GREAT LAKES FISHERY COMMISSION

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# A COUPLED PHYSICAL-BIOLOGICAL MODEL TO FORECAST LARVAL YELLOW PERCH DISTRIBUTIONS, GROWTH RATES, AND POTENTIAL RECRUITMENT IN LAKE ERIE

by:

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**A COUPLED PHYSICAL-BIOLOGICAL MODEL TO FORECAST LARVAL YELLOW PERCH DISTRIBUTIONS, GROWTH RATES, AND POTENTIAL RECRUITMENT IN LAKE ERIE**

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**ABSTRACT:**

Yellow perch (*Perca flavescens*; YP) is an economically and ecologically important species across the Great Lakes, which demonstrates variable recruitment to the fishery that we hypothesized is regulated by physical processes operating during early life stages. Previous research has found recruitment success is positively correlated with Maumee River inflow during spring, with individuals that use the Maumee River plume (MRP) as larvae contributing disproportionately to the new year-class. Research also has identified water turbidity as a key regulator of larval recruitment success because it reduces the ability of predators to forage on planktivorous fish such as larval YP. However, uncertainty in predicting the plume dynamics, as well as its effect on movement, predation risk, consumption, growth, and survival of YP larvae remains a major impediment to fully understanding and forecasting recruitment to the fishery in this system. To address these important questions, we built a coupled biophysical model of western Lake Erie. This model coupled general linear models developed to accurately predict YP growth and length ($r^2 = 0.84$) with a physical (hydrodynamics and sediment) model that uses a flexible, unstructured grid to capture current dynamics, even in shallow nearshore areas. Using the biophysical model, we (a) evaluated the interactive effects of river discharge and wind-driven currents on the creation and expansion of high-quality nursery habitat within the MRP, (b) determined the relative importance of advection-caused loss of YP larvae to the observed disproportionate recruitment of MRP individuals relative to non-MRP individuals and (c) identified mechanistic linkages between physical processes and YP year-class strength.

Our analysis found that the MRP area is most strongly influenced by Maumee River discharge and wind strength and direction, with larger plumes occurring at high discharge events when winds were from the E and NE. Other factors such as the Detroit River discharge and sediment input, local and distant wind forcing, wave climate and sediment resuspension can also influence MRP dynamics at a smaller scale. Advection of MRP and non-MRP YP out of the western basin was unimportant whether larvae exhibited an active swimming behavior or not (mean # particles lost < 5 %). This retention of larvae in the basin is likely due to an anticyclonic circulation pattern that is commonly exhibited in the basin that could help retain larvae. Further model and empirical analysis suggested, however, that in order to remain in the MRP (i.e., not simply the basin), larvae are required to exhibit an active swimming behavior. Finally, our results suggest the mechanisms influencing YP survival are dependent upon average plume size during the spring and on water temperature during early May. Year-classes that experienced low water temperature during May of their first year of life recruited at higher levels (>20 million 2-year olds) and were positively related to the size of the plume, modeled retention of larvae in the plume and modeled survival rates. Year-classes that experienced high water temperatures during May of their first year of life recruited at low levels (<20 million 2-year olds) regardless of the size of the plume, modeled retention of larvae in the plume and modeled survival rates. The causes behind these different relationships may be due to a match-mismatch with prey and predators, or differences in larval quality between cold and warm early springs. In conclusion, these results suggest that the size of the MRP, a high quality habitat for larval YP, is largely determined by wind forcing and river discharge, and that the size of the plume, in addition to spring water temperature, can be used to predict the number of these fish that survive to enter the fishery at age-2. Managers may therefore want to continue updating our hydrodynamics model with recent years to help forecast future year-classes.

**INTRODUCTION:**

The ability to forecast recruitment is the 'holy grail' of fisheries management. Attaining this predictive capability, however, has proven difficult in most systems, owing in large part to an inability to understand mechanisms that drive recruitment variation. This lack of understanding is attributable to a complexity of physical, chemical, and biological factors that can simultaneously influence fish recruitment and fisheries dynamics (Houde 1987, 1989, 1994; Miller et al. 1988; Leggett and Deblois 1994; reviewed in Cowan and Shaw 2002; Govoni 2005; Smith and Ludsin 2009). An improved ability to better understand processes affecting fish recruitment variation can be attributed to advancements in computer technology, automation of data collection methods (e.g., remotely sensed imagery, observation buoys), establishment of long-term datasets, and the general willingness of scientists with diverse backgrounds and areas of expertise (e.g., biologists, physical scientists) to collaborate. Each of these components has contributed to the recent growth of coupled biological-physical studies in both marine and freshwater systems that focus on fish recruitment (Miller 2007; Smith and Ludsin 2009), an inherently interdisciplinary research and management problem.

A method often used to study the mechanisms driving fish recruitment variability are individual-based, coupled physical-biological models (ICPBM), which can realistically simulate the dynamics of individual fish in a spatially and temporally variable environment (Miller 2007). These large numerical exercises are typically individual-based fish models that are forced (i.e., one-way coupling) by an underlying hydrodynamics model that predicts the transport of fish and the environmental changes they experience. These models are particularly powerful because they can be used to develop testable hypotheses that cannot be obtained otherwise and that can be investigated either within an ICPBM framework or with independent, empirical data (Miller 2007; North et al. 2009). In marine systems over the past 20 years, ICPBMs have been instrumental to understanding recruitment processes, including answering questions related to the distribution, transport/retention, feeding, growth, and survival of marine fish during early life stages (reviewed in Miller 2007). Particularly germane to nearshore, tributary-influenced environments, such as those observed in western Lake Erie (our study system), has been the use of ICPBMs in conjunction with field data to study recruitment of species (Chesapeake Bay striped bass, *Morone saxatilis*; white perch, *M. Americana*; and oysters, *Crassostrea virginica* and *C. ariakensis*) that have a pelagic larval stage (North et al. 2002; North et al. 2004; North and Houde 2006; North et al. 2008). Here, North and colleagues have identified how physical processes such as episodic flooding and wind events, which modify nearshore nursery habitats through their effect on water circulation patterns and prey production, can retain larvae within a food-rich nursery and drive recruitment variation.

Relative to marine research, use of ICPBMs in the Great Lakes is still in its infancy, even though most Great Lakes fishes have life histories (e.g., pelagic eggs; a long pelagic larval duration with provision of no parental care) that are perfectly suited for ICPBM approaches (Smith and Ludsin 2009). These few Great Lakes ICPBM applications, however, have provided useful insights despite being quite preliminary in nature (reviewed by Smith and Ludsin 2009). For example, Zhao et al. (2009) used an ICPBM to simulate walleye (*Sander vitreus*) transport in western Lake Erie, finding that pelagic larvae could be advected by lake currents into and out of regions of high food (zooplankton) availability, which in turn may have influenced walleye recruitment strengths. In Lake Michigan, Beletsky et al. (2007) used an ICPBM to find that large-scale circulation patterns may advect yellow perch, *Perca flavescens* (YP), larvae away from their western spawning and nursery areas to potential settlement areas in eastern Lake Michigan. Similar observations of larval advection away from nearshore nursery habitats have been demonstrated with Lake Michigan alewife (*Alosa psuedoharengus*) (Höök et al. 2006).

Unfortunately, each of these previous Great Lakes ICPBMs are limited in their application to nearshore, tributary-dominated (via plume formation in the open lake) environments, which have been shown to be important for early life (egg, larval, and juvenile) development, growth, and survival (e.g., Klumb et al. 2003; Roseman et al. 2005; Höök et al. 2008; Stockwell et al. 2009; Reichert et al. 2010). Specifically, these previous Great Lakes ICPBM applications lacked the capability of simulating wave-induced nearshore circulation at an appropriate spatial resolution (<2 km) to accurately simulate complex coastal physics. These studies also did not include a lower food-web model that could predict spatial variation in food resources for fish larvae. As well, these previous models treated larvae as passive particles, whereas larvae show strong movement responses to light, depth, food, and predators (Miller et al. 1988; Fulford et al. 2006b; Paris et al. 2007; Fiksen et al. 2007). Even the minimal swimming capabilities of fish larvae can have dramatic effects on their spatial trajectories and dispersal locations (Codling et al. 2004; Vikebø et al. 2007).

Using previous ICPBM studies from both marine and freshwater systems as a basis, as well as a suite of physical and biological information gathered from previous and ongoing research and monitoring activities, we followed a hypothesis-driven, ICPBM-based research approach to better understand the role of physical processes on fish recruitment in the Great Lakes. We overcame deficiencies of previous Great Lakes ICPBM applications by using a state-of-the-art physical model that can more realistically describe coastal circulation patterns, by coupling this model with a lower food web model that predicts zooplankton prey production, and by developing an individual-based model that incorporates larval fish behavior. For this investigation, we used Lake Erie YP as a model organism, as: 1) this species in this system demonstrates high recruitment variation (Yellow Perch Task Group Report 2009) that is not fully understood or predictable (but see Ludsin 2000 and Reichert et al. 2010);, 2) this species is recreationally, commercially, or culturally important across all of the Laurentian Great Lakes (Smith and Ludsin 2000); 3) an abundance of historical monitoring and research data exists for this species in Lake Erie and elsewhere regarding feeding, growth, and recruitment variation; and 4) this species has a life history (i.e., long pelagic larval stage in which no parental care is provided and individuals are obligate zooplanktivores; Ludsin 2000; Bremigan et al. 2003; Reichert et al. 2010) that suggests its recruitment is likely highly influenced by physical processes (Dettmers et al. 2005; Beletsky et al. 2007; Smith and Ludsin 2009).

In Lake Erie, YP exhibit extraordinarily high (>50-fold) inter-annual variation in recruitment into the fishery at age-2 (Fig. 1a), which is the age at which individuals enter the fishery. Age-2 YP abundance can be predicted from relative densities of juvenile YP during August two years prior ($R^2 = 0.82$; $p < 0.001$ during 1987-2012; YPTG 2013), indicating that recruitment is set during the larval or early juvenile period. Year-class strength (i.e., age-0 juveniles during August) and recruitment to age-2 has been has been strongly linked to Maumee River inflows during spring (March through May), a time just prior to and during the larval production period (Fig. 1b; Ludsin 2000). More recently Ludsin et al.'s GLFC-funded project has shown that Maumee River discharge influences recruitment through inputs of sediments and nutrients that form open-lake plumes in both nearshore and offshore of Lake Erie (Reichert et al. 2010). Specifically, Reichert et al. (2010) demonstrated that turbidity was higher in MRP than non-MRP waters, thus potentially offering a survival advantage by reducing predation mortality on larvae, and disproportionally more YP juvenile recruits emanated from MRP than non-MRP waters, as estimated using otolith microchemical techniques to trace back larval habitat-use patterns. The importance of the MRP to YP recruitment has been furthered by the use of satellite imagery, as the spring-average areal extent of the MRP is an even stronger predictor of YP recruitment (K. Pangle, J. Tyson, and S. Ludsin, unpublished data; $R^2 = 0.90$, Fig. 1c) than Maumee River discharge. This latter finding suggests that the absolute amount of nutrients and sediments entering Lake Erie, while important, is not the only factor driving recruitment success. How allochthonous materials are distributed around the lake (via water circulation) to create nursery habitat for larvae also appears critical to recruitment success. These findings clearly support the notion that the MRP is important to the YP recruitment process through its influence on larval survival to juvenile stages. However, many critical questions remain. First, given the general approach and data collected in this previous work, we still cannot disentangle the relative importance of different physical processes (e.g., nutrient transport, sediment suspension, and advection) to fish recruitment. The ability to do so is critical, if we are to identify ways in which agencies can affect recruitment (e.g., management of sediment or nutrient delivery from the watershed), as well as build general knowledge of biological-physical coupling that is applicable to other areas of the Great Lakes. Second, the years (2006-2008) in which Ludsin et al.'s GLFC project fieldwork was conducted were relatively "average" spring Maumee River discharge years. Thus, whether these mechanisms of larval YP survival hold in extreme years of high or low recruitment remains enigmatic. Finally, the fate of larvae that do not recruit to juvenile stages is unknown. Thus, the possibility exists that the disproportionately low contribution to recruitment of larvae from outside the MRP is not due to higher mortality, but perhaps due to lake currents that advect slow-growing larvae from the west basin into the central basin. In this way, these non-contributors to the west basin fishery may contribute to the central basin population.

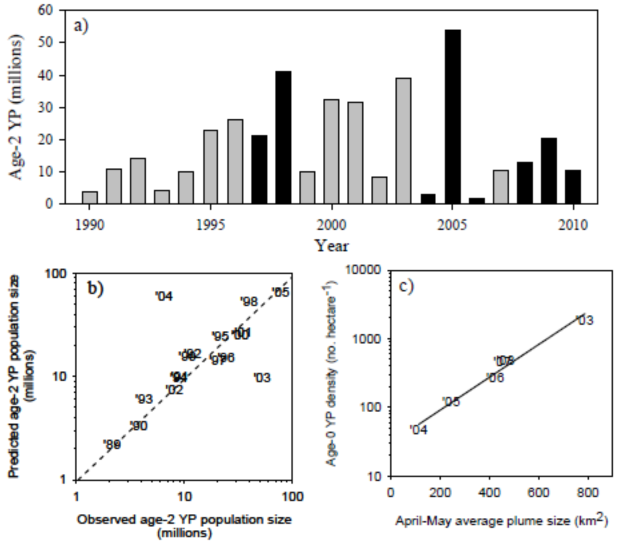


Fig. 1. a) Recruitment of age-2 YP (i.e., year-class two years prior) into the western Lake Erie fishery. Black bars indicate our study years. B) Observed vs. predicted YP population size (at age 2) in western Lake Erie, 1989-2005. Predicted values were derived from mean annual March-May discharge (2 yr previous) from Maumee River. C) Satellite derived April-May average Maumee River plume size vs. age-0 YP August abundance in western Lake Erie.

To address these lingering questions and also help identify general ways that physical processes could drive YP recruitment in Lake Erie and other systems, we used a high-resolution ICPBM approach, focused on Lake Erie YP. For this purpose, we accomplished three main objectives. First, we delineated the relative importance of water circulation versus tributary inputs to understand intra- and inter-annual spatiotemporal variation in habitat quality (i.e., MRP, Objective 1). With this understanding, we next discerned the relative importance of advective processes in explaining the lower survival of larvae produced in non-MRP waters and therefore their failure to contribute to the new year-class in western Lake Erie (Objective 2). Finally, we used our ICPBM modeling approach to better understand long-term variability in YP recruitment to the fishery in Lake Erie, as well as identified general physically-driven conditions to help understand recruitment of YP and fishes with similar life-histories in other areas of the Great Lakes (Objective 3).

## OBJECTIVES:

### Objective 1

### Evaluate the interactive effects of river discharge and wind-driven currents on the creation and expansion of high-quality nursery habitat

A clear correlative link exists between Maumee River discharge, the MRP, and the success of YP in western Lake Erie; however, it is also clear that years exist in which this linkage is somehow decoupled (e.g., outlier years in Fig. 1b). This decoupling may be explained by the complex processes that underlie the formation of plumes and subsequent nursery habitat. River plumes are extraordinarily dynamic features of the Great Lakes (Rao and Schwab 2007; Reichert et al. 2010), and, although high discharge events are necessary precursors for the occurrence of large river plumes, other physical processes (e.g., wind conditions, lake circulation) can strongly magnify or negate a plume's spread (Masse and Murthy 1990). Indeed, remote sensing analysis of the MRP found that river discharge (with consideration for time lags) could only explain 11% of the variation in daily plume size (n = 75 days; K. Pangle, unpublished data). Obviously, other physical processes are at play.

*We hypothesized that river discharge strongly interacts with wind-driven currents and waves to control the spatial extent and quality of YP nursery habitat.* Specifically, we used the hydrodynamics model to test how various factors (Maumee River flow, Detroit River flow, wind-driven currents and waves, sediment re-suspension via waves and wind, and wind strength and direction) influenced the size of the MRP by shutting each variable "off" one at a time and comparing plume size and location.

**METHODS AND RESULTS:**

The hydrodynamics model underlying the ICPBM was developed using the Finite-Volume Coastal Ocean Model (FVCOM) (Chen et al. 2006). Our version of the FVCOM was parameterized, calibrated and evaluated for Lake Erie (Current Project Progress Report; Niu et al. Submitted; Appendix 1). FVOCM is a free surface, three dimensional, primate equation coastal model with first order accuracy. This model was employed because of its flexible unstructured grid that accommodates complex shoreline geometry and allows for high nearshore resolution, as is the case in Lake Erie. The model domain covered Lake Erie and included the Detroit River channel and part of the Niagara River, with a variable grid resolution (0.02 to 7.7 km) that was higher in Western Lake Erie, and a minimum depth of 0.5 m (Fig. 2). The hydrodynamics model incorporated river and wind forcing. The Detroit, Maumee (both as flow boundaries) and Niagara (open boundary) rivers were incorporated in the model. To incorporate wave action and sediment dynamics, the FVCOM was coupled with an unstructured grid, finite-volume surface wave (FVCOM-SWAVE, Qi et al. 2009) and eutrophication/water quality model (CE-QUAL-ICM, Cerco and Cole 1993, 1995; Kim and Khangaonkar 2012) that has also been parameterized and evaluated for Lake Erie (Jiang et al. Submitted, Appendix 2). The FVCOM-SWAVE and CE-QUAL-ICM models allow the estimation of 26 state variables: total suspended solids, cyanobacteria, diatoms, green algae, microzooplankton, mesozooplankton, labile/refractory dissolved organic carbon, labile/refractory particulate organic carbon, ammonia, nitrite and nitrate, labile/refractory dissolved organic nitrogen, labile/refractory particulate organic nitrogen, phosphate, labile/refractory dissolved organic phosphorus, labile/refractory particulate organic phosphorus, particulate inorganic phosphorus, chemical oxygen demand, dissolved oxygen (DO), and particulate/dissolved silica. The effect of horizontal and vertical grid resolution, and various wind sources to the lake simulation were evaluated during model calibration using observed data from different sources (Niu et al. Submitted; Jian et al. Submitted). Models were thoroughly evaluated by comparing observed and estimated variables, including water elevation, circulation and temperature, significant wave height, and nutrient, phytoplankton and zooplankton abundance (Niu et al. Submitted; Jian et al. Submitted).

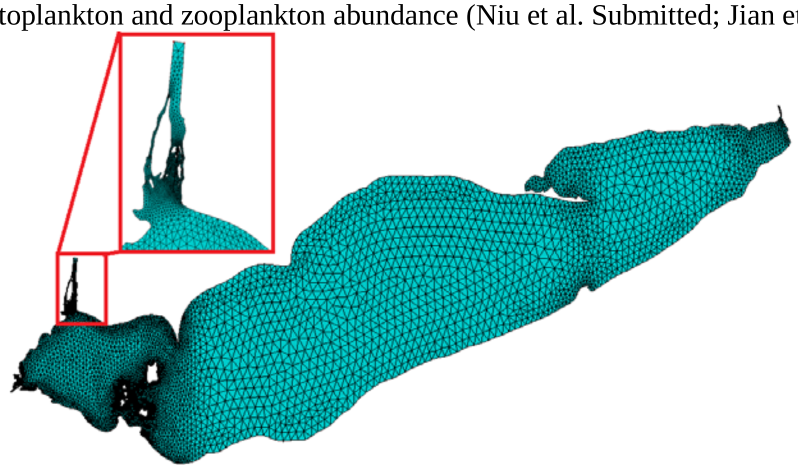

Fig. 2. Schematic of unstructured grid used to model Lake Erie hydrodynamics. Model resolution was 0.017 km to 7.77 km

**<u>The Interannual Variability of Sediment Dynamics in the Western Lake Erie</u>**

In spring, areas with high suspended sediment concentration (SSC) (> 10 mg $l^{-1}$) were located at the Maumee River mouth, the southern shore of the western basin, and upper Sandusky Bay, with areas and intensities varying annually (Fig. 3). The MRP was extremely large during 2002, 2003 and 2008 (Fig. 3c, d, 7i), and relatively small during 2004, 2005 and 2006 (Fig. 3e - g). These variations are likely caused by Maumee River discharge and its sediment loading. During large MRP years, there were high sediment loads (8313 tons) and river discharge (341 $m^3s^{-1}$) from the Maumee River (Fig. 4), compared to small plume years (2610 tons and 181 $m^3s^{-1}$). It should also be noted that although the sediment loading and river discharge from the Maumee River during the springs of 2002 (7063 tons with 325 $m^3s^{-1}$ river discharge) and 2008 (7655 tons with 352 $m^3s^{-1}$ river discharge) were comparable (Fig 4), the MRP was bidirectional during 2002 (Fig. 3c) as opposed to 2008 when it was along one direction (Fig 3i). This indicates the significance of other mechanisms aside from river loading, such as wind forcing, to riverine sediment plume dynamics in the basin.

