great Lakes within NOAA. As user requirements become

408 better defined, additional skill assessment can guide avenues for model improvement and  
409 refinement.

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411 carried out the model simulations and post-processing of results. The upgrade of GLOFS was conceived of and  
412 is being carried out by E.A., P.C., J.G.W.K., and G.L. The CICE model was adapted to the Great Lakes by A.F.  
413 and J.W. Model skill assessment was conceived of by J.G.W.K., Y.C., A.F., and E.A., and carried out by A.F.  
414 and J.K.

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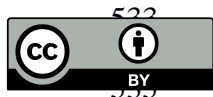
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