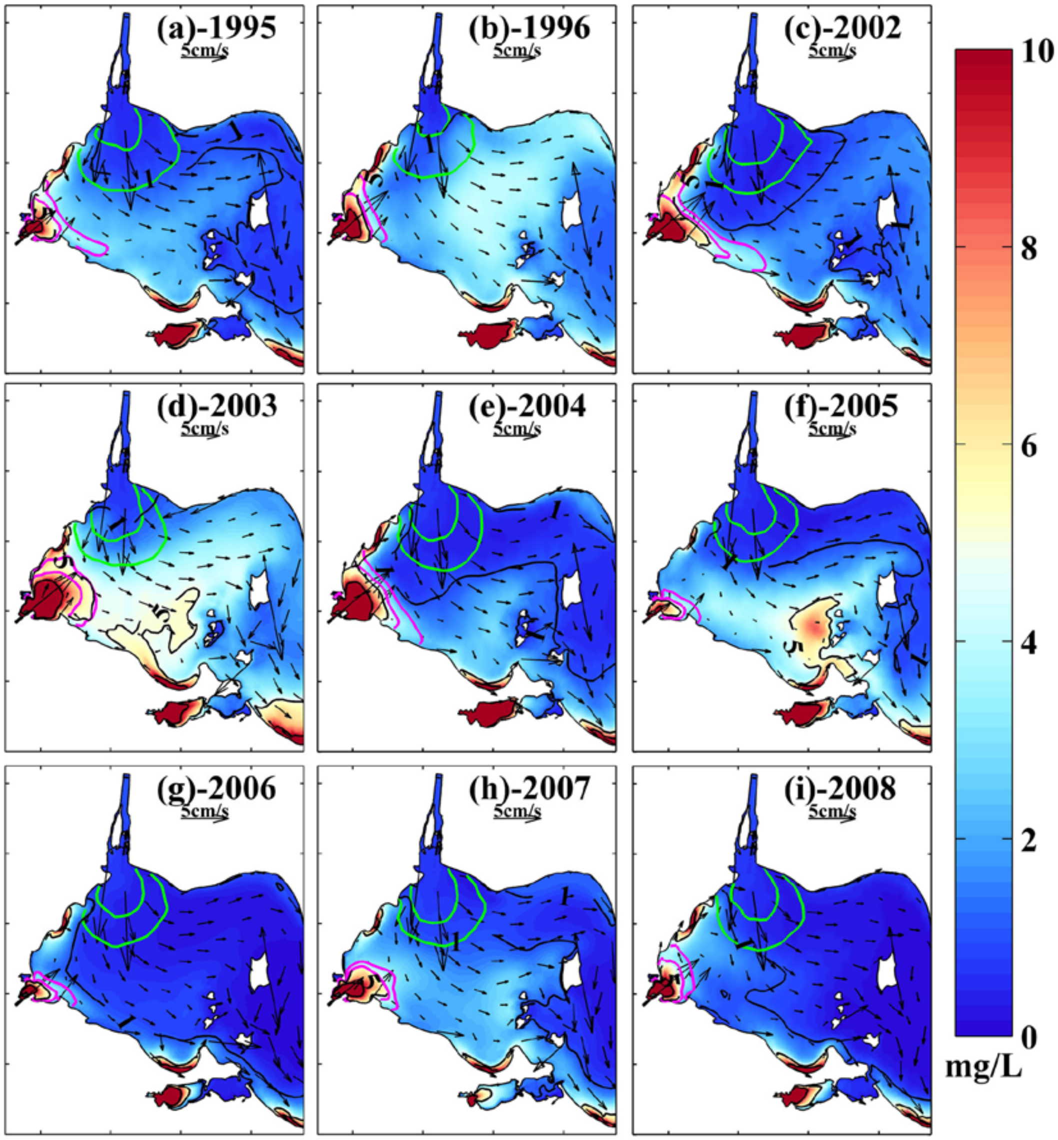


Fig. 3. Modeled surface sediment concentration in the western basin of Lake Erie during springs of 1995, 1996, and 2002-2008. Green and pink lines stands for the Detroit and Maumee River plumes respectively, black arrows represent mean current speed and direction.

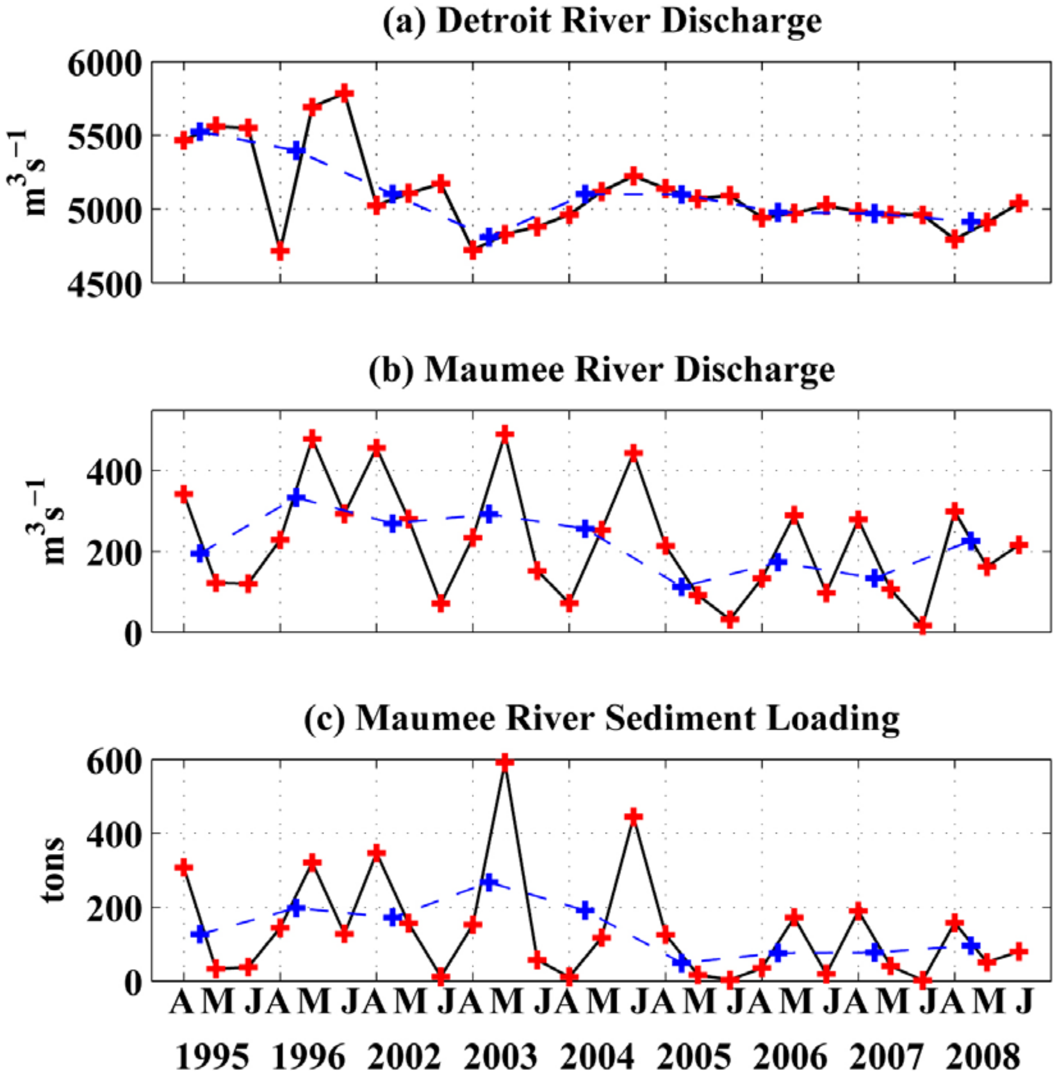


Fig. 4. Monthly mean (red crosses) and seasonal mean (blue crosses) river discharge from (a) the Detroit River and (b) the Maumee River, and (c) sediment loading from the Maumee River during April, May, and June (spring) of years 1995, 1996, and 2002 to 2008.

High SSC during the spring also occurred at the center of the basin mostly due to sediment resuspension. These high sediment episodes also varied interannually (Fig. 3). More intense resuspension occurred at the center of the basin during the spring of 1996, 2002, 2003 and 2005 (Fig. 3b, 7c,d,f) as opposed to during 1995, 2004, 2006-2008 (< 3 mg $l^{-1}$; Fig. 3a,e,g-i). These variations were likely related to different atmospheric forcings at the water surface in the basin. Years that had high SSC in the center of the basin had relatively higher mean wind speed (5 % higher than average), wave height (12 %) and current velocity (4.5 %) than low SSC years (Fig. 5). Opposite to the MRP and resuspension events, the Detroit River plume generally had a dilution effect around its river mouth during spring, which was also observed on satellite images from MODIS (Binding et al. 2010). Compared to the variation in the direction and size of the MRP and sediment resuspension events (114 ± 67 $km^2$ and 233 ± 66 $km^2$, respectively), the shapes of the Detroit River plume were relatively constant among model simulation years, with slight variations in the areas of core plume areas (253 ± 53 $km^2$).

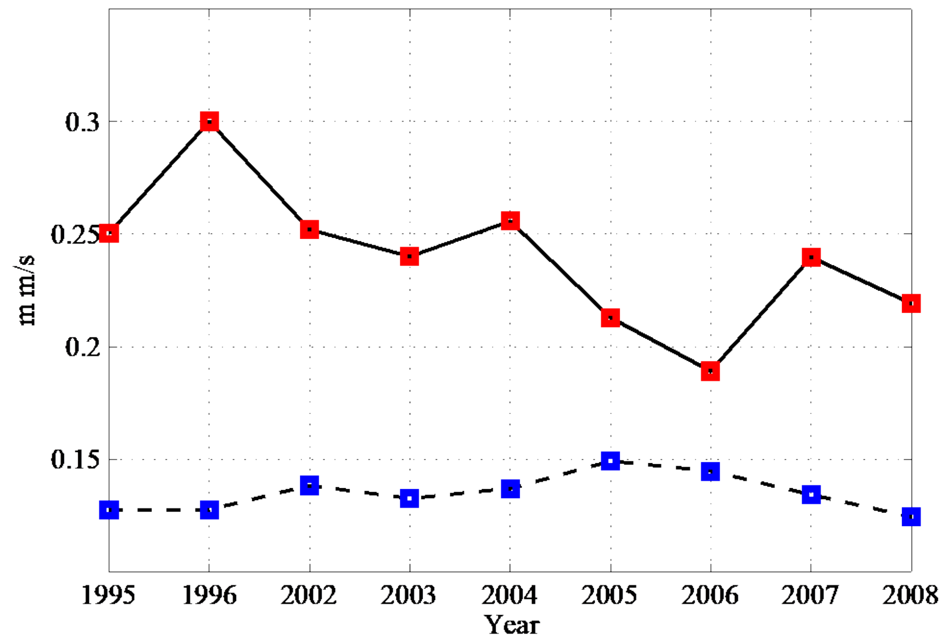

Fig. 5. Mean significant wave height (red solid) and circulation (blue dash) in the western basin during spring of years 1995, 1996, and 2002 to 2008.

**Sediment Model Experiments**

Using a calibrated version of our model (case C1), runs were conducted for years 1995, 1996, 2002 to 2008 to investigate the interannual variability of the spring sediment plume dynamics in western Lake Erie. To investigate the driving mechanisms of MRP dynamics in the basin, five additional cases were carried out using case C1 as a base model (Table 1). The influences of the Detroit and Maumee River loadings on each other and on the resuspension sediment events were examined through the exclusion of the Maumee River (case C2) or Detroit River (case C3) respectively. To investigate the contribution of both the local wind forcing and remote wind forcing to sediment plume dynamics in the western basin, the local wind (in the western basin) and remote wind (in the central and eastern basins) were excluded respectively in the cases C4 and C5. The contribution of surface gravity waves was studied by excluding wave dynamics (case C6). To investigate the influence of sediment dynamics on the MRP dynamics, two additional cases, with the exclusion of sediment loading from the Detroit River (case C7) and resuspension processes turned off (case C8) were carried out. Results from the spring of 2003 for each of these cases are presented in this report, as both significant wind forcing and sediment loading appeared during this period (Fig. 4, Appendix1-2).

Table 1. Summary of Model Runs

| Case Name | River Inflows | Wind Forcing | Wave Climate | Detroit Sediment Input | Resuspension |
|---|---|---|---|---|---|
| C1 | Regular | Regular | Wave and WCI | On | On |
| C2 | No Detroit River | Regular | Wave and WCI | On | On |
| C3 | No Maumee River | Regular | Wave and WCI | On | On |
| C4 | Regular | Only in the central and eastern basins | Wave and WCI | On | On |
| C5 | Regular | Only in the western basin | Wave and WCI | On | On |
| C6 | Regular | Regular | No wave or WCI | On | On |
| C7 | Regular | Regular | Wave and WCI | Off | On |
| C8 | Regular | Regular | Wave and WCI | On | Off |

## The Influence of Major External Forcing on Sediment Dynamics in Western Lake Erie

### River Inflows from Detroit and Maumee Rivers

The Detroit River generated strong southeastward flow in the western basin (Fig. 6a), which restrained the northward propagation of both the MRP and resuspension of sediments. With the high discharge from the Detroit River (case C1), the MRP area shrank by 9 % compared to the result of case C2 during spring 2003, while the surface resuspension plume area decreased by 157 %. The influence of the Maumee River was indeed the major driver on the MRP, extending the plume out 24 km during extreme flooding events (1500 $m^3s^{-1}$). Previous observations in the western basin indicated that the Maumee River is one of the major sources of sediment loadings to Lake Erie (Bolsenga and Herdendorf 1993), and our model provided similar results. With the exclusion of the Maumee River (case C3), the MRP and sediment resuspension in the southern part of the basin was greatly reduced (Fig. 6e, f), which indicated the prominence of the MRP over the resuspension events in these areas at a seasonal scale.

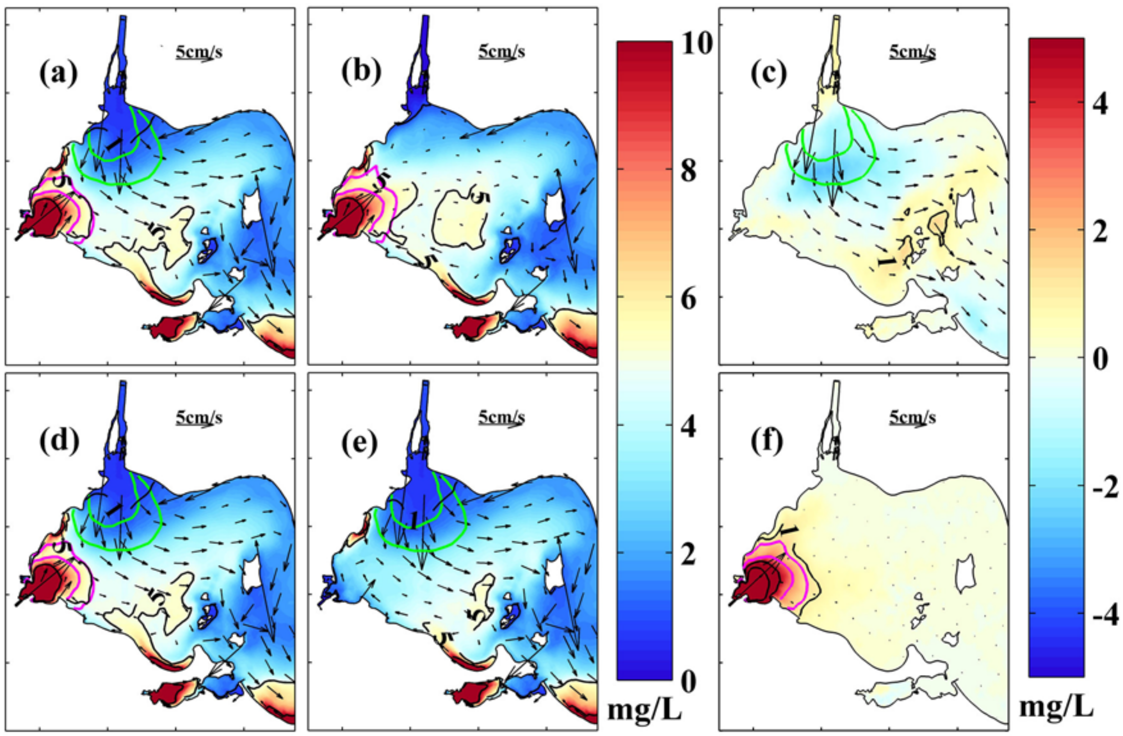


Fig. 6. Modeled surface sediment concentration and depth-averaged circulation in the western basin of Lake Erie under realistic (a and d), without Detroit River (b), and without Maumee River (e) conditions during spring 2003; and their bias with the realistic case: (c) Realistic (case C1)-No Detroit River (case C2), (f) Realistic (case C1)-No Maumee River (case C3).

### Wind-driven Circulation

*Local Wind Forcing*

During the spring of 2003, the prevailing easterly and northeasterly winds (mean speed of 6.4 m $s^{-1}$) exerted on the surface of western Lake Erie, produced a local anticyclonic gyre in the basin (Fig. 7c). Accordingly, the MRP was transported to the northeast (Fig. 7a) instead of diverting to the east with the exclusion of local wind forcing (case C4; Fig. 7b). The eastward movement of the MRP in case C4 was a result of the plume's response to the Coriolis Effect and the eastward current generated by the Detroit River discharge. Moreover, the reduced circulation due to the absence of local wind forcing resulted in an 11 % decrease in bottom stress induced by currents. Accordingly, the sediment resuspension, which was prominent at the southern shore of the basin during 2003 (Fig. 7), was reduced by 76 % (Fig. 8Ig, h). This verified the conjecture of previous theoretical models of Lake Erie, which assumed that current-induced bottom stress is one of the major mechanisms for the onset of sediment resuspension (Lick et al. 1994).

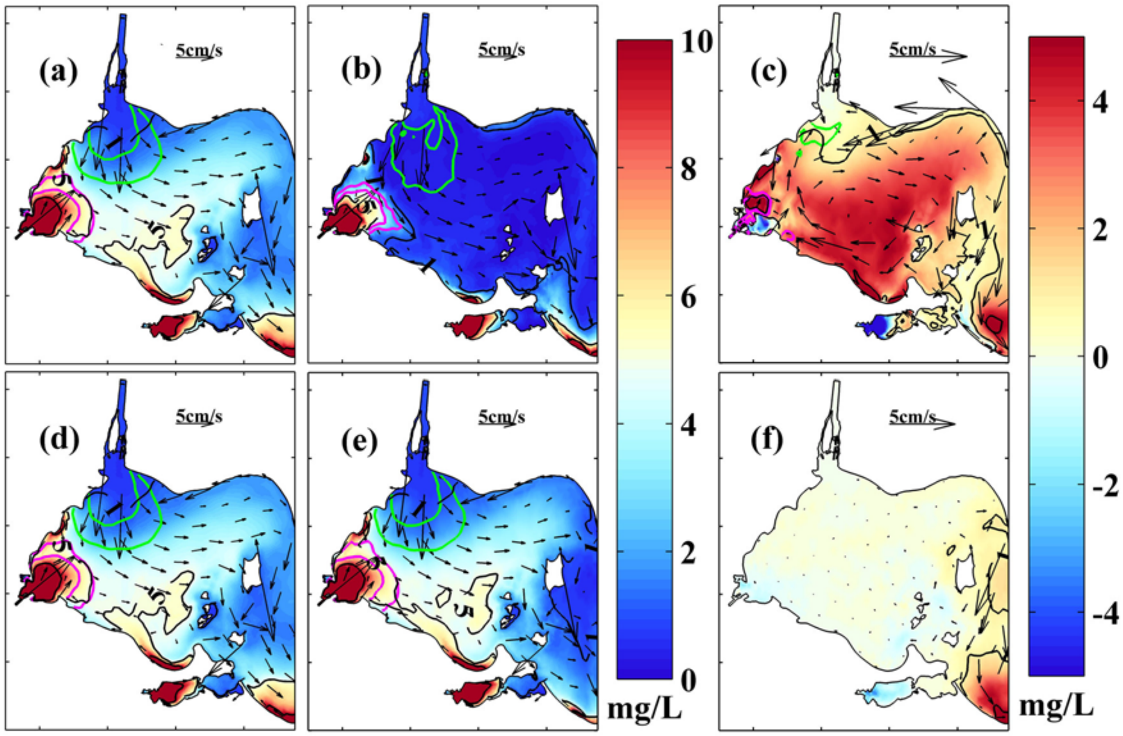


Fig. 7. Modeled surface sediment concentration and depth-averaged circulation in the western basin of Lake Erie under realistic (a and d), without local wind forcing (b), and without remote wind forcing (e) conditions during spring 2003; and their bias with the realistic case: (c) Realistic (case C1)-No Local Wind (case C4), (f) Realistic (case C1)-No Remote Wind (case C5).

When the local wind forcing was excluded, the Detroit River plume intruded into the center of the basin along its western shore (Fig. 7b). With the anticyclonic gyre generated by the local wind forcing in spring, however, the southward movement of the Detroit River plume was restrained, and the plume was transported to the east along the northern shore with the strong wind-induced current (Fig. 7a). This eastward diversion of the Detroit River plume is consistent with previously observed strong eastward flows at the northern shore of the western basin (Beletsky et al. 1999). The response of the Maumee and Detroit River plumes to the earth's rotation when local wind forces are shut off indicates the more significant role of wind forcing over the Coriolis effect in the plume dynamics of these two rivers, which is a major difference between them and large oceanic plumes, such as the Columbia River plume (Berdeal et al. 2002).

*Remote Wind Forcing*

The currents induced by the remote wind forcing (i.e. wind forcing in the central and eastern basins) were concentrated at the intersection between the western and central basins (Fig. 7f). However, possibly due to the block of islands at the basin intersection, these remote wind-induced currents had little impact on the circulation in the western basin, and thus had limited influence on the MRP dynamics in the basin (i.e. C5, mean variation of 0.3 mg $l^{-1}$ compared to 2.3 mg $l^{-1}$ for the local wind). This differs from the sediment resuspension event dynamics in the open coastal system, in which the ambient currents are one of the major mechanisms for sediment transport (Berdeal et al. 2002; Denamiel et al. 2013).

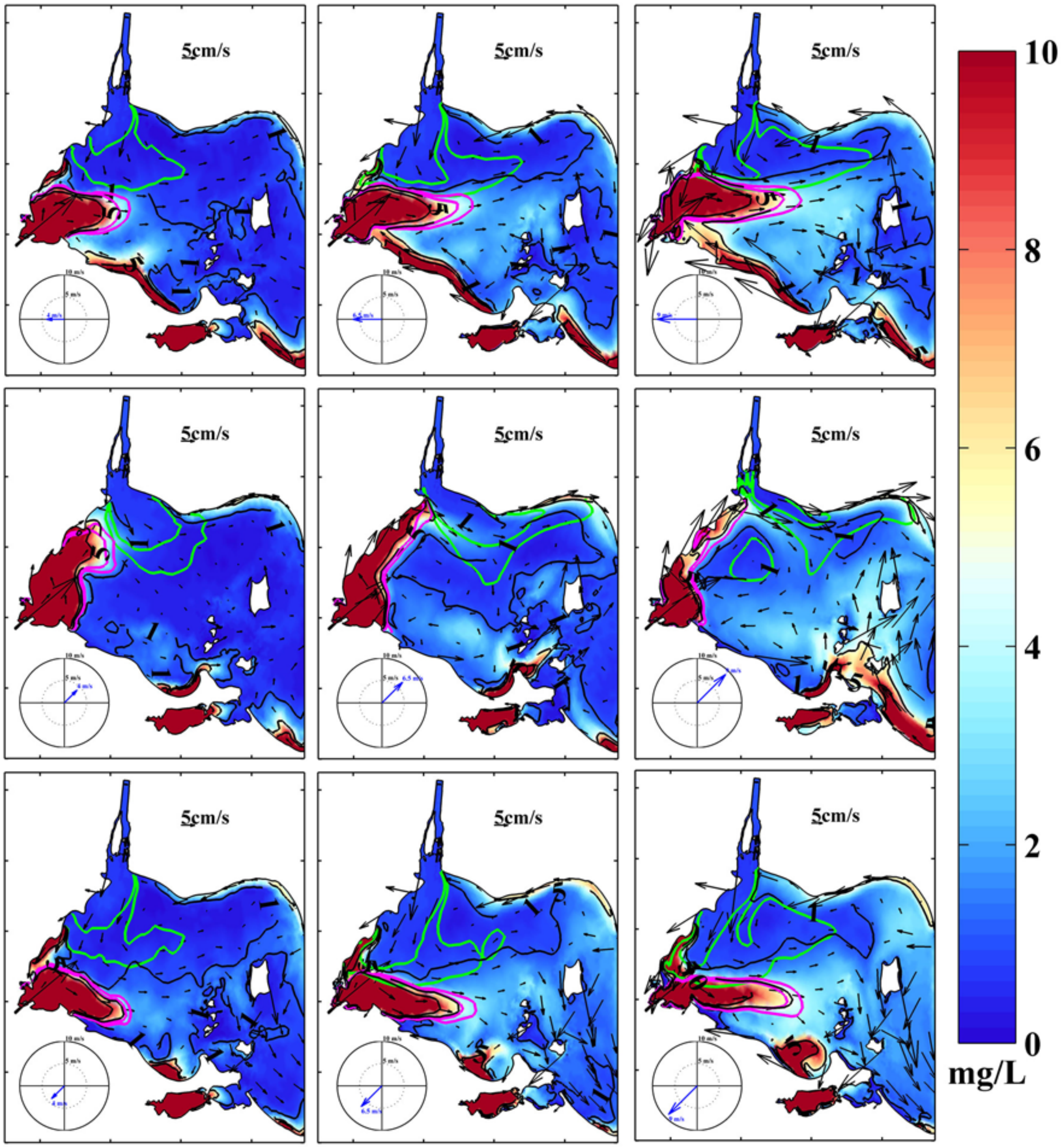


Fig. 8. Modeled surface sediment concentration in the western basin during 1 to 15 May 2003 with wind from E (first row), SW (second row) and NE (third row) with wind speed of 4 m $s^{-1}$ (first column), 6.5 m $s^{-1}$ (second column) and 9 m $s^{-1}$ (third column). Green and pink lines stands for the Detroit and Maumee River plumes respectively.

*Plume Patterns Under Various Wind Forcing*

The importance of the local wind forcing to sediment plume dynamics in western Lake Erie was further explored. The spatial averaged wind forcing in the western basin was 6.5 ± 2.5 m $s^{-1}$ during spring across model simulation years, with the prevailing directions being from the southwest (34 %), northeast (28 %), and east (21 %). The model was run with a uniform wind speed of 4, 6.5 and 9 m $s^{-1}$ in the three main wind directions during a spring Maumee River flood (peak value = 1767 $m^3s^{-1}$) from 1 to 15 May 2003 (Fig. 8).

Circulation in the basin was dominated by a cyclonic gyre with northeasterly winds. Accordingly, the Detroit River plume initially diverted to the west, propagated south along the western shore, and was transported to the east along the eastward currents at the southern part of the basin (Fig. 8, 3rd row). The MRP diverted to the east with the eastward basin circulation at its river mouth, and was transported further east after it was detached from the southern shore (Fig. 8, 3rd row). When there were southwesterly winds exerting at the lake's surface, an anticyclonic gyre was generated in the western basin (Fig. 8, 2nd row). The Detroit River plume diverted to the east along the northern shore, and the Maumee River plume was transported to the north along the western shore (Fig. 8, 2nd row). When easterly winds were prevailing, a two-gyre pattern dominated circulation in the basin, with strong westward nearshore currents at both the northern and southern shores and a strong eastward current at the center of the basin (Fig. 8, 1st row). The Maumee and Detroit River plumes initially propagated to the north and south respectively along the western shore. Once they met each other, both plumes detached from the western shore, and were transported to the east with the eastward flow (Fig 8, 1st row).

With increasing wind speed, the MRP became narrower, and was transported further away from its mouth (Fig. 8). When winds were from the E and N, the Maumee and Detroit River plume size increased with increasing wind speed. When Easterly winds increased from 4 to 9 m $s^{-1}$, the Maumee and Detroit River plume size increased by 10 % and 45 % respectively. The plume sizes were more sensitive to the variation of NE wind speed. With increasing NE winds (4 to 9 m $s^{-1}$), the Maumee and Detroit River plume size increased by 13 % and 63 % respectively. Moreover, with increasing Easterly and Northeasterly wind speeds, the detachment of the MRP occurred further from the western shore and closer to the southern shore respectively. This is related to the increased downwelling and upwelling events at the western and southern shores under various wind conditions. The response of the Detroit and Maumee River plume to the increasing SW winds, however, differed from the conditions under the other two directions. When SW winds increased from 4 to 9 m $s^{-1}$, the MRP area decreased by 33 %. The Detroit River plume area increased by 11 % when SW winds increased from 4 6.5 m $s^{-1}$, and then decreased by 10 % when SW winds increased from 6.5 to 9 m $s^{-1}$.

**Surface Gravity Waves**

The contribution of surface gravity waves to the basin's sediment plume dynamics are mostly through the onset of sediment resuspension events during spring, when wave climate is more severe when compared to the summer. This is mainly through the wave-induced bed stress, which is much higher (0.65 N $m^{-2}$) in the presence of wave dynamics than in its absence (case C6). Note that although it is larger than the current-induced bed stress during spring 2003 (0.12 N $m^{-2}$), they are still at the same order and their contributions to sediment resuspension are comparable (bias of mean sediment concentration of 11 mg $l^{-1}$ for currents, and 14 mg $l^{-1}$ for waves; Fig. 9). This is consistent with the conjecture of Kang et al. (1982) and Lick et al. (1994) that found that bed stress and currents might be important forces for sediment resuspension in Lake Erie.

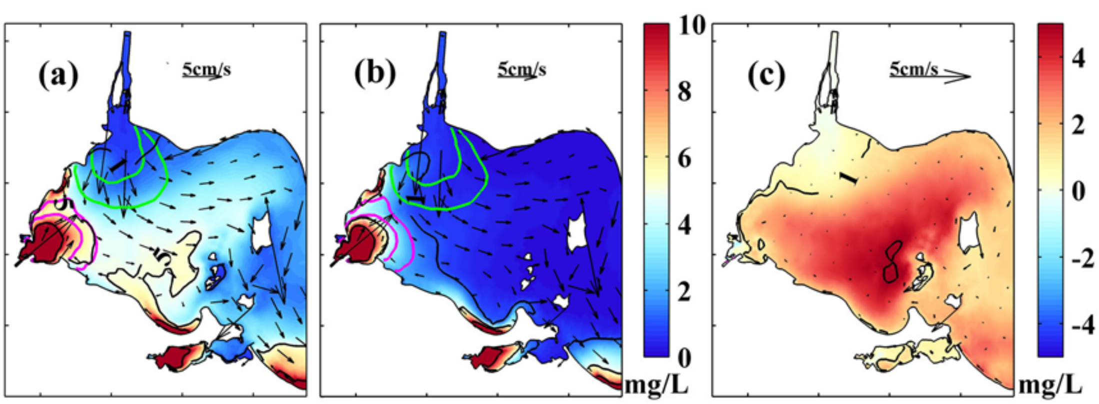


Fig. 9. Modeled surface sediment concentration and depth-averaged circulation in the western basin of Lake Erie under (a) realistic and (b) without wave dynamics conditions during spring 2003, and (c) the bias with each other (Realistic (case C1)-No Wave (case C6)).

Though surface gravity waves had little impact on the riverine plume patterns (Fig. 8), it was found that the incorporation of wave dynamics tend to slow the eastward propagation of the Detroit and Maumee river plumes (Fig. 10), especially for the Detroit River plume during spring storm events (Fig. 10b, c). A similar phenomenon was found in a theoretical work by Gerbi et al. (2013) that found that through the incorporation of wave breaking parameterization, the buoyant plume tends to be thicker and narrower, with a slower offshore propagation rate. According to Lentz (2004), shear dispersion plays a critical role in plume widening. Gerbi et al. (2013) stated that the contribution of wave breaking to the river plumes are mainly through its magnification of turbulent viscosity, which is reversely related to the shear stress. A similar mechanism was found in our model as well. With the incorporation of wave dynamics, the vertical plume shear was decreased. As a result, the Detroit and Maumee River plume areas were reduced by 53 $km^2$ and 4 $km^2$ respectively with the incorporation of wave dynamics.

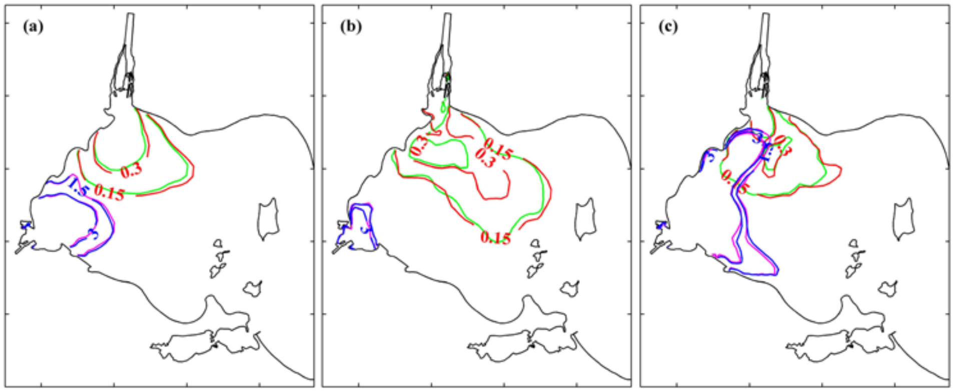


Fig. 10. The Detroit River plume of case C1 (green) and case C6 (red), and the Maumee River plume of case C1 (pink) and case C6 (blue) during spring (a), summer (b), 5 to 8 Apr (c), and 10 to 13 May (d) 2003.

**Influence of Sediment Dynamics on Plume Dynamics**

The Detroit River sediment loading has limited influence on the sediment or MRP dynamics in western Lake Erie (Fig. 11). It contributes ~ 5 % of total suspended sediment and SSC in the basin. When the Detroit River sediment loading was excluded (case C8), there was only 1 % variance in the Maumee River plume area. When the resuspension processes in the basin was turned off, the Detroit and Maumee River plume patterns remained similar (Fig. 12), with variations in surface plume areas less than 1 %.

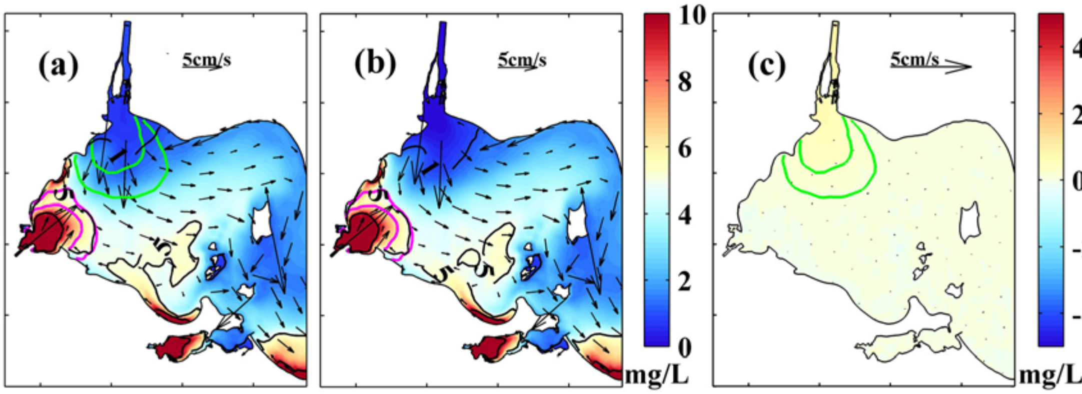


Fig. 11. Modeled surface sediment concentration and depth-averaged circulation in the western basin of Lake Erie under (a) realistic and (b) without Detroit sediment loading conditions during spring 2003, and (c) the bias with each other (Realistic (case C1)-No Detroit Sediment (case C7)).

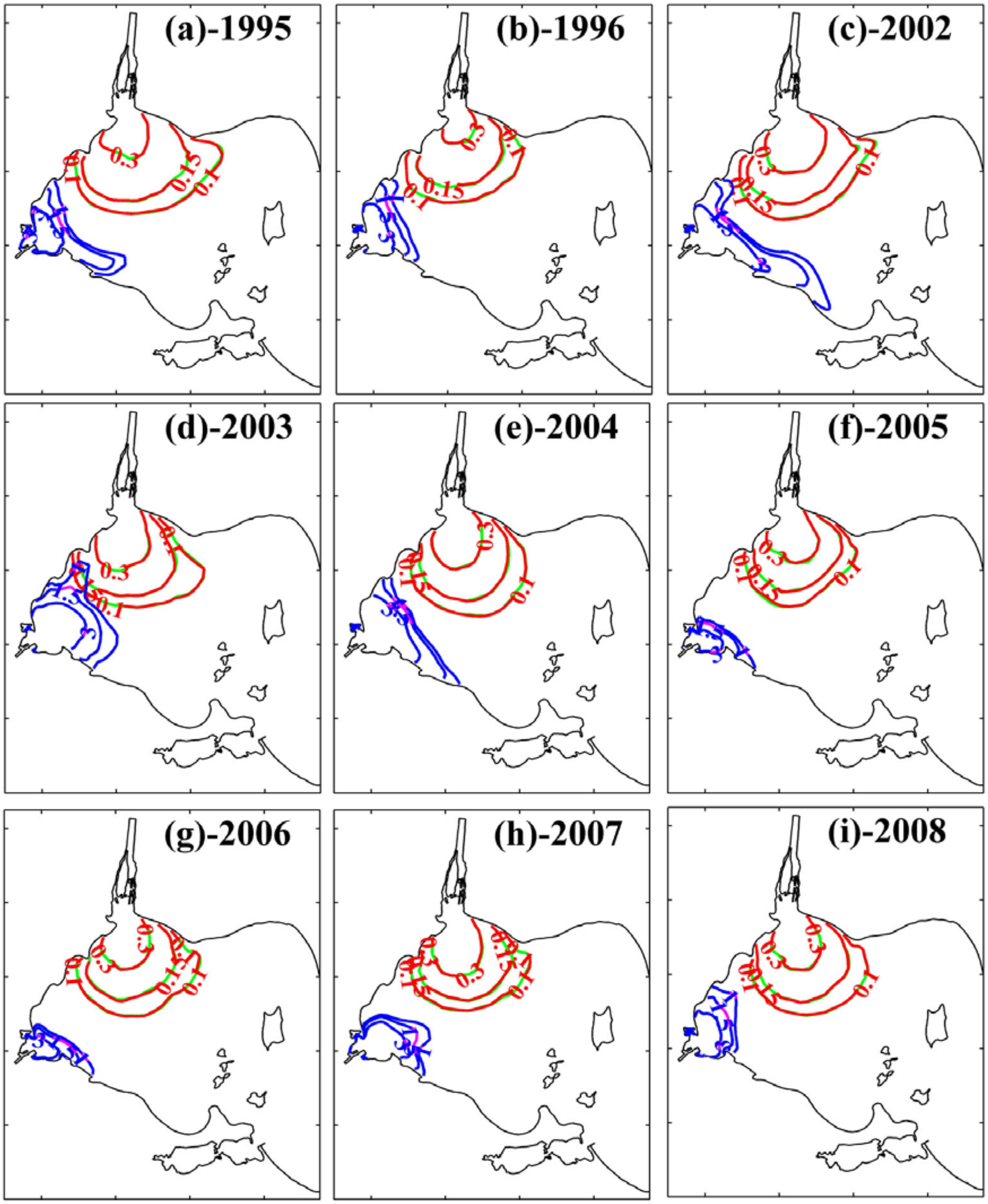


Fig. 12. The Detroit River plume of case C1 (green) and case C8 (red), and the Maumee River plume of case C1 (pink) and case C8 (blue) during spring of years 1995, 1996, and 2002 to 2008.

## Impacts of Physical Forcing on Planktonic Production in Western Lake Erie

### Spatial Distribution of High Productive Areas

During the spring and early summer bloom in 1996, the MRP was one of the most productive surface areas of Lake Erie with high nutrient loading, while Detroit River waters were nutrient poor and less productive (Fig. 13a, b, d and e). The semi-enclosed Sandusky Bay was characterized by weak outward and sometimes reversed flow that interacted with the littoral circulation of the southern shore (Fig. 13c). The several islands offshore from Sandusky Bay deflected the westward lake circulation and generated a peculiar flow pattern around them. Influenced by the above flow characteristics, the retention time of nutrients is relatively long in Sandusky Bay and around islands, and the shallow bathymetry and the shoreline deflection can accelerate the nutrient resuspension, which contributes to the high nutrient concentration (Fig. 13d, e) and plankton production in these areas (Fig. 13a, b). In the offshore regions, phytoplankton production was often restrained where zooplankton was abundant, indicating a strong top-down ecological control.

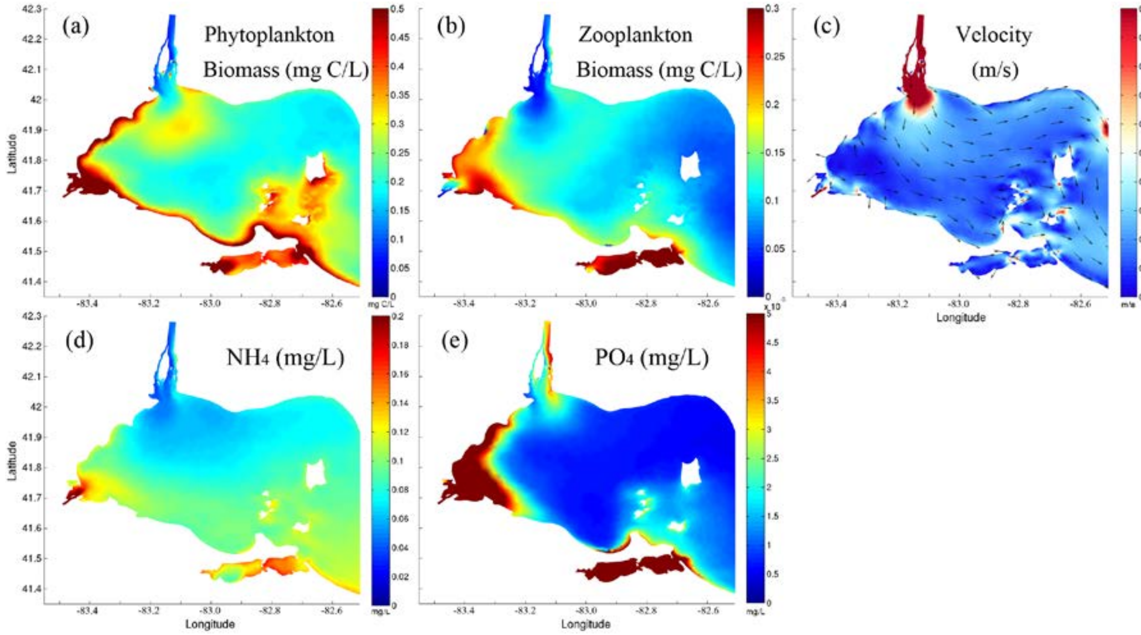


Fig. 13. Average simulated surface (a) phytoplankton biomass, (b) zooplankton biomass, (c) water velocity, (d) ammonia concentration and (e) phosphate concentration in calibration run of western Lake Erie in the model period (15 March 1996 to 31 July 1996).

**Influence of Detroit River on Plankton Production**

Detroit River contributes more than 90% of the discharge and almost 50% of the phosphorus to western Lake Erie, while the Maumee River contributes about 5 % of the discharge, but also nearly 50% of the phosphorus load (Schwab et al. 2009). As depicted in Fig. 8c, eastward flows driven by the Detroit River dominated most of the western Lake Erie basin. The MRP advects along the shoreline both northward and eastward (Schwab et al., 2009). The discharge of the Detroit River affects the northward transport of nutrient-rich MRP waters and delivers part of nutrients and phytoplankton offshore. When the Detroit River flux was shut down without changing its nutrient loading, the eastward current all over the western basin was prominently decreased and the Maumee River extended further northward and eastward along the shoreline (Fig. 14a). Accordingly, the lake production was greatly increased near the southern and western coast (Fig 14c, e). Production increment was even found in the western branches of the Detroit river channels, which suggested that the alteration in phytoplankton and zooplankton distribution was induced by the northward transport of Maumee River nutrients. The nutrient contribution of the Detroit River is mainly in the northern part of the western basin (Schwab et al. 2009). Without Detroit flux, the northern basin, which is flushed by Detroit River waters, received much less nutrients and reduced notably in production. Hence, the Detroit River, although poor in chlorophyll, sediment and nutrients, was responsible for the eastward nutrient transport and determined the distribution of primary production by its interaction with the Maumee River.

**Influence of Wind on Planktonic Production**

As the shallowest basin in Lake Erie, the western side could be strongly influenced by wind forcing and surface gravity waves, while wind stress can be modified by the circulation pattern in the western basin driven by the Detroit inflow (Beletsky et al. 2013). When the wind forcing was turned off, the surface flow difference on average displayed an anticlockwise gyre (figures 14b). Under such shift in circulation pattern, the primary and secondary production was redistributed (Fig. 14d, f). The nutrients were further transported to the center and north of the western basin especially near the mouth of the Detroit River leading to enhanced primary production in these areas. The wind-driven upwelling could be a substantial source of internal loading for the shallow nearshore regions in western Lake Erie (Porta et al. 2005), and reduction in phytoplankton and zooplankton was detected in some shallow waters after wind was eliminated. Wind-driven nutrient advection and vertical mixing were two key ways how wind influenced the plankton production in western Lake Erie.

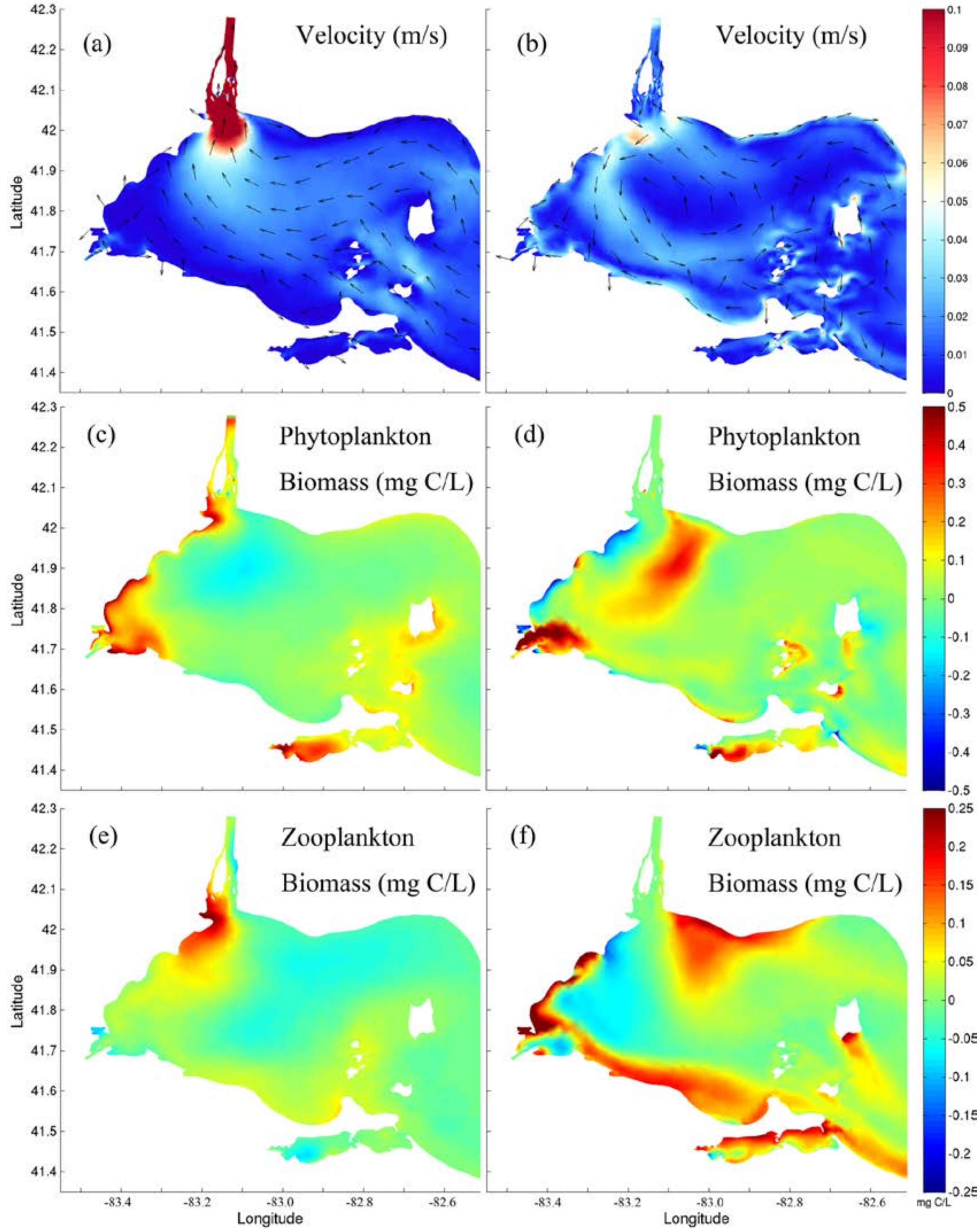


Fig. 14. Simulated difference in average surface velocity of western Lake Erie in the model period (15 March 1996 to 31 July 1996): (a) Case DT - Calibration, (b) Case WD - Calibration; simulated difference in average surface phytoplankton biomass of western Lake Erie in the same period: (c) Case DT - Case Calibration, (d) Case WD - Case Calibration; simulated difference in average surface zooplankton biomass of western Lake Erie in the same period: (e) Case DT - Calibration, (f) Case WD - Calibration. (Case DT: no Detroit River flux. Case WD: no surface wind. Case Calibration: calibration run shown in Figure 11)

## Objective 2

**Understand the relative importance of advection-caused loss of YP larvae to the observed disproportionate recruitment of MRP individuals relative to non-MRP individuals**

Our previous GLFC research has shown that, although larval YP densities were initially higher in non-MRP waters than the MRP during average spring discharge years, MRP individuals recruited disproportionally better to the new year-class (juvenile stage) in the western basin than their non-MRP counterparts (Reichert et al. 2010). One hypothesis for this pattern is that higher turbidity acts as a predation refuge, allowing YP larvae to survive at higher rates in the MRP than in non-MRP waters. An alternative hypothesis is that YP larvae residing in non-MRP waters are advected out of the west basin and into the central or eastern basin. While efforts seeking to document larval YP transport out of the west basin have not been attempted, other observations provide ancillary support for this latter alternative hypothesis: 1) Detroit River discharge is an order of magnitude greater than the Maumee River discharge and has much greater influence on the velocity and direction of lake currents (Bolsenga and Herdendorf 1993); 2) currents emanating from the Detroit River tend to be directly shunted between Point Pelee and Pelee Island (Pelee Passage) and into the central basin (Hamblin 1971; Herdendorf 1975); and 3) a Lake Michigan ICPBM indicates that YP can be transported larger distances than those required for larvae to reach the central basin (e.g., Beletsky et al. 2007). In this way, these larvae may not die in the western basin, but perhaps survive to contribute to Lake Erie's central basin fishery.

To test the *hypothesis that advection-driven emigration plays a larger role in the failure of most non-MRP larvae to recruit to the west basin fishery than does biological mortality agents (i.e., starvation, predation mortality)*, we quantified the percentage of larvae advected into the central basin from both MRP and non-MRP waters. We paid particular attention to how advection-driven emigration varies with spring Maumee River discharge and the biological state (e.g., age, size) of larvae. In so doing, we can test the *hypothesis that slow-growing larvae are more likely to (passively) emigrate, if active movement is important to retention*.

**METHODS:**

In order to accomplish this objective we employed our hydrodynamics model (FVCOM), and a particle trajectory tracking model. The hydrodynamics model was developed, set-up and parameterized for the previous objective (Appendix 1).

The transport of YP larvae was modeled with a particle trajectory model using water velocity fields outputted from FVCOM. Our approach followed North et al. (2008), whose model was devised to accurately capture the complex hydrodynamics that transport organisms in nearshore, tributary-driven systems (in this case, Chesapeake Bay). Because particles were often not at locations (nodes) where water velocity was estimated, we used bilinear fitting to interpolate velocity fields over space (three dimensions). Using interpolated current velocities, we estimated the trajectory of particle motion using a 4th order Runge-Kutta scheme and added stochasticity in the three dimensions (Dippner 2004; North et al. 2009).

**<u>Model Validation</u>**

In western Lake Erie, YP are able to maintain themselves within the MRP for up to 30 days which is the approximate length of their larval period in Lake Erie (Ludsin 2000; Reichert et al. 2010). However, it is unclear if staying in the plume requires larval YP to exhibit a swimming behavior. To validate the model and study whether larval YP exhibit active swimming behavior (Appendix 3), we ran the particle tracking model under different scenarios in order to determine if larvae require a swimming behavior in order to maintain their position within the plume. Specifically, we: (1) estimated the hatching locations of YP larvae collected in MRP, (2) starting from these hatching locations, modeled dispersal of larvae during 30 days (~length of larval stage in Lake Erie and residence in the plume, Ludsin 2000; Reichert et al. 2010) using different swimming behaviors to determine which matched observed data, and (3) using empirical data, further tested whether active movement would lead to more similar observed distributions than if particles exhibited no behavior. Our results suggest that in order for larval YP to stay in the plume for up to 30 days, they must exhibit an active swimming behavior. In particular swimming towards the mouth of the Maumee River (i.e. South West) may allow larvae to stay twice as long in the plume when compared to not exhibiting a swimming behavior, swimming randomly, and swimming towards the top or bottom part of the water column.

**<u>Estimate of advection-caused loss of YP larvae</u>**

To estimate the proportion of larvae that could be lost from the western basin due to advection, we used our particle tracking model, released particles in the MRP and non-MRP and determined what percentage of these particles were advected from the basin. During these models, we conducted forward-tracking particle trajectory model runs with two different scenarios where particles did not exhibit a swimming behavior or swam south west (towards the mouth of the Maumee River) to obtain a range of potential outcomes. For each run, 10,000 particles were released in a total of 20 locations within the area the MRP and non-MRP are commonly located (Fig. 15, Reichert et al. 2010), that are known YP hatching locations (Goodyear et al. 1982; Reichert et al. 2010) and were defined as hatching locations in our model validation (Appendix 3). Models were run from 1 to 30 May during 1995, 1996, 2002-2008. Model start and length was chosen based on hatch dates and length of larval periods described for Lake Erie in the current and previous studies (Gopalan et al. 1998; Ludsin 2000; Manning et al. 2014).

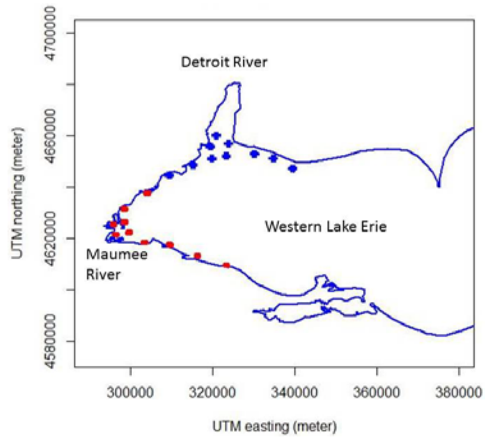


Fig. 15. Map detailing 20 locations in Maumee River plume (MRP, red particles) and non-MRP (blue particles) where particles were released in forward-particle trajectory models to determine the percentage of larvae that are potentially lost from the basin due to advection.

For model runs that incorporated swimming behaviors, we used maximum sustainable swimming speeds measured by Houde (1969) divided these values by two as a conservative estimate of active movement (similar results were also obtained when we used ¼ of measured maximum sustainable swimming speeds, Marin Jarrin and Pangle, unpublished data). Swimming speeds were allowed to increase with YP length. Larval YP length increased with time and was modeled using the equation:

$$YP\ Length\ (mm) = 0.00000003 * t^3 - 0.000011 * t^2 + 0.002 * t + 6.79$$

where *t* is the number of hours that have passed since the model began. The equation was obtained by modifying an equation from Marin Jarrin et al. (In preparation, Appendix 4) that calculated length at a daily time scale. We used this linear regression because Marin Jarrin et al. (In review) found it to be more accurate at predicting length than using a general or Lake Erie YP individual based model (Appendix 4). To model swimming speed we developed a linear regression between swimming speed and larval YP length (TL, mm) using data from Houde (1969).

$$Speed\ (m\ h^{-1}) = -1.4517 * TL^2 + 50.734 * TL - 261.43$$

Particles were considered to have left the basin when they moved past an imaginary line extending from Pelee Point, Ontario to Huron, Ohio by the end of the model runs. We tallied the number of particles that left the basin with the Maumee and Detroit River flow and determined the age at which particles exited the basin.

**RESULTS:**

In our model simulations, only a small percentage of particles exited the western basin of Lake Erie during 1995, 1996, 2002-2008 (0 – 21.46 %, Table 2). Particles that did not exhibit a swimming behavior and that were released in the non-MRP locations had a higher probability of exiting the basin than particles that swam south west or that were released in the MRP, respectively (3.16 ± 6.34 and 3.10 ± 6.38 vs. 0 ± 0 and 0.06 ± 0.16 %, respectively). Particles released in non-MRP waters that did not exhibit a swimming behavior started to leave the basin after an average of 13 ± 4 days (range: 6 days in 2007 to 18 days in 1995). The percentage of MRP and non-MRP particles were not related to mean May Maumee River or Detroit River flows ($n = 9$, $r^2 < 0.20$, $p > 0.05$).

Table 2. Mean percentage of particles released in the Maumee River plume (MRP) and non-MRP that exited the western basin of Lake Erie, which was defined as waters west of an imaginary line extending from Pelee Point, Ontario to Huron, Ohio. Particle distributions were modeled using forward-particle trajectory models under two different scenarios: no swimming behavior (No Behavior) and swimming south west or towards the mouth of the Maumee River.

| | No Behavior | | South West | |
|---|---|---|---|---|
| Year | MRP | non-MRP | MRP | non-MRP |
| 1995 | 0 | 1.88 | 0 | 0 |
| 1996 | 0.58 | 21.46 | 0 | 0 |
| 2002 | 0 | 4.8 | 0 | 0 |
| 2003 | 0.06 | 0.24 | 0 | 0 |
| 2004 | 0 | 0.3 | 0 | 0 |
| 2005 | 0.14 | 17.58 | 0 | 0 |
| 2006 | 0 | 0.64 | 0 | 0 |
| 2007 | 0.38 | 8.16 | 0 | 0 |
| 2008 | 0 | 0.72 | 0 | 0 |

## Objective 3

### Identify mechanistic linkages between physical processes and YP year-class strength.

An end goal of our project was to develop a mechanistic understanding of the determinants of Lake Erie YP year-class strength so that we can forecast future recruitment into the fishery. This type of understanding extends previous correlative models because it can identify causal relationships and account for future changes in the Lake Erie ecosystem, its watershed, and the climate it experiences. Conditions in Lake Erie have changed continuously owing to natural and anthropogenic influences (e.g., invasive species, habitat alteration, altered nutrient loading regimes, fishery harvest, climate; Munawar et al. 1999). Thus, knowledge of mechanisms influencing recruitment would allow management agencies to anticipate when correlative models might fail, and help guide decisions regarding annual harvest quotas.

Given the strong Maumee River discharge – YP recruitment relationship, we *hypothesized that YP recruitment in western Lake Erie is largely controlled by external physical (climatic) forces that drive western Lake Erie*. To test this hypothesis, we developed a model-based index of basin-wide YP recruitment and related this index to observed recruitment.

**METHODS:**

Model-derived variables considered for our recruitment index included Lake Erie water temperature on 1 May, the mean May MRP area, mean YP retention in MRP during their larval period, and survival rates. We included water temperature in our analysis because it can influence hatching date, and recent research has found that winter temperatures can impact embryo development and quality (Rose et al. 1999, Farmer 2013). In the initial analysis we also considered using different time scales for each of these factors; however, we did not pursue these options as our pilot analysis found their relation with number of 2-year olds to be poorer than those employed.

Mean Lake Erie 1 May water temperature (°C) was obtained from the hydrodynamics model output. Mean area of May MRP was calculated using the daily hydrodynamics output ($m^2$) and defined as waters with TSS >0.001 g $l^{-1}$. Larval retention rates were estimated using the hydrodynamic output and our forward tracking particle trajectory model detailed in objective 2. Retention of larvae in the MRP was calculated by comparing MRP particle distribution to turbidity. To estimate retention, we released 8500 particles in our model in 17 different locations throughout the area where the MRP is usually located and where results from previous analysis suggested YP hatch (Goodyear et al. 1982; Reichert et al. 2010, Appendix 3). The model was run for 30 days (approximate larval period in Lake Erie, Ludsin 2000), and started from the annual mean hatch date specifically recorded for that year in the MRP (day of year 133 in 1996, 123 in 2006, 126 in 2007 and 125 in 2008, Ludsin, unpublished data) or on a mean hatch date (5 May) for years where we did not have data (1995, 2002-2005). Particles were allowed to increase in size and swim south west as detailed in the previous objective. If particles were in a cell with total suspended solids >0.001 g $l^{-1}$, we considered them retained in the plume. For these simulations, sediment input to Lake Erie was only allowed to originate from the Maumee River and sediment was not allowed to become re-suspended to isolate the MRP. The location of particles relative to the plume was carried out on an hourly basis during the simulations.

Survival rates were predicted by combining a modified version of Fulford et al.'s (2006b) predation model to our hydrodynamics and particle trajectory model. The predation model was modified by including a predator encounter rate that incorporates the effect of turbidity, a factor suggested to strongly influence YP survival rates (Reichert et al. 2010; Ludsin et al. 2011; Carreon-Martinez et al. 2014; Van Tassel J. and Ludsin S., unpublished data). Fulford et al.'s predation model considers known larval YP predators, including white bass *Morone chrysops*, white perch *Morone americana*, and adult YP as potential predators (Carreon-Martinez et al. 2014). Predator densities (ind. $ml^{-1}$) used in the model were estimated using bottom trawl data (7.6-m semi-balloon design, 13-mm stretched-mesh cod-end liner, Carreon-Martinez et al. 2011, 2014). Trawls were conducted with an average tow time of 18 minutes (range: 5-31 minutes) at a boat speed of about 3-4 knots. Upon retrieval of the trawl, fishes were immediately euthanized using clove oil. Calculation of the modified encounter rate (T) varied depending on turbidity

$$\text{If: } 0.7048 * \exp(-0.04874 * \text{turbidity}) < 1;\ T = 1.637*\exp(-0.122 * \text{turbidity});$$

$$\text{Else: } T=1$$

Daily survival rates were calculated for each particle, and then multiplied to calculate rates for the larval period.

We used the observed number of 2-year old fish from each year-class as our measure of actual recruitment, and we related our model-derived variables to observed recruitment using general linear models.

**RESULTS:**

Observed recruitment, defined as the number of 2-year olds, varied from 1.6 to 53.6 million YP in our study years (Table 3). May 1st water temperature varied from 8.7 to 12.5 °C and was negatively related with the number of 2-year olds ($r^2 = 0.59$, $p = 0.05$, Fig. 16). This relationship strongly separated high and low recruitment years (22.7 to 53.6 vs. 1.6 to 15.9 million fish, respectively) depending on whether water temperature on 1 May was above or below 10.5 °C.

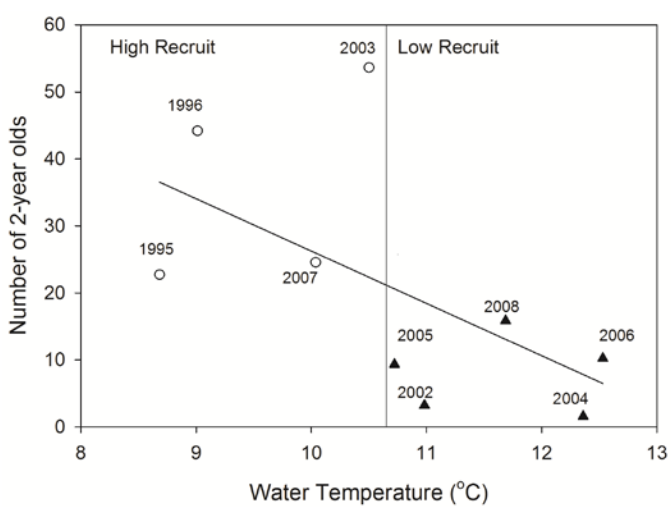

Fig. 16. Relationship between mean Lake Erie water temperature on 1 May during the year YP hatch, and number of fish from that year class that entered the fishery at age 2 (Number of 2-year olds). Years are separated into high and low recruitment based on whether water temperature on 1 May was below or above 10.5 °C.

Based on this relationship with temperature, we considered whether MRP size, larval retention rates and survival rates was related differently with high and low recruitment years (Table 3). Mean May Maumee River flows, MRP, larval retention in MRP and number of potential parents and survival rates exhibited a positive and negative relationship with high and low recruitment years, respectively (Fig. 17).

Table 3. Age class studied (Year), number of 2-year old YP that survived from each size class (millions of fish, 2-year olds), mean May Maumee River Plume size ($km^2$, MRP size), percent of time modeled larvae were retained in MRP (Larval Retention), and modeled survival rates of YP throughout their larval period.

| Year | 2-yearsOlds | MRP Size | Larval Retention | Survival Rates |
|---|---|---|---|---|
| 2004 | 1.60 | 434.32 | 47.63 | 3.65674E-05 |
| 2002 | 3.25 | 654.90 | 50.16 | 3.17997E-05 |
| 2005 | 9.33 | 438.94 | 14.70 | 2.893E-05 |
| 2006 | 10.25 | 59.11 | 40.36 | 3.45235E-05 |
| 2008 | 15.86 | 43.60 | 38.28 | 2.932E-05 |
| 1995 | 22.72 | 346.45 | 12.95 | 3.07005E-05 |
| 2007 | 24.55 | 59.29 | 14.25 | 2.72116E-05 |
| 1996 | 44.19 | 779.32 | 53.00 | 3.09575E-05 |
| 2003 | 53.63 | 696.32 | 63.68 | 3.71497E-05 |
| | Full Model $r^2$ | 0.91 | 0.96 | 0.89 |

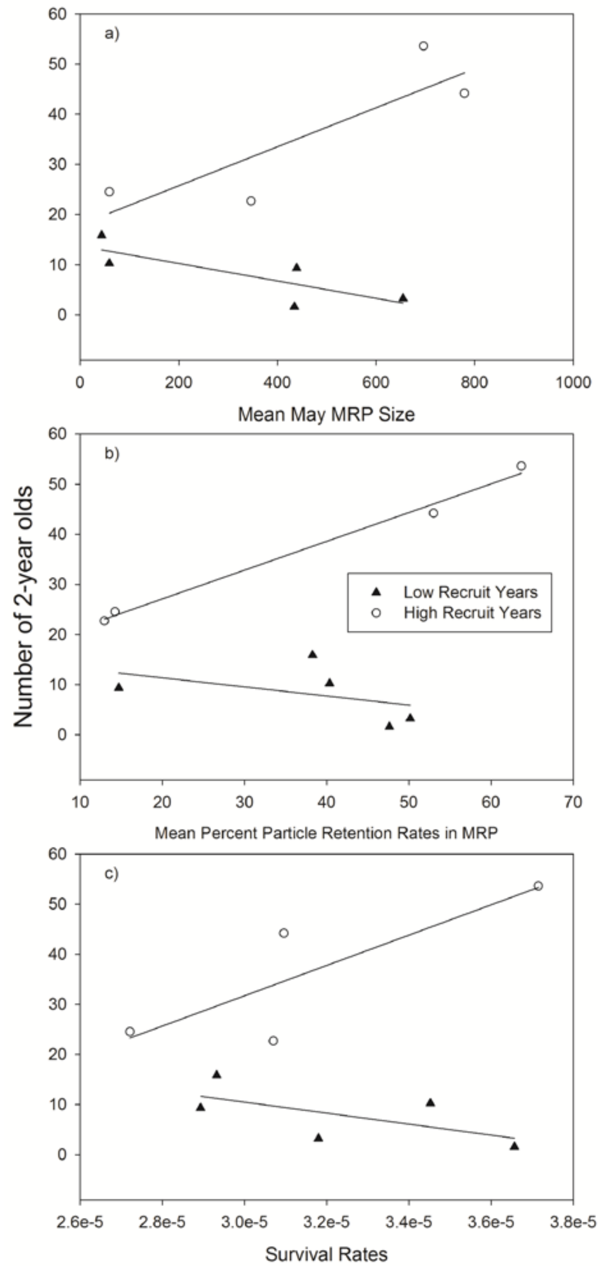


Fig. 17. Relationship between number of Lake Erie Yellow Perch that entered the fishery at age-2 and (a) mean May Maumee River Plume size ($km^2$, MRP), (b) percent of time modeled larvae were retained in MRP, and (c) modeled survival rates of YP throughout their larval period. Years were separated into high and low recruitment years due to the difference in their relationships.

Daily survival rates exhibited a polynomial relationship with larval age, with highest rates at the beginning and end of their larval period and lowest rates in the middle (Fig. 18). Due to the separation we observed for high and low recruitment years in MRP size, larval retention in MRP, and survival rates, we included each of these factors, a dummy variable that groups data based on level of recruitment and their interaction, into general linear models to determine the slopes between the two groups were significantly different. The interaction in the three models was significant ($F_{1,5}$ = 6.73 – 15.17, p = 0.01 - 0.05), suggesting the slopes between these three factors and high and low recruitment years were different.

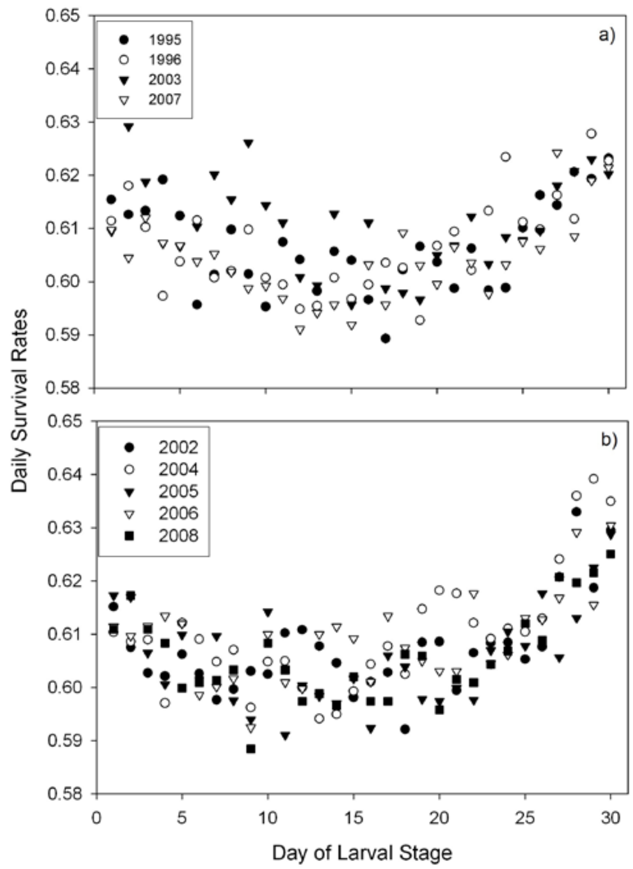


Fig. 18. Modeled daily survival rates of Yellow Perch in the western basin of Lake Erie along their larval period during years of (a) high (>20 million YP entered fishery) and (b) low recruitment (< 20 million YP entered fishery).

**DISCUSSION:**

Western Lake Erie was characterized by high interannual variability in sediment dynamics, especially around the Maumee River mouth and southern part of the basin. The variations at the Maumee River mouth area are highly related to the sediment loading and river discharge from the Maumee River, and those at the southern basin are related to the intensity of current and wave dynamics in the basin, which are both driven by surface wind forcing. The Detroit River contributes significant momentum flux to the western basin, and its high discharge restrains the distribution of the MRP and resuspension events to the southern part of the basin. The inflow of the Maumee River has limited influence on the circulation inside the basin, even during flood events, and thus has little influence on the Detroit River plume dynamics; however the Maumee River is the major source of sediment loading to the basin. With the exclusion of the Maumee River, the surface sediment concentration in the basin was reduced, especially around the Maumee River mouth. Surface wind forcing plays a critical role in both riverine and resuspension plume dynamics, and this is mainly referred to the local surface wind forcing. The direction of wind forcing determines the shape of riverine plumes. Increasing speeds of E and NE winds can lead to increasing of Detroit and Maumee River plume areas, while increasing SW winds would decrease them. Wind-driven circulation is also important for the onset of sediment resuspension, though not as significant as the influence of wave dynamics, their influences are at the same order. The wave-induced bed stress is the most important source for sediment resuspension in the basin. Meanwhile, the incorporation of wave dynamics would result in the narrower plume patterns, and slower plume propagation rate. It is thus important to consider wave dynamics in the numerical simulation of plume dynamics, which was deliberately ignored in previous studies. The sediment dynamics, such as the sediment loading from the Detroit River and resuspension events, have limited influence on the riverine plume dynamics, with relative contribution of 1% to modify Maumee River plume size, and 5% to the total SSC in the basin. The most productive areas of western Lake Erie were in the Maumee River plume and some nearshore shallow waters. The Detroit River was responsible for the eastward transport of nutrients and determined the distribution of planktonic production by its interaction with Maumee River in western Lake Erie. The plankton distribution in the shallow western basin was sensitive to wind forcing, in particular, to the wind-driven nutrient advection and vertical mixing. These results further highlight the need for physical models that consider discharge, water currents and the forces that influence these as well to adequately describe plume dynamics.

In western Lake Erie, larval YP that inhabit the MRP have been found to survive to the juvenile stage at a higher rate than non-MRP fish (Reichert et al. 2010). Recently published research has suggested these differences in survival rates are due to higher predation rates outside of the plume (Carreon-Martinez et al. 2014). However, another possibility is that larvae produced in non-MRP waters are advected out of the basin at higher rates than MRP fish (Reichert et al. 2010). Our work found that loss of MRP and non-MRP YP due to advection is likely unimportant whether larvae exhibit active swimming behavior or not. This is likely due to the anticyclonic circulation commonly exhibited in the basin that could help retain the larvae. Further, additional analysis found that MRP larval YP are most likely exhibiting an active swimming behavior in order to remain in the plume and therefore survive at higher rate than they would if they were to exit the MRP (Reichert et al. 2010; Carreon-Martinez et al. 2014).

Results from objective 3 suggests the mechanism influencing survival rates of MRP YP larvae varies depending on the water temperature embryos experienced prior to hatching, with lower temperatures producing larger age classes than high values. When analyzing the factors influencing recruitment in low and high water temperature years separately, we found that the relationship between number of 2-year olds that survived per year class with MRP size, larval retention and survival rates was different, suggesting larger plumes may allow more larvae that hatched during cold years to survive but less during warm years. These results could be because embryo development is positively related to water temperature, potentially leading to earlier hatching dates during warm years and a mismatch with prey items or a match with their potential predators (Rose et al. 1999, Farmer 2013). An alternative hypothesis is that, because embryo and larval quality is higher during years with cold winters (Farmer 2013), larvae that hatch during cold years may be better at escaping predators than fish that are produced during warm springs. Further work is needed to increase the number of years studied and therefore be able to test these hypotheses.

Survival rates were higher at the beginning and end of the 30 day long modeled larval period and lower during the middle. These results may have occurred because at the beginning of the period, larvae are closest to the shoreline where the plume is more likely to be present and survival rates are therefore higher, while at the end larvae are largest and therefore more able to escape predators. During the middle of the larval stage, fish were not close to the shoreline or at their largest size, and therefore suffered highest predation rates. These results suggest mortality rates vary throughout the larval stage following similar patterns in high and low recruitment years.

In conclusion, we found that the size of the MRP is most strongly influenced by Maumee River discharge, and wind direction and speed. The MRP is particularly large when river flows are high and winds are from the E and NE. Despite high current speeds in Lake Erie, model results suggest advection of larvae out of the basin is negligible and further points to differences in predation rates as the main factor determining the higher survival rates of MRP YP. Our results also suggest that water temperature during embryo development and the size of the MRP during the larval stage are the main mechanisms driving western Lake Erie YP recruitment dynamics. Managers may therefore be able to use these characteristics to forecast future size of age classes.

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**DELIVERABLES:**

**Peer-reviewed manuscripts**

Jiang L., Xia M., Ludsin S.A., Rutherford E.S., Mason D.M., Marin Jarrin J.R., Pangle K.L. In Review. Biophysical modeling assessment of the drivers for plankton dynamics in western Lake Erie. Ecological Modeling.

Marin Jarrin J.R., Pangle K.L., Reichert J.M., Johnson T.B., Tyson J., Ludsin S.A. Accepted. Influence of habitat heterogeneity on the foraging ecology of first feeding yellow perch larvae, *Perca flavescens,* in western Lake Erie. Journal of Great Lakes Research.

Marin Jarrin J.R., Ludsin S.A., Pangle K.L. In Preparation. Evaluation of predictive ecological models for larval fish. Canadian Journal of Fisheries and Aquatic Sciences.

Marin Jarrin J.R., Ludsin S., Xia M., Mason D., Rutherford E., Pangle K. In Preparation. Combining particle tracking models and otolith chemistry to study the swimming behavior of larval fish in the Great Lakes. Ecological Applications.

Niu Q., Xia M., Rutherford E., Mason D., Anderson E.J., Schwab D.J. In Review. Investigation of inter-basin exchange and inter-annual variability in Lake Erie using an unstructured-grid hydrodynamic model. Journal of Geophysical Research-Oceans.

**Other Manuscripts**

Xia M., Pangle K., Marin Jarrin J.R., Ludsin S., Mason D., Rutherford, E., and Wiley, M. 2013. A coupled physical-biological model to forecast larval yellow perch distributions, growth rates, and potential recruitment in Lake Erie. 2013 Project Progress Report, Great Lakes Fishery Commission. 49 pp.

**Presentations**

Marin Jarrin J.R., Pangle K., Xia M., Ludsin S., Mason D., Rutherford E. 2014. Combining particle tracking models and otolith chemistry to study the swimming behavior of larval Yellow Perch in western Lake Erie. Joint Aquatic Science Meeting, Portland, Oregon. Oral presentation.

Marin Jarrin J.R., Pangle K., Xia M., Ludsin S., Mason D., Rutherford E. 2013. Linking river discharge and wind-driven currents to the success of larval yellow perch in western Lake Erie: working through assumptions and unknowns. 56th Annual Conference of the International Association for Great Lakes Research. West Lafayette, Indiana. Oral Presentation

Niu, Q., Xia, M. 2014. Dynamics of Spring Sediment Plume and Summer Circulation in Lake Erie. 2014 Marine Estuary and Environmental Science Colloquium, Solomons, Maryland

Niu, Q., Xia, M. 2014. Dynamics of Spring Sediment Plumes in the Western Lake Erie. 41st Annual Mid-Atlantic Bight Physical Oceanography and Meteorology, Gloucester Point, Virginia

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Niu, Q., Xia, M., Schwab, D. 2014. Application of a finite volume coastal ocean model to Lake Erie. 2014 Chesapeake Modeling Symposium, Annapolis, Maryland

Pangle K., Marin Jarrin J.R., Xia M., Ludsin S., Mason D., Rutherford E. 2014. Combining particle tracking models and otolith chemistry to study the swimming behavior of larval Yellow Perch in western Lake Erie. 144th American Fisheries Society Annual Meeting, Quebec City, Canada. Oral presentation.

Xia, M., Niu, Q., Cao, Z., Jiang, L., Rutherford, E., Schwab, D., Anderson, E., Pangle, P., Marin Jarrin, J.R., Ludsin, S., Mason, D.M. 2013. The application of an unstructured based bio-physical model to Lake Erie. 13th International Conference on Estuarine and Coastal Modeling, San Diego, California.

Xia, M., Niu, Q., Jiang, L., Rutherford, E., Schwab, D., Anderson, E., Pangle, P., Marin Jarrin, J.R., Ludsin, S., Mason, D.M. 2014. The application of an unstructured based bio-physical model to Lake Erie. 57th Annual Conference on Great Lakes Research, Hamilton, Ontario

Xia, M., Niu, Q., Jiang, L., Rutherford, E., Schwab, D., Anderson, E., Pangle, K., Marin Jarrin, J.R., Ludsin, S., Mason, D.M. 2014. The development of an unstructured based bio-physical model to Lake Erie yellow perch recruitment. IMBER Future Oceans conference, Bergen, Norway

**Training and Education**

Marin Jarrin J.R. Postdoctoral Fellow. Biology Department, Central Michigan University, 2013-Present. Supervisor: Dr. Kevin Pangle.

Jiang L. Ph.D. Student. Department of Natural Sciences, University of Maryland Eastern Shore, 2012-Present. Advisor: Dr. Meng Xia.

Niu, Q. M.Sc. Student. Department of Natural Sciences, University of Maryland Eastern Shore, 2012-2014. Advisor: Dr. Meng Xia.

**PRESS RELEASE:**

**Big plumes aid yellow perch fishery in western Lake Erie**

Yellow perch (YP) is a commercial and recreational fishery species in western Lake Erie. Previous research suggested that the Maumee River plume (MRP) benefited YP by provided a nursery area. To test this hypothesis, a multidisciplinary team of researchers was assembled to examine fluctuations in MRP and the movement, growth, and survival of YP larvae. They found that Maumee River discharge, and wind speed and direction are the main factors influencing expansion and contraction of the MRP. In support of their hypothesis, the size of the plume was positively correlated to YP success; however, the water temperature was important, with cooler springtime temperatures having a positive effect on YP. This work sheds light on the factors that drive changes in YP population and may help managers improve forecasts of future recruitment to the fishery.

**APPENDIX FIGURES:**

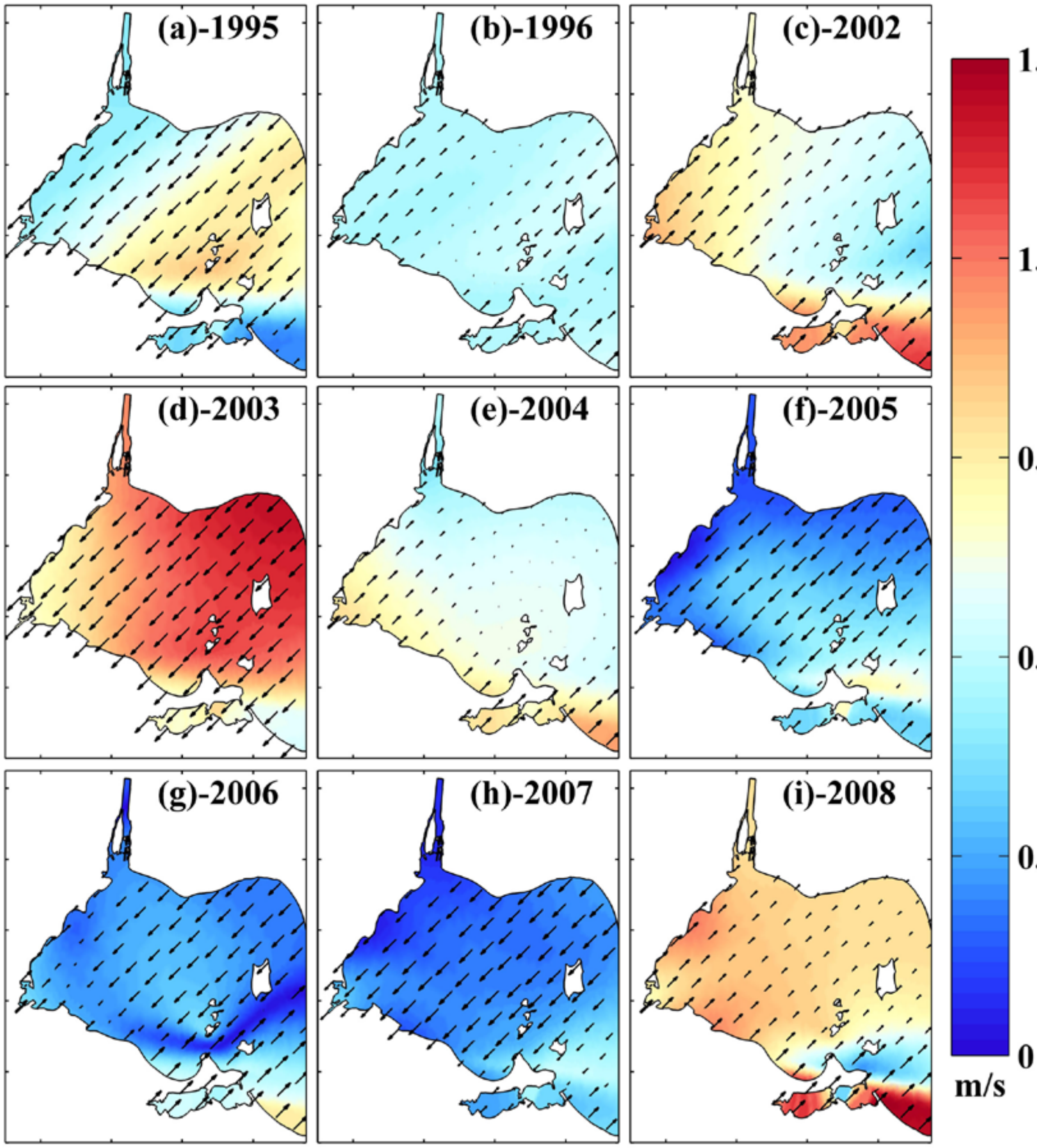
**Appendix 1. Atmospheric Forcing**

The model is forced with hourly air temperature, net downward shortwave radiation ($H_{sr}$), and upward longwave radiation ($H_l$), combined with cloud cover and relative humidity at the lake's surface. These data were provided by NOAA Great Lakes Environmental Research Lab (GLERL). The heat fluxes were processed based on *McCormick and Meadows* [1988], where $H_{sr}$ was calculated based on the in situ latitude and longitude, time of day, day of year and cloud cover, and $H_l$ was calculated using the bulk aerodynamic transfer formulas related to specific humidity of air and water and surface wind speed. Precipitation and evaporation are not considered in the model, because the net evaporation in Lake Erie is only ~ 40 $m^3 s^{-1}$, which is trivial compared to the contribution of surrounding rivers (~ 5500 $m^3 s^{-1}$) [*Neff and Nicholas*, 2005]. Wind speed at 10 m above ground is used as surface momentum forcing. It is provided by NOAA GLERL, and is generated based on meteorological stations and buoys within and around Lake Erie from both NOAA National Data Buoy Center (NDBC) (http://www.ndbc.noaa.gov/), and NOAA National Climate Data Center (NCDC) (http://www.ncdc.noaa.gov/). Similar methods applied in Lake Michigan [*Beletsky and Schwab*, 2001] were used to interpolate wind speed from observations to the computational domain, including an empirical adjustment for the difference between overland and overlake aerodynamic roughness. It has better performance in the western basin and nearshore areas than the outputs of meteorological models [*Niu et al.*, 2014], such as the North America Regional Reanalysis (NARR) model [*Mesinger et al.*, 2006] and the Global Environmental Multi-scale (GEM) model [*Côté et al.*, 1998].

***Figure Ap1-1.*** *Mean (a) shortwave and (b) longwave radiation in the western basin during the springs of years 1995, 1996, and 2002 to 2008.*

The $H_s$ and $H_l$ have little variation during the springs of model simulation years with CVs of 2.6 % and 8.8 % respectively, and the mean $H_s$ and $H_l$ across 9 years in the western Lake Erie are shown in Appendix Figure Ap1-1. Higher $H_s$ and $H_l$ appeared at the western and eastern parts of the basin, respectively. The surface wind forcing, on the other hand, varied significantly year by year, with CVs of 45 % in wind speed and 131 % in wind direction. The mean surface wind forcing field during the springs of the model simulation years are illustrated in figure 4. The surface wind forcing in the basin is dominated by northeast and southwest wind (Appendix Figure 1-2). There were extreme spring storms in the basin during years 2003 and 2008, and moderate ones during 1995, 2002 and 2004.

***Figure Ap1-2.*** *Mean wind speed at 10 m above ground in western Lake Erie during the springs of 1995, 1996, and 2002 to 2008.*



**Appendix 2. Surface Sediment Concentration of Idealized Cases**

***Figure Ap2-1.*** *Surface sediment concentration and depth-averaged circulation in the western basin during the springs of years 1995, 1996, and 2002 to 2008, with the exclusion of Detroit River (case C1).*

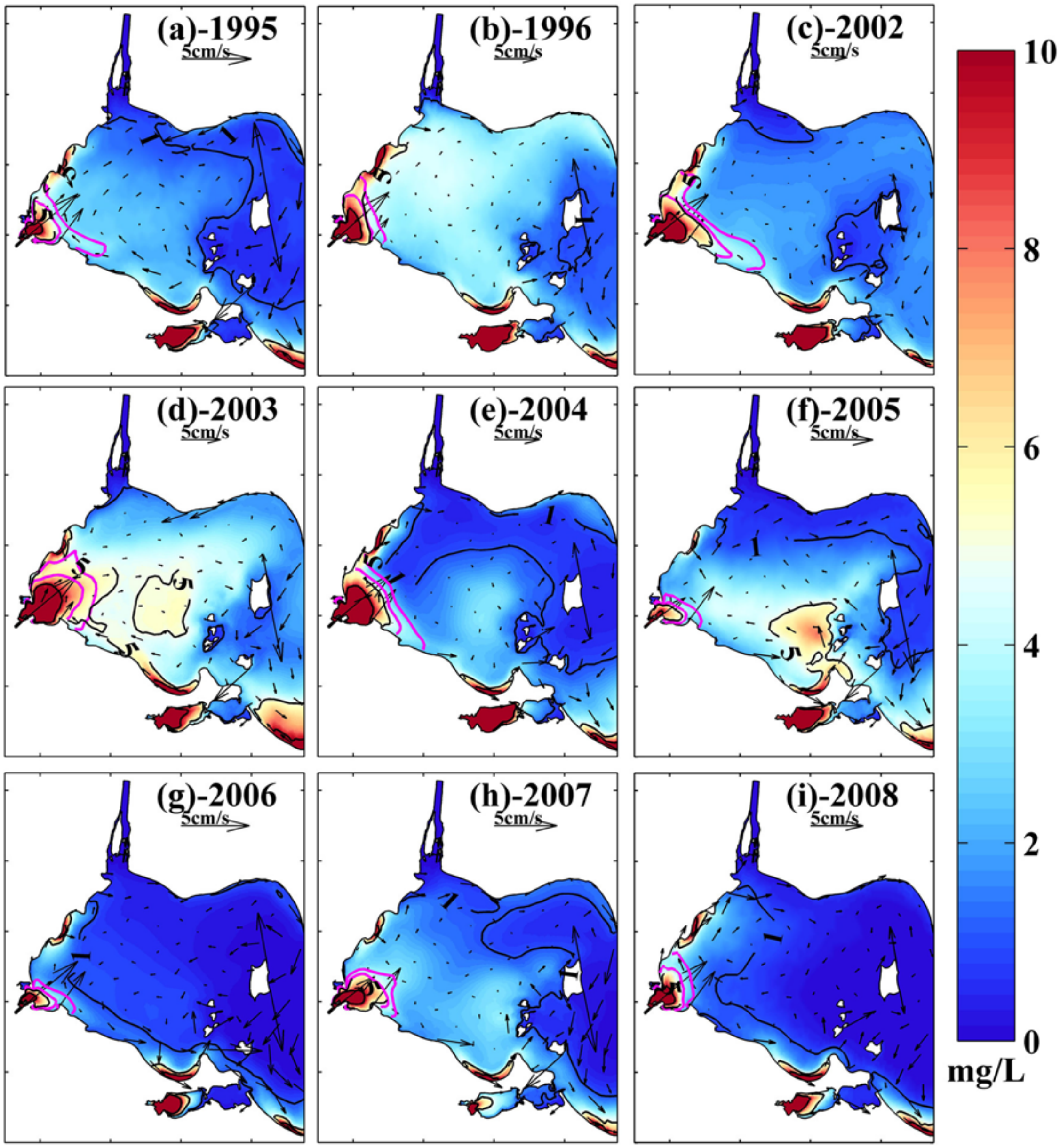
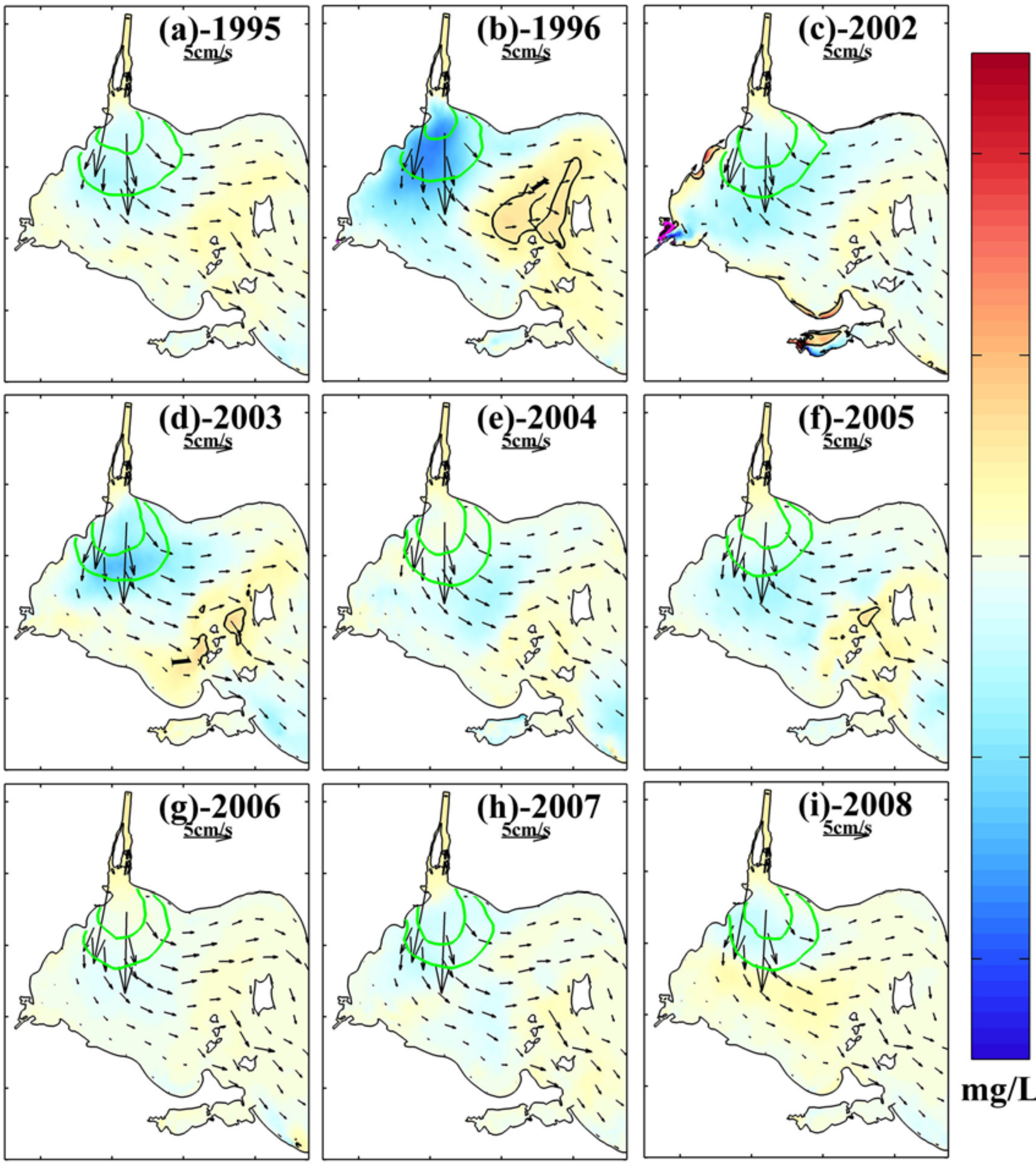


***Figure Ap2-2.*** *Bias in the surface sediment concentration and depth-averaged circulation in the western basin during the springs of years 1995, 1996, and 2002 to 2008. (With Detroit River-Without Detroit River)*




Note that the Detroit River has the most profound influence on the basin's sediment dynamics during spring 1996. This is due to the anomalous high discharge from the Detroit River during the May and June of 1996 (see Appendix Figure 2-2b).

***Figure Ap2-3.*** *Surface sediment concentration and depth-averaged circulation in the western basin during the springs of years 1995, 1996, and 2002 to 2008, with the exclusion of Maumee River (case C2).*

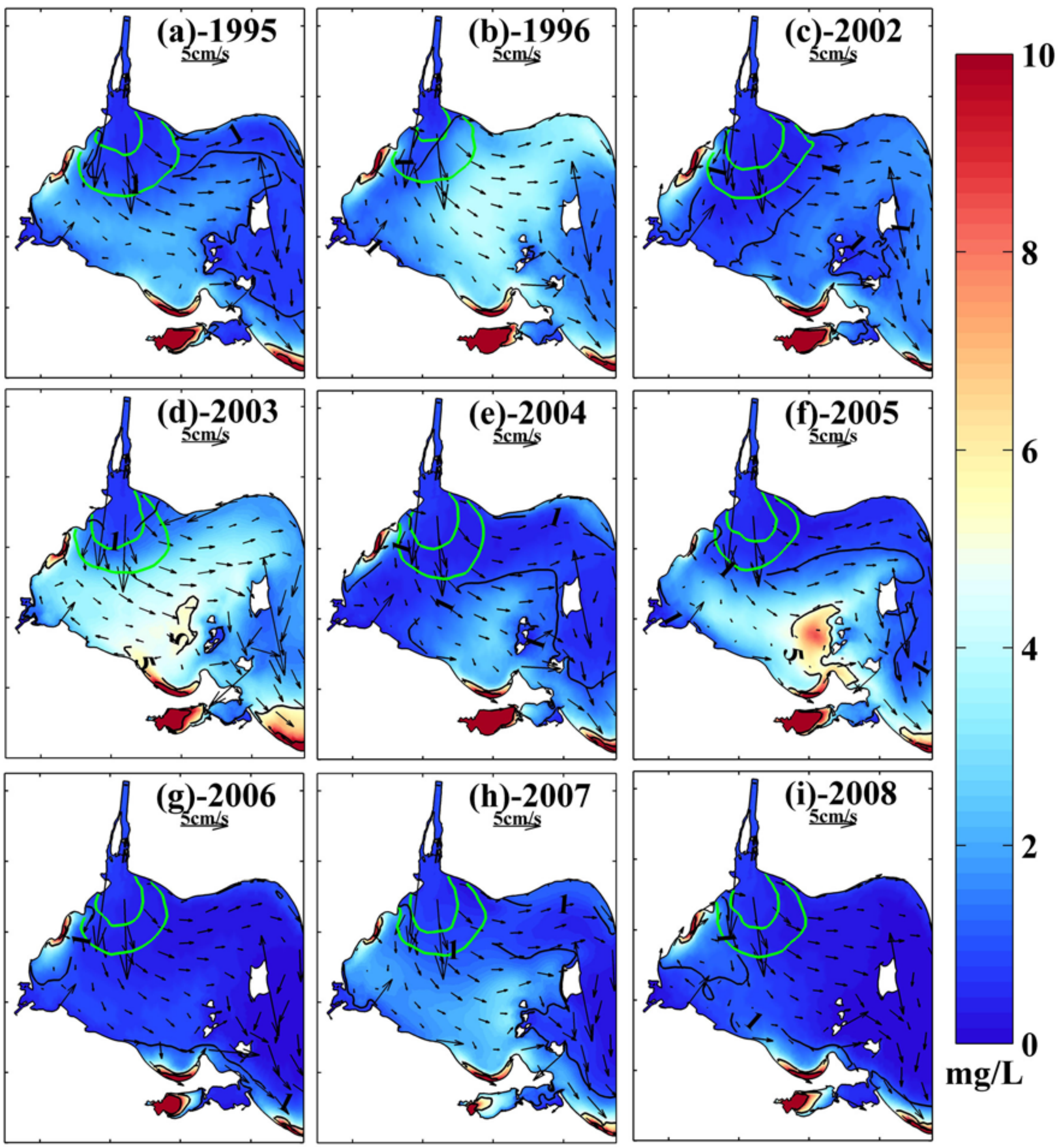


***Figure Ap2-4.*** *Bias in the surface sediment concentration and depth-averaged circulation in the western basin during the springs of years 1995, 1996, and 2002 to 2008. (Realistic-Without Maumee River)*

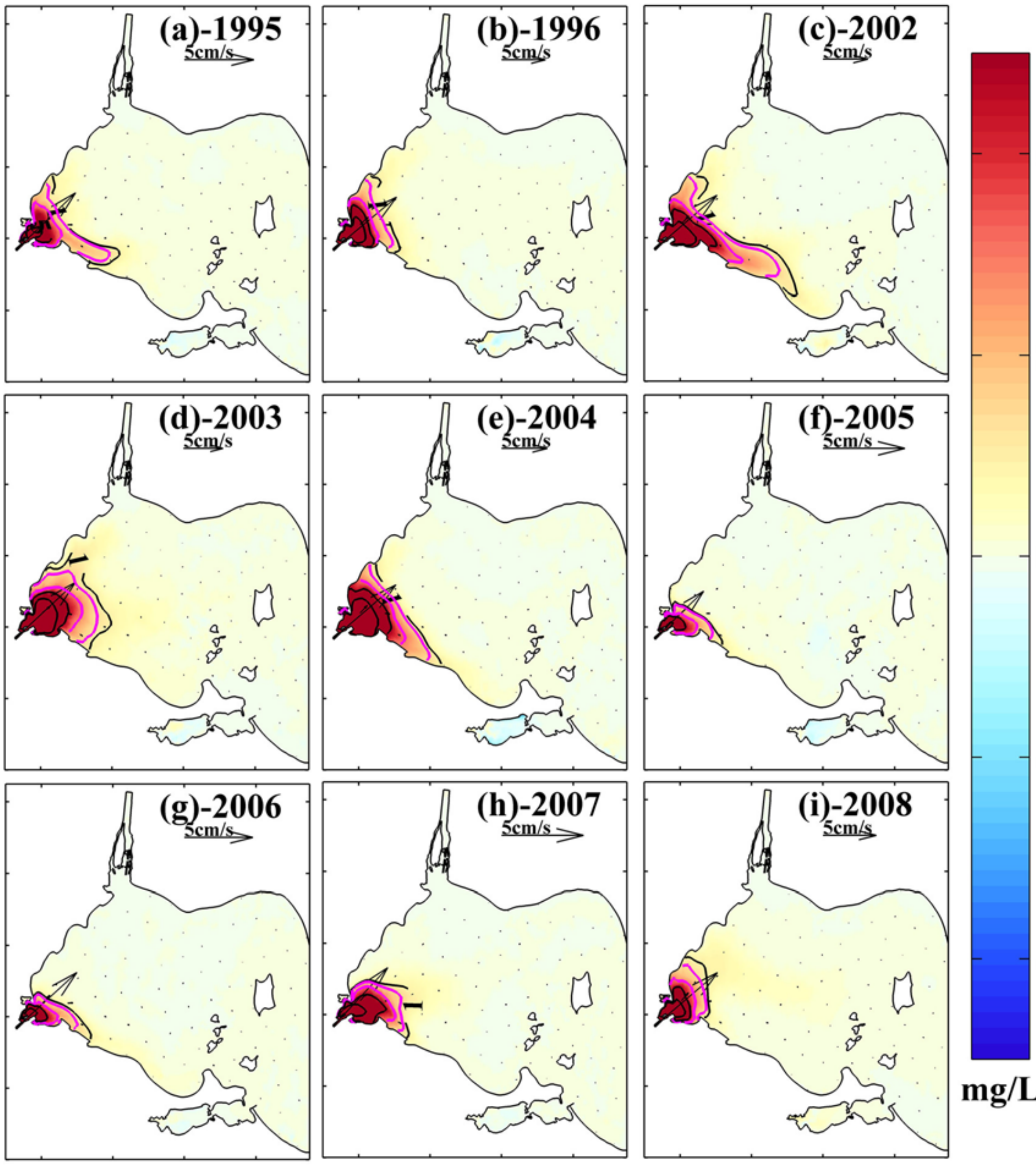


***Figure Ap2-5.*** *Modeled surface sediment concentration and depth-averaged circulation in the western basin of Lake Erie under realistic (a and d), without local wind forcing (b), and without remote wind forcing (e) conditions during spring 2002; and their bias with the realistic case: (c) Realistic (case C1)-No Local Wind (case C4), (f) Realistic (case C1)-No Remote Wind (case C5).*

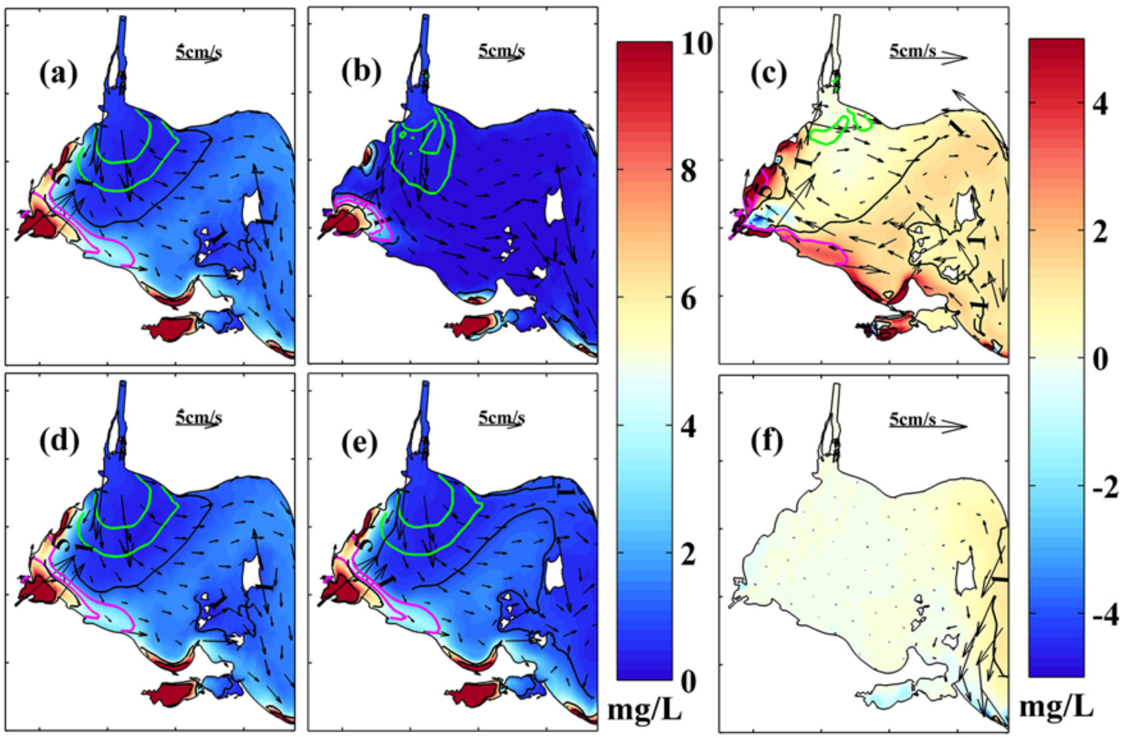


***Figure Ap2-6.*** *Surface sediment concentration and depth-averaged circulation in the western basin during the springs of years 1995, 1996, and 2002 to 2008, with the exclusion of wave dynamics (case C6).*

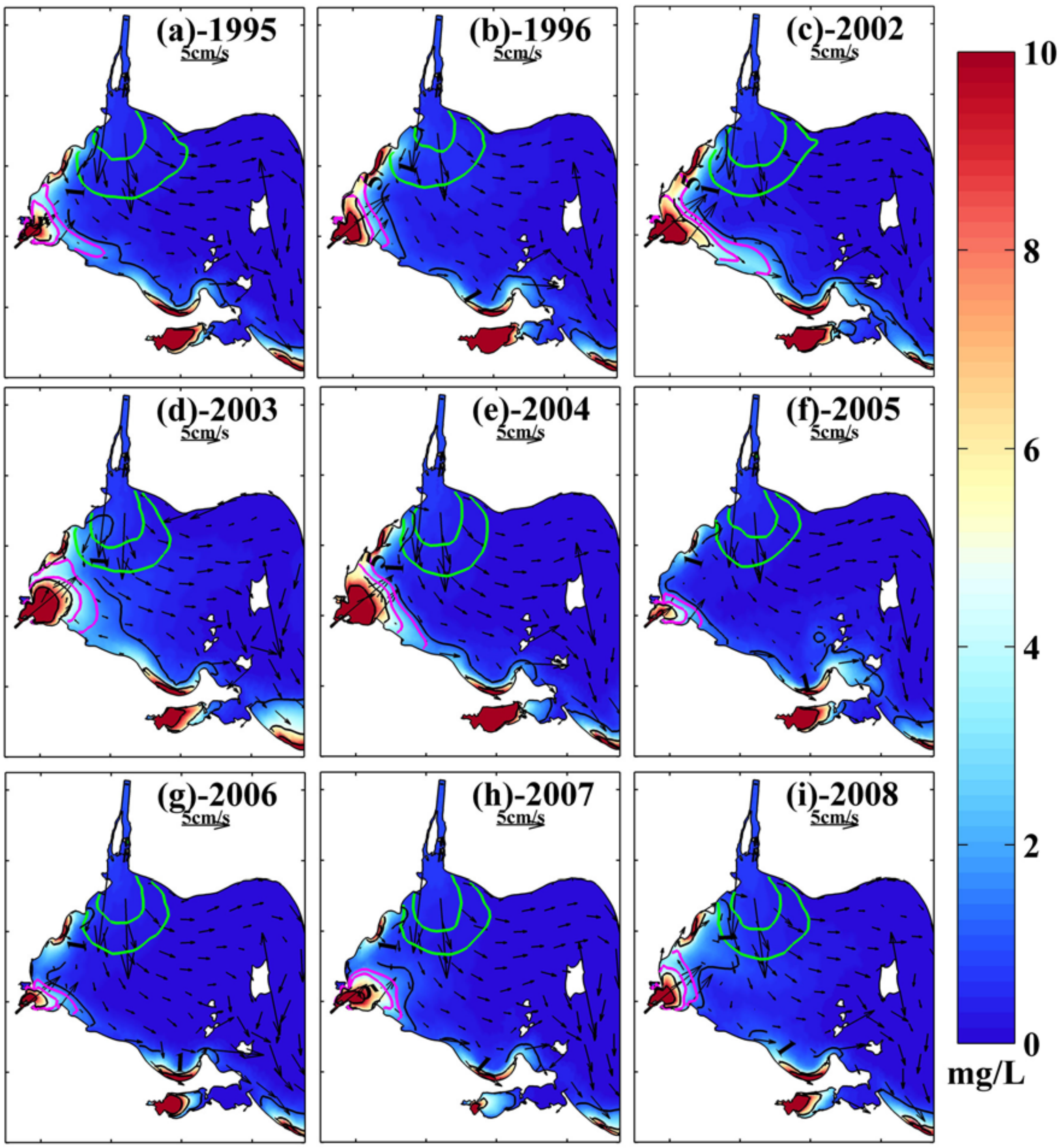


***Figure Ap2-7.*** *Bias in the surface sediment concentration and depth-averaged circulation in the western basin during the springs of years 1995, 1996, and 2002 to 2008. (Realistic-Without Wave Dynamics)*

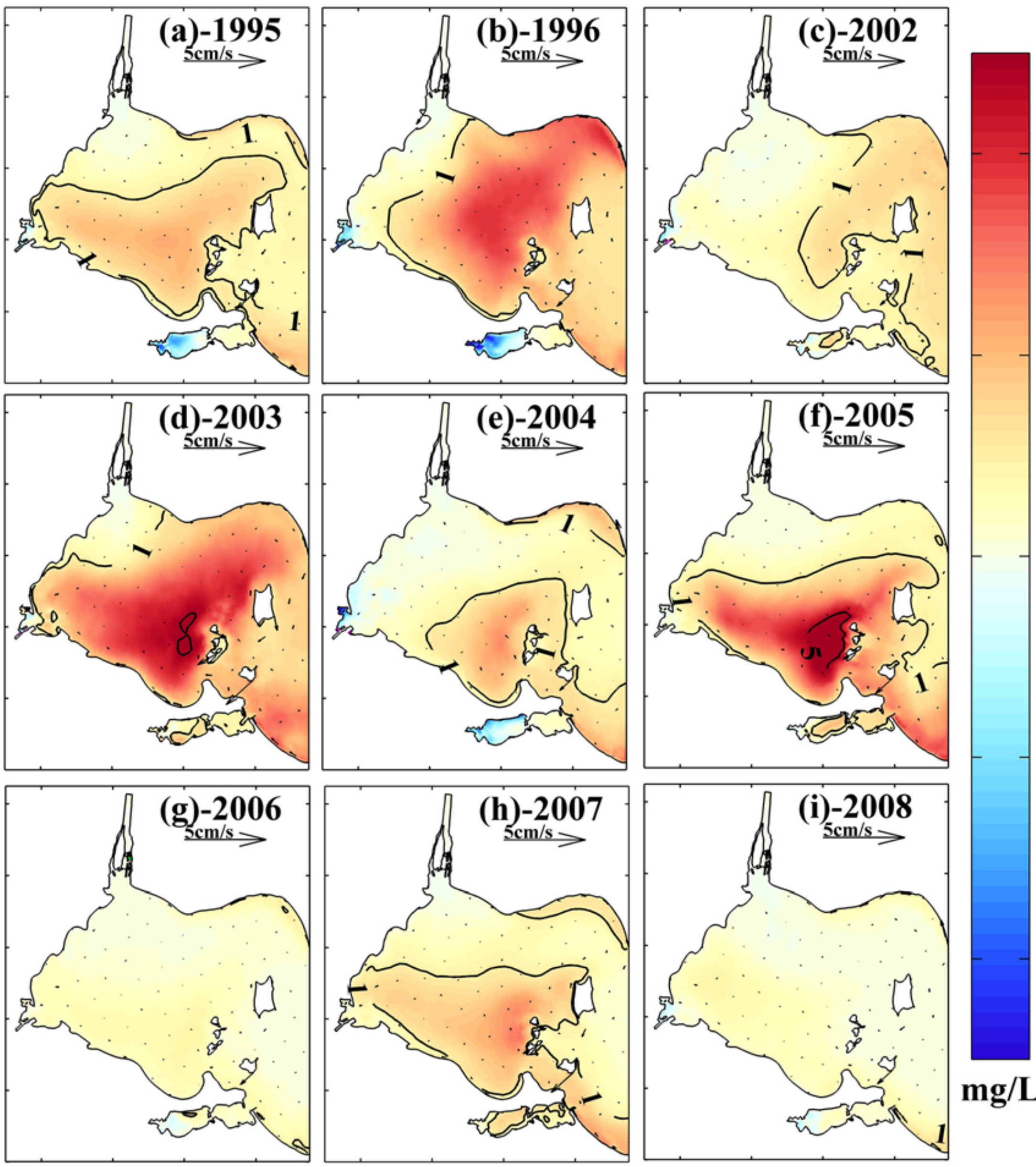


*Figure Ap2-8.* *Surface sediment concentration and depth-averaged circulation in the western basin during the springs of years 1995, 1996, and 2002 to 2008, with the exclusion of Detroit sediment loading (case C7).*

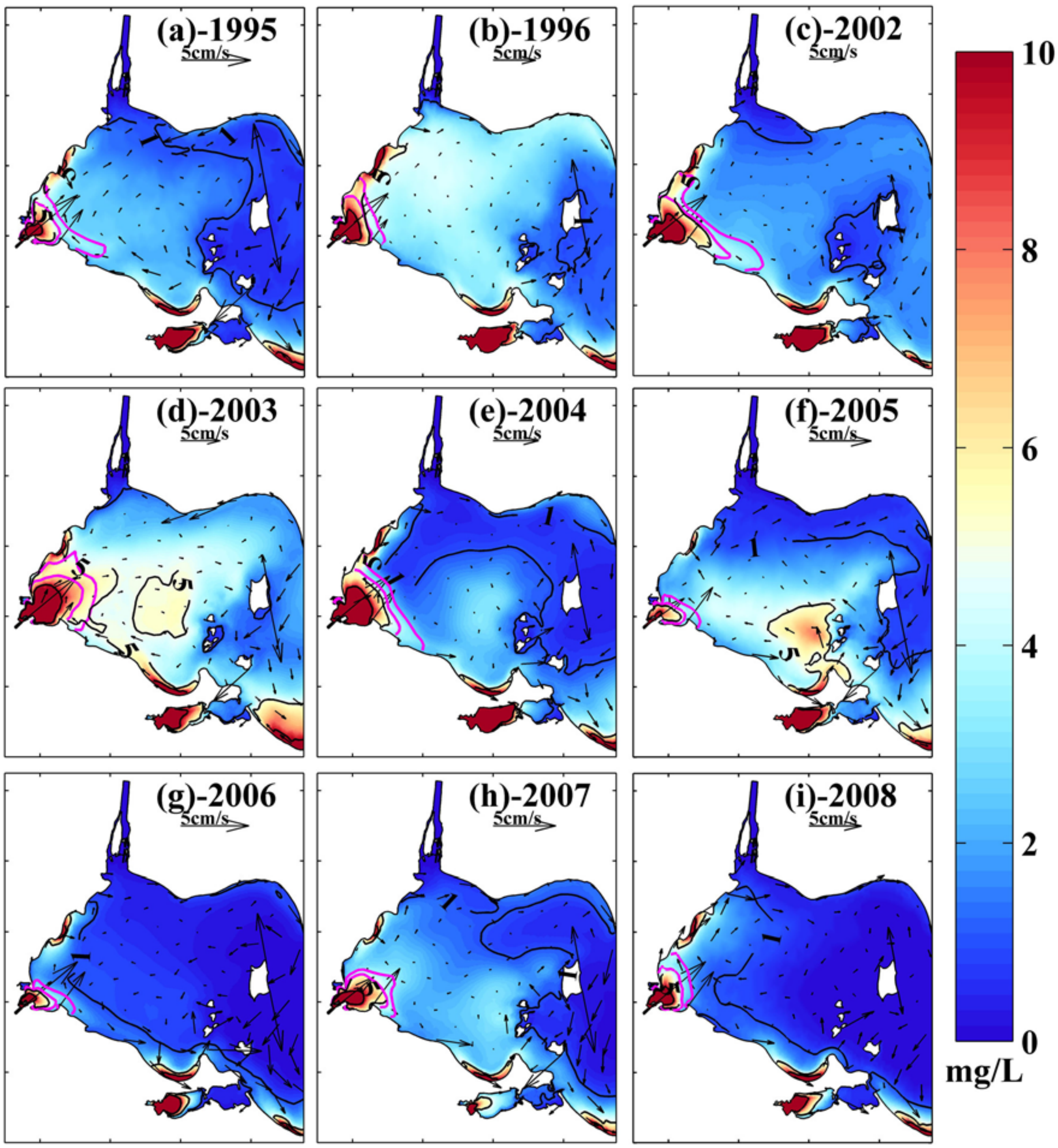
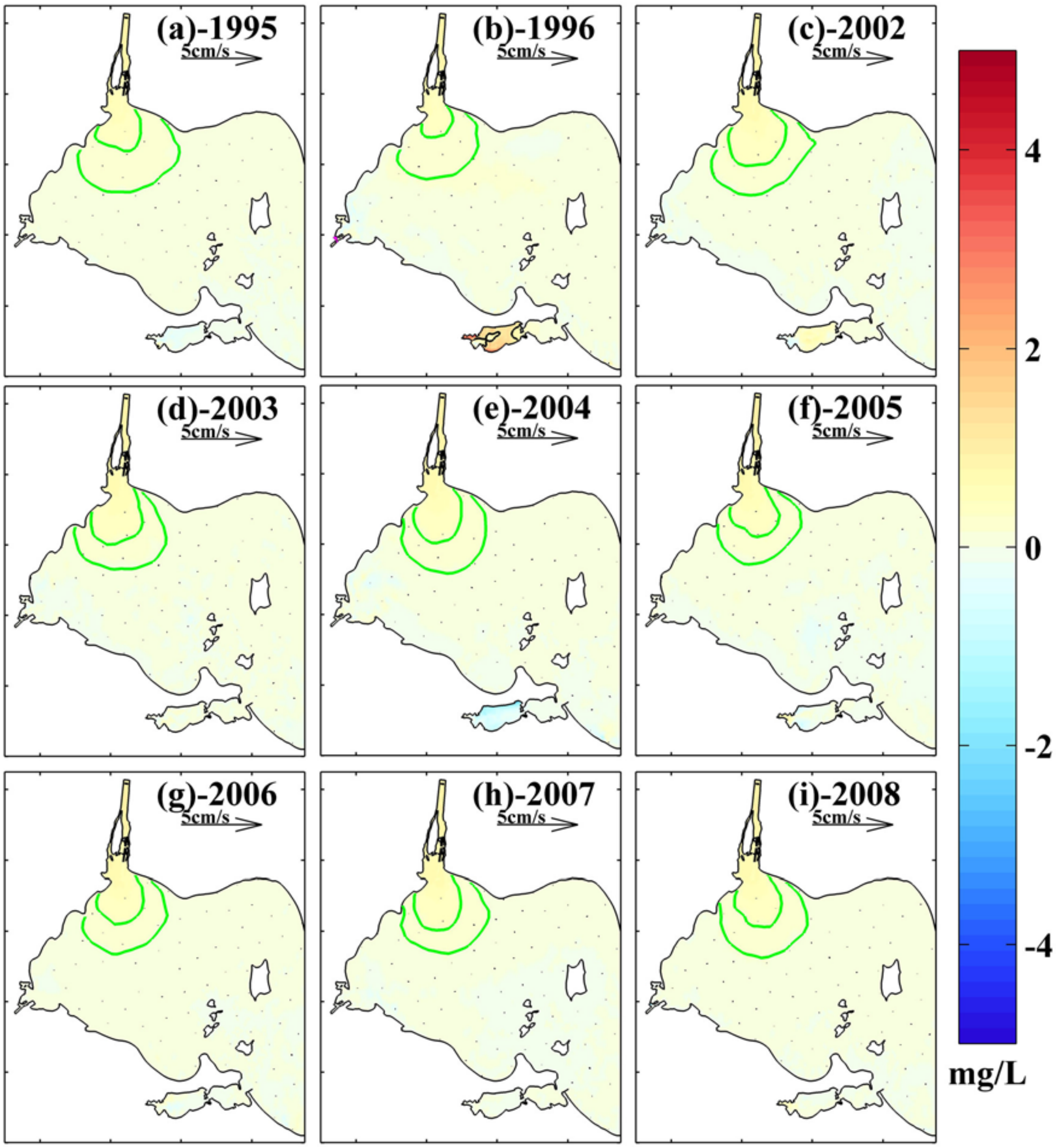


***Figure Ap2-9.*** *Bias in the surface sediment concentration and depth-averaged circulation in the western basin during the springs of years 1995, 1996, and 2002 to 2008. (Realistic-Without Detroit Sediment Loading)*



**APPENDICES:**

**APPENDIX 1:**

**Journal:** Ecological Modeling, In review.

**Title**: Biophysical modeling assessment of the drivers for plankton dynamics in western Lake Erie.

**Authors**: Jiang L., Xia M., Ludsin S.A., Rutherford E.S., Mason D.M., Marin Jarrin J.R., Pangle K.L.

Given that phytoplankton and zooplankton communities have served as key ecological indicators of anthropogenic and other perturbations, a high-resolution Finite Volume Coastal Ocean Model (FVCOM) based Integrated Compartment Model (FVCOM-ICM) was implemented to investigate the plankton dynamics with the inclusion of dreissenid invasion in Lake Erie, particularly in the most productive western basin. After identifying suitable horizontal and vertical resolutions that allowed for accurate depiction of in-lake nutrient concentrations and plankton biomass, we explored how variation in nutrient (phosphorus, nitrogen) loading and dreissenid mussel biomass could influence plankton dynamics. Our scenario-testing showed that western Lake Erie's phytoplankton community appeared more limited by phosphorus than nitrogen on both seasonal and interannual scales with light limitation occurring in the nearshore and Maumee River plume areas. Dreissenid mussel impacts varied temporally, with phytoplankton communities being highly influenced by dreissenid nutrient excretion at times (under low nutrient availability) and dreissenid grazing at other times (under bloom conditions). It was concluded that the effect of zooplankton predation on phytoplankton was stronger than that of dreissenid mussels, and that multiple algal groups could promote the efficiency of nutrient assimilation and the overall planktonic production. Additionally, river inputs and wind-driven water circulation were important by causing heterogeneity in habitat conditions through nutrient advection and vertical mixing, and wind-induced surface waves could result in non-negligible effects on phytoplankton and zooplankton dynamics.

**APPENDIX 2:**

**Journal:** Journal of Great Lakes Research, Accepted

**Title**: Influence of habitat heterogeneity on the foraging ecology of first feeding yellow perch larvae, *Perca flavescens*, in western Lake Erie.

**Authors**: Marin Jarrin J.R., Pangle K.L., Reichert J.M., Johnson T.B., Tyson J., Ludsin S.A.

The diet of first-feeding fish larvae can influence their future growth and survival. The foraging ecology of yellow perch (YP) larvae was studied in western Lake Erie, a region characterized by habitat heterogeneity associated with the Maumee River Plume (MRP) and a high prevalence of invasive species. To determine the influence of the MRP on YP foraging, we compared water physical characteristics, the zooplankton prey community, and larval YP diet and foraging selectivity between MRP and non-MRP waters, 2006-2008. Water temperature was higher, while water clarity was lower in the MRP when compared to non-MRP waters. The zooplankton prey community (groups constituting >1 % of YP prey items) did not differ between MRP and non-MRP waters, being composed of small cladocerans, cyclopoid and calanoid copepods, and non-native dreissenid mussel veligers. Ration increased with YP total length, with no differences found between MRP and non-MRP waters. Diet composition also varied with larval YP length, with smallest larvae preying more heavily on dreissenid veligers than larger fish, and no differences between MRP and non-MRP waters. Most sizes of larvae positively selected for cyclopoid copepods in MRP and non-MRP waters, whereas selection for other prey was neutral or negative. Our study reveals a similar zooplankton community and larval foraging ecology between MRP and non-MRP waters during spring season, despite habitat physical differences, and points to mechanisms unassociated with larval foraging (e.g., predation) as a reason for higher recruitment of YP residing inside versus outside of the MRP as larvae.

**APPENDIX 3:**

**Journal:** Canadian Journal of Fisheries and Aquatic Sciences, In Preparation

**Title**: Evaluation of predictive ecological models for larval fish

**Authors**: Marin Jarrin J.R., Ludsin S.A., Pangle K.L.

Fish growth and length during early life stages can strongly influence the probability of survival to adulthood. Because of their importance, several methods have been employed to study and estimate these parameters; however, the forecast accuracy of these approaches has rarely been evaluated. In the present study, the prediction accuracy of three different models used to estimate diet composition, stomach content biomass, growth rates and length of yellow perch (YP) larvae (<15 mm in length) in western Lake Erie (USA-Canada) were evaluated and compared. These models were (1) a general Individual-Based Model (IBM) for YP larvae, (2) a modified version of the general IBM that uses western Lake Erie data, and (3) general linear models developed using western Lake Erie data. To develop and evaluate these models several environmental variables were measured, and the potential prey, YP larvae and potential predators sampled during 2006-2008. Models 2 and 3 were developed using data on diet composition, stomach content biomass and growth rates from larvae collected in 2006 and 2008. The three models were then evaluated using 2007 data. In the evaluation process, all models tended to underestimate observed values, except for the general IBM which appeared to randomly over- and underestimate growth values and the linear model which underestimated fish length when larvae were < 8mm. On average, predictions from the general linear models were 17 % closer to observed values than those obtained with the two IBMs. These differences were potentially due to the flexibility of linear models which allowed the inclusion of turbidity and abundance of predators while the IBMs did not. Based on these results, we conclude that despite the current popularity of IBMs, general linear models that include local physical and biological data may provide better estimates of fish growth and length.

**APPENDIX 4:**

**Journal:** Ecological Applications, In preparation

**Title**: Combining particle tracking models and otolith chemistry to study the swimming behavior of larval fish in the Great Lakes

**Authors**: Marin Jarrin J.R., Ludsin S., Xia M., Mason D., Rutherford E., Pangle K.

Dispersal can influence the population dynamics of animal and plant species that exhibit free propagules as an early life stage. In freshwater, larval fish are often considered too small for their movements to affect its distribution; however, evidence from the marine literature suggests that limited swimming capabilities can influence their advection. In the western basin of Lake Erie, USA-Canada, Yellow Perch larvae (YP, *Perca flavescens*, <20 mm in length) can inhabit the Maumee River plume (MRP) for up to 30 days, where they experience lower predation pressure than in surrounding waters. At present it is unclear how larval YP are able to remain within the plume. To study the swimming behavior of larval YP, a hydrodynamics and particle trajectory model, and empirical information on fish age and present and past habitats obtained from otolith analysis were used. Forward tracking trajectory models were conducted for 30 days under five scenarios: (a) no swimming behavior, swimming in (b) random directions, towards the (c) top and (d) bottom of the water column, and (e) the Maumee River mouth to determine which would allow particles to remain in the plume for a longer period of time. To further test these results, back-tracking trajectory models were then conducted to determine the hatching locations of larval YP (15 – 33 days old) that had inhabited the MRP under two scenarios: passive and whichever active swimming behavior increased the time particles would reside in the plume. In both forward and back-tracking model exercises, particles that swam towards the mouth of the Maumee River remained in the plume for a longer period of time than any of the other scenarios. These results suggest that despite their small size and fast water currents encountered, larval YP exhibit active swimming behavior. Therefore, because larvae that inhabit the MRP have higher survival rates than non-MRP fish, active swimming behavior may play an important role in YP population dynamics in western Lake Erie. Due to the large number of Great Lakes species with similar early life history ecology, further work should be conducted on the swimming behavior of freshwater larval fish.

**APPENDIX 5:**

**Journal:** Journal of Geophysical Research-Oceans, In review

**Title**: Investigation of inter-basin exchange and inter-annual variability in Lake Erie using an unstructured-grid hydrodynamic model

**Author:** Niu Q., Xia M., Rutherford E., Mason D., Anderson E.J., Schwab D.J.

With the help of a three-dimensional, unstructured-grid based Finite Volume Coastal Ocean Model (FVCOM) and its surface WAVE, or FVCOM-SWAVE model, inter-annual Lake Erie dynamics were investigated between its three basins. The was calibrated through improving the existing FVCOM overheating issue in the eastern basin (EB), and also considering the source of wind forcing and horizontal grid resolution. Based on the calibrated model, how lake dynamics responded to major external forcing, including major river inflows and atmospheric forcing, and wave dynamics were also given discussion. Most importantly, key mechanisms for dominating the inter-basin water exchange and interannual variability of lake's hydrodynamics were found, and the seasonal climatological circulation patterns were presented and compared with the observational data and existing model results. It was found that water exchange from the western basin (WB) to the central basin (CB) was mainly driven by hydraulic flows, while density-driven flows dominated the interaction of the CB and EB. The influence of surface wind forcing to these processes were through shifting the pathway of hydraulic flow in the WB, and its contribution to thermal mixing. Meanwhile, the westward transport in the lake was deferred by the eastward hydraulics flows in the lake. Interannual variability was mainly driven by surface heat flux and wind forcing, and has more variation in CB. We found high-resolution horizontal grids and wave-current interaction (WCI) had major impacts on reproducing dynamics in the nearshore and coastal lake dynamics.

**APPENDIX 6:**

**Conference:** Joint Aquatic Science Meeting, Portland, Oregon., 06/02/2013-06/06/2013

**Title**: Combining particle tracking models and otolith chemistry to study the swimming behavior of larval Yellow Perch in western Lake Erie

**Authors**: Marin Jarrin J.R., Pangle K., Xia M., Ludsin S., Mason D., Rutherford E.

Swimming behavior can impact the direction and magnitude of plankton transport and dispersal. We evaluated the importance of swimming behavior to dispersal of larval Yellow Perch (YP) in western Lake Erie, a region characterized by habitat heterogeneity created by the Maumee River Plume (MRP). MRP waters have a distinct, temporally stable chemistry signature that is imprinted in larval YP otoliths inhabiting the plume. Using otolith chemistry and spatial distribution data, we determined that many larval YP (<33 days) found in MRP had inhabited the plume throughout their life. Using these observations, we ran particle tracking models under different behavior scenarios to determine how they were able to stay in the MRP. We found that modeled larvae that followed simple behaviors (i.e., swim towards river mouth) were able to stay within the plume, whereas those treated as passive particles or swam in random directions were advected from the plume. Because larval YP that inhabit the MRP have lower mortality rates than non-MRP fish, our results suggest that active swimming behavior plays an important role in fish surviving to the juvenile stage.

**APPENDIX 7:**

**Conference:** 56th Annual Conference of the International Association for Great Lakes Research, West Lafayette, Indiana, 06/02/2013-06/06/2013

**Title**: Linking river discharge and wind-driven currents to the success of larval yellow perch in western Lake Erie: working through assumptions and unknowns.

**Authors**: Marin Jarrin J.R., Pangle K., Xia M., Ludsin S., Mason D., Rutherford E.

Yellow perch (*Perca flavescens*) is an economically and ecologically important species across the Great Lakes that exhibits highly variable recruitment. In western Lake Erie, this variability appears to be driven largely by the Maumee River plume, which creates advantageous habitat for larvae. To better understand the processes underlying this plume effect, we used field observations and an individual-based, coupled physical-biological model to *i*) evaluate the effects of river discharge and wind-driven currents on the creation and expansion of high-quality nursery habitat and *ii*) examine the role of water currents in moving larvae into and out of the plume. We found that high discharge events did not always lead to a large plume, due to a strong interaction between discharge and open-lake circulation. Further, rather than facilitating larval retention, currents were predicted to passively advect larvae out of the plume at surprisingly high rates. Predicted residency durations (< 2 weeks) were shorter than observed residency durations (> 1 month) estimated using otolith microchemistry of larvae collected from within the plume. The discrepancy suggests that active movement behavior allows larvae to remain within plumes. We discuss the implications of these findings to understanding fish recruitment both in Lake Erie and beyond.

**APPENDIX 8:**

**Conference:** 2014 Marine Estuary and Environmental Science Colloquium, Solomons, Maryland, 10/24/2014-10/25/2014.

**Title:** Dynamics of Spring Sediment Plume and Summer Circulation in Lake Erie

**Authors:** Niu, Q., Xia, M.

Sediment plumes are of great implications to the biochemical and ecological dynamics in the receiving water bodies. The western basin of Lake Erie has long been recognized as the most turbid basin among the Great Lakes, and is experiencing intermittent occurrences of harmful algal blooms. The interannual variability of sediment plumes in the western basin during spring was investigated. It was found that areas adjacent to the Maumee River mouth and at the southern part of the western basin have high interannual variability in sediment dynamics.

Lake circulation plays significant role in material transport and redistribution. Driven mechanisms of summer circulation in the whole Lake Erie were investigated. During summer, circulation in the western basin is driven by hydraulic flows and surface wind forcing; circulation in the central basin is dominated by surface forcing and baroclinic processes; and the cyclonic gyre in the eastern basin is driven by the baroclinic processes.

**APPENDIX 9:**

**Conference:** 41st Annual Mid-Atlantic Bight Physical Oceanography and Meteorology, Gloucester Point, Virginia, 10/30/2014-10/31/2014

**Title:** Dynamics of Spring Sediment Plumes in the Western Lake Erie

**Authors:** Niu, Q., Xia, M.

Sediment plumes are of great implications to the biochemical and ecological dynamics in the receiving water bodies. The western basin of Lake Erie has long been recognized as the most turbid basin among the Great Lakes, and is experiencing intermittent occurrences of harmful algal blooms. The sediment plumes in the basin are mainly from three sources: the loading of Maumee River (1.8 million tons/year), the loading of Detroit River (1.2 million tons/year), and the in-situ sediment resuspension. Both the horizontal patterns and vertical structures of these plumes were investigated. It was found that the local surface wind forcing dominated the dynamics of both the Detroit and Maumee River plumes. Baroclinic processes played important role in the dynamics of the Detroit River plume as well, especially for those during summer. Also, the Maumee River plume tended to be suppressed to the southern part of the basin due to the strong hydraulic flows from the Detroit River. The resuspended sediment plume was mainly driven by the combined effects of surface gravity waves and wind-driven currents, and it was slightly influenced by the baroclinic processes during summer.

**APPENDIX 10:**

**Conference:** 2013 Marine Estuary and Environmental Science Colloquium, Cambridge, Maryland, 09/27/2013-09/28/2013

**Title:** Application of a finite volume coastal ocean model to Lake Erie

**Authors:** Niu, Q., Xia, M., Schwab, D.

Lake Erie experiences the most severe environmental problems among the Great Lakes. A sound hydrodynamic model is the backbone for further study of ecological and fishery processes. In this study, a three-dimensional, unstructured-grid, Finite Volume Costal Ocean Model (FVCOM) is applied to simulate spatial and temporal variation of key physical processes in Lake Erie.

The model is calibrated and validated using available historical measurements at different sites from the International Field Years on Lake Erie (IFYLE) project and the 'tides and current' project from National Oceanic and Atmospheric Administration (NOAA). Water elevation and the current velocity are consistent with the observed data from these projects. In order to eliminate the deficiency of overheating of bottom water mass associated with sigma-coordinate models (Bai et al. 2013, Wilson et al. 2013), we modified interlayer thermal advection and intralayer horizontal diffusion. With the modification, the overheating problem is alleviated and the basic thermal structure is better simulated.

Model experiments of the boundary condition at Detroit River show that with flow boundary, instead of open boundary, the flow out of western basin and around the river mouth of Niagara River is enhanced. The influence of resolution of horizontal grids in western basin has been tested with Detroit River as the flow boundary. It turns out that the resolution of horizontal grids in western basin influences the flow pattern not only in western basin, but also in the whole lake, especially during the summer.

In future work, FVCOM will be coupled with FVCOM-SWAVE (an unstructured-grid, finite-volume surface wave model) and FVCOM-SED (a three dimensional sediment transport module included in FVCOM) in order to understand the wave-current-interaction system and its impact on sediment transportation in Lake Erie.

**APPENDIX 11:**

**Conference:** 2014 University of Maryland Eastern Shore Regional Research Symposium, Princess Anne, Maryland, 04/16/2014

**Title:** Application of a finite volume coastal ocean model to Lake Erie

**Authors:** Niu, Q., Xia, M., Schwab, D.

Different partitions of Lake Erie experience various environmental issues, including harmful algae blooms and oxygen depletion. To better understand the hydrodynamic background of these problems, a three-dimensional, unstructured-grid based Finite Volume Costal Ocean Model (FVCOM), combining with FVCOM-Surface WAVE (FVCOM-SWAVE) model, was applied to investigate dynamics of physical processes in Lake Erie. Model was calibrated for elimination of pressure gradient error, grid resolution and surface wind forcing, and showed a good skill in simulation of water elevation, water temperature, current velocity and surface gravity waves. Model's sensitivity to topography, Long Point spit, wind stress curl and wave-current interaction was further examined. The results show that topographic effect is substantial for circulation in deep eastern Lake Erie, while that of central basin is dominated by wind stress curl. Long Point Spit has profound impacts on dynamics in eastern basin during stratified period and gust events. Wave-current interaction is significant on nearshore currents during episodic events. During certain period, it also contributes to mixing within epilimnion when the lake is stratified.

**APPENDIX 12:**

**Conference:** 2014 Chesapeake Modeling Symposium, Annapolis, Maryland, 05/28/2014-05/29/2014.

**Title:** Application of a finite volume coastal ocean model to Lake Erie

**Authors:** Niu, Q., Xia, M., Schwab, D.

A three-dimensional, unstructured-grid based finite-volume coastal ocean model (FVCOM) is applied to study dynamics of physical processes in Lake Erie. A preliminary solution was raised to eliminate spurious heat transfer in sloping regions. Model was calibrated for horizontal grid resolution and specifications of wind forcing. Significance of wave current interaction processes and geographic features, including rivers and the intrusion of Long Point Spit, to the lake's physical structures was investigated.

**APPENDIX 13:**

**Conference:** $144^{th}$ American Fisheries Society Annual Meeting, Quebec City, Canada 05/28/2014-05/29/2014.

**Title:** Combining particle tracking models and otolith chemistry to study the swimming behavior of larval Yellow Perch in western Lake Erie.

**Authors:** Pangle K., Marin Jarrin J.R., Xia M., Ludsin S., Mason D., Rutherford E.

Swimming behavior can impact the direction and magnitude of plankton transport and dispersal We evaluated the importance of swimming behavior to dispersal of larval Yellow Perch (YP) in western Lake Erie, a region characterized by habitat heterogeneity created by the Maumee River Plume (MRP) MRP waters have a distinct, temporally stable chemistry signature that is imprinted in larval YP otoliths inhabiting the plume Using otolith chemistry and spatial distribution data, we determined that many larval YP (<33 days) found in MRP had inhabited the plume throughout their life Using these observations, we ran particle tracking models under different behavior scenarios to determine how they were able to stay in the MRP We found that modeled larvae that followed simple behaviors (ie, swim towards river mouth) were able to stay within the plume, whereas those that were treated as passive particles or swam in random directions were advected from the plume Thus, observed patterns in otolith chemistry could not be explained without consideration for active, orientated movement Because larval YP that inhabit the MRP have lower mortality rates than non-MRP fish, our results suggest that active swimming behavior plays an important role in fish surviving to the juvenile stage

**APPENDIX 14:**

**Conference:** 13th International Conference on Estuarine and Coastal Modeling, San Diego, California, 11/01/2013-11/06/2013

**Title**: The application of an unstructured based bio-physical model to Lake Erie

**Authors**: Xia, M., Niu, Q., Cao, Z., Jiang, L., Rutherford, E., Schwab, D., Anderson, E., Pangle, K., Marin Jarrin, J.R., Ludsin, S., Mason, D.M.

Yellow perch (*Perca flavescens*; YP) is an economically and ecologically important species across the Great Lakes, which demonstrates variable recruitment to the fishery that we hypothesize is regulated by physical processes operating during early life stages. For example, Ludsin et al.'s GLFC-sponsored YP-River Discharge project has shown that Lake Erie YP recruitment success is positively correlated with Maumee River inflow and plume size during spring. However, uncertainty in predicting the distribution of these attributes, as well as their effect on movement, predation risk, consumption, growth, and survival of YP larvae in dynamic, shallow waters remains a major impediment to fully understanding and forecasting recruitment to the fishery in this system. We built a coupled biophysical model to better understand and predict YP foraging, growth, survival, and recruitment in western Lake Erie. It is widely known that nearshore and coastal water is the important region in Great Lakes and ocean and it has complex geometry of coastline, a high-resolution unstructured grid model is required for the nearshore region. So an extant three-dimensional, wave-current, coupled Finite Volume Coastal Ocean Model (FVCOM) was used to simulate water movement in Lake Erie, particularly the western Lake Erie and its tributaries. In this study, we also present the improved water quality model and theirs application to Lake Erie. We will evaluate the interactive effects of river discharge and wind-driven currents on the plume and nutrient, phytoplankton and zooplankton distribution which are important to the creation and expansion of high-quality nursery habitat. The Erie model is also coupled with wave model or FVCOM-SWAVE to simulate the effect of waves on nearshore circulation and velocity fluctuations. The effect of wave to the nutrient/zooplankton dynamics is further investigated. We also calibrate and validate the model using physical (e.g., temperature, water clarity, currents) and biological (e.g., zooplankton, nutrient) data collected in western Lake Erie via prior GLFC-sponsored research and agencies (e.g., ODNR, OMNR). Several methods to estimate the Detroit inflow have been given discussion because the inflow form Detroit River is crucial to the Western Lake Erie circulation. It was concluded that river discharge and wind have strong influence on the nearshore and lake circulation as we the plume dynamics, and they also influence the nutrient and zooplankton transport. Detailed results and model development will be given this this presentation. This model will also be potentially linked to a model of larval YP movement, foraging, growth, and survival. Few studies have been conducted to explore how physical factors influence transport and survival of fish larvae in nearshore environments of the Great Lakes. We will be using the model to test hypotheses about the influence of physical factors on larval YP transport and recruitment success by analyzing patterns of fish larvae transport, growth, and survival under various conditions, including seasonal river floods, strong wind-induced wave conditions, and fluctuating prey fields. Thus, our research will shed insight into how lake physics influence fish distributions, survival rates, and population dynamics in Lake Erie and other Great Lakes nearshore environments in the future.

**APPENDIX 15:**

**Conference:** 57th Annual Conference on Great Lakes Research, Hamilton, Ontario, 05/26/2014-05/30/2014

**Title**: The application of an unstructured based bio-physical model to Lake Erie

**Authors**: Xia, M., Niu, Q., Jiang, L., Rutherford, E., Schwab, D., Anderson, E., Pangle, P., Marin Jarrin, J.R., Ludsin, S., Mason, D.M.

Yellow perch (*Perca flavescens*; YP) is an economically and ecologically important species across the Great Lakes, which demonstrates variable recruitment to the fishery that we hypothesize is regulated by physical processes.

To help understand the recruitment, a coupled biophysical model was built to better hindercast/forecast the hydrodynamics and water quality in western Lake Erie. An extant three-dimensional, wave-current, coupled Finite Volume Coastal Ocean Model (FVCOM) was used to simulate water movement in Lake Erie, particularly the western Lake Erie. In additional, we also present the improved water quality model and theirs application. We will evaluate the interactive effects of river discharge and wind-driven currents on the plume and nutrient, phytoplankton and zooplankton distribution which are important to the creation and expansion of high-quality nursery habitat. The Erie model is also coupled with wave model or FVCOM-SWAVE to simulate the effect of waves on nearshore circulation and velocity fluctuations. The effect of wave to the nutrient/zooplankton dynamics is further investigated. We also calibrate and validate the model using physical (e.g., temperature, water clarity, currents) and biological (e.g., zooplankton, nutrient) data collected in western Lake Erie.

Several methods to estimate the Detroit inflow have been given discussion because the inflow form Detroit River is crucial to the Western Lake Erie circulation. It was concluded that river discharge and wind have strong influence on the nearshore and lake circulation as we the plume dynamics, and they also influence the nutrient and zooplankton transport. Detailed results and model development will be given this this presentation.
This model will also be potentially linked to a model of larval YP movement, foraging, growth, and survival. Few studies have been conducted to explore how physical factors influence transport and survival of fish larvae in nearshore environments of the Great Lakes. We will be using the model to test hypotheses about the influence of physical factors on larval YP transport and recruitment success by analyzing patterns of fish larvae transport, growth, and survival under various conditions, including seasonal river floods, strong wind-induced wave conditions, and fluctuating prey fields. Thus, our research will shed insight into how lake physics influence fish distributions, survival rates, and population dynamics in Lake Erie and other Great Lakes nearshore environments in the future.

**APPENDIX 16:**

**Conference:** IMBER Future Oceans conference, Bergen, Norway, 06/23/2014-06/27/2014

**Title**: The development of an unstructured based bio-physical model to Lake Erie yellow perch recruitment

**Authors**: Xia, M., Niu, Q., Jiang, L., Rutherford, E., Schwab, D., Anderson, E., Pangle, K., Marin Jarrin, J.R., Ludsin, S., Mason, D.M.

Yellow perch (*Perca flavescens*; YP) is an economically and ecologically important species across the Great Lakes, which demonstrates variable recruitment to the fishery that we hypothesize is regulated by physical processes operating during early life stages. For example, Ludsin et al.'s GLFC-sponsored YP-River Discharge project has shown that Lake Erie YP recruitment success is positively correlated with Maumee River inflow and plume size during spring. However, uncertainty in predicting the distribution of these attributes, as well as their effect on movement, predation risk, consumption, growth, and survival of YP larvae in dynamic, shallow waters remains a major impediment to fully understanding and forecasting recruitment to the fishery in this system.

We built a coupled biophysical model to better understand and predict YP foraging, growth, survival, and recruitment in western Lake Erie. It is widely known that nearshore and coastal water is the important region in Great Lakes and ocean and it has complex geometry of coastline, a high-resolution unstructured grid model is required for the nearshore region. So an extant three-dimensional, wave-current, coupled Finite Volume Coastal Ocean Model (FVCOM) was used to simulate water movement in Lake Erie, particularly the western Lake Erie and its tributaries. In this study, we also present the improved water quality model and their application to Lake Erie. We will evaluate the interactive effects of river discharge and wind-driven currents on the plume and nutrient, phytoplankton and zooplankton distribution which are important to the creation and expansion of high-quality nursery habitat. The Erie model is also coupled with wave model or FVCOM-SWAVE to simulate the effect of waves on nearshore circulation and velocity fluctuations. The effect of wave to the nutrient/zooplankton dynamics is further investigated. We also calibrate and validate the model using physical (e.g., temperature, water clarity, currents) and biological (e.g., zooplankton, nutrient) data collected in western Lake Erie via prior GLFC-sponsored research and agencies (e.g., ODNR, OMNR). Overall, we found the Erie bio-physical simulation is highly sensitive to the model grid resolution; the circulation is highly sensitive to the boundary condition types; and wave is very critical to the circulation pattern, particularly under some episodes.

This model will be linked to a model of larval YP movement, foraging, growth, and survival. Few studies have been conducted to explore how physical factors influence transport and survival of fish larvae in nearshore environments of the Great Lakes. We will be using the model to test hypotheses about the influence of physical factors on larval YP transport and recruitment success by analyzing patterns of fish larvae transport, growth, and survival under various conditions, including seasonal river floods, strong wind-induced wave conditions, and fluctuating prey fields. Thus, our research will shed insight into how lake physics influence fish distributions, survival rates, and population dynamics in Lake Erie and other similar water bodies in the future.