Modeling summer circulation and thermal structure of Lake Erie

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[1] A three-dimensional primitive equation numerical model was applied to Lake Erie on a 2 km grid to study its summer circulation and thermal structure. Model results were compared to long-term observations of currents and temperature made in 2005 at several locations, mostly in its central basin. In the shallow and mostly unstratified western basin circulation is driven by Detroit River inflow (modified to some extent by wind) and is from west to east. In the central basin (which is of intermediate depth and has a relatively flat bottom), the modeled circulation is anticyclonic (clockwise), driven by anticyclonic vorticity in the surface wind, and the thermocline is bowl-shaped, in line with observations. In the deep part of the eastern basin, the thermocline is dome-shaped and circulation is cyclonic (counter-clockwise), due to density gradients (a configuration typical for other large deep lakes), while shallower areas are occupied by anticyclonic circulation driven by anticyclonic wind vorticity. In the central basin, modeled temperature and circulation patterns are quite sensitive to the specification of the wind field. Anticyclonic wind vorticity leads to thinning of the hypolimnion in the central basin and earlier destratification in the fall.

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1. Introduction

[2] Lake Erie (Figure 1) is the smallest by volume of the Laurentian Great Lakes. It is about 400 km long, 90 km wide, and has three distinct basins [*Bolsenga and Herdendorf*, 1993]: a shallow western basin (mostly less than 10 m deep), a deep eastern basin (maximum depth 64 m), and a relatively flat central basin (mostly 20–25 m deep), which is the largest by surface area. Lake Erie is positioned downstream of the three largest Great Lakes (Superior, Michigan, and Huron); their waters enter from Lake Huron (via Lake St. Clair) at its western end (Detroit River) and exit via the Niagara River into Lake Ontario in the east. Despite its relatively small size, Lake Erie is large enough to feel the effects of the earth's rotation, especially in the summer when it becomes stratified (internal Rossby radius is about 5 km). Due to its relatively small volume, circulation in the lake is driven by a combination of hydraulic (tributary) flow, temperature gradients, and wind [*Simons*, 1976].

[3] Lake Erie has recently received significant attention due to exceptionally large and detrimental algal blooms [*Stumpf et al.*, 2012; *Michalak et al.*, 2013]. In addition, large areas of the lake experience hypoxia/anoxia in summer with severe negative effects to the biota [*Vanderploeg et al.*, 2009] and degradation of drinking water for municipalities. As lake scientists and resource managers work to understand the complex interplay between natural and anthropogenic factors leading to hypoxia and to develop policy recommendations for nutrient abatement programs, research on lake physics has received increased attention because physical processes often play a critical role in ecosystem functioning. For instance, hypoxia is commonly linked to lake thermal structure [*Burns et al.*, 2005; *Rao et al.*, 2008; *Vanderploeg et al.*, 2009], while circulation patterns determine transport paths of nutrients and anthropogenic pollutants [*Schwab et al.*, 2009; *Raikow et al.*, 2010].

[4] Accurate modeling of lake hydrodynamics is a prerequisite to successful application of 3-D ecological [*Pauer et al.*, 2011] or particle transport models [*Beletsky et al.*, 2007]. While various hydrodynamic models have been applied to Lake Erie in the past [*Simons*, 1976; *Schwab and Bennett*, 1987; *O'Connor et al.*, 1999], it has recently become clear that they only partially described its thermal regime and circulation patterns. Modeling studies in the last decade took only a cursory look at summer hydrodynamics because of their focus on either ice processes [*Wang et al.*, 2010; *Fujisaki et al.*, 2012], ecological aspects [*Leon et al.*, 2005; *Schwab et al.*, 2009], particle transport [*Prakash et al.*, 2007], or hydrodynamic forecasting [*Dupont et al.*, 2012]. In addition, inclusion of hydraulic flow (absent in some applications) is necessary for correct description of circulation in the western basin and nutrient transport in the lake overall.

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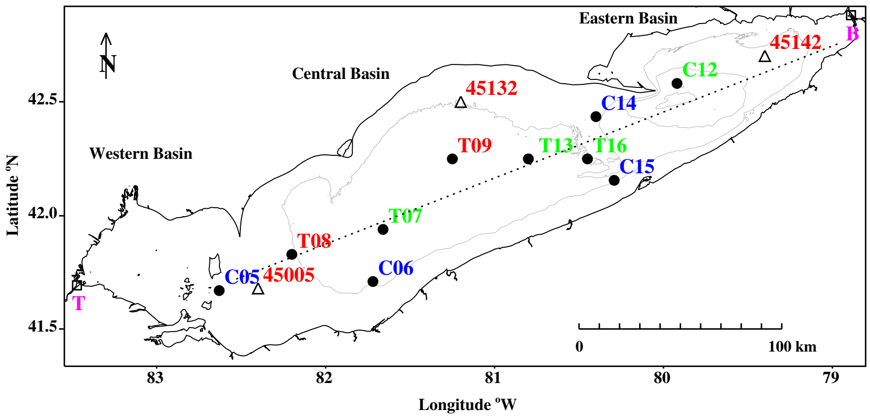

Figure 1. Lake bathymetry and mooring locations (filled circles). Red color—temperature observations, blue—current observations, green—both temperature and current observations in 2005. Isobaths shown every 20 m. NOAA (45005) and Environment Canada (45132 and 45142) buoy locations are shown with triangulars, water level gauges are shown by rectangulars (T-Toledo, B-Buffalo). Dotted line shows model transect. Short transect is bounded by 20 m isobath (between moorings T08 and T16).

[5] Significant efforts to improve the understanding of Lake Erie hydrodynamics were recently undertaken as part of the NOAA ECOFORE (Ecological Forecasting) program, which is studying the dynamics and interannual variability of hypoxia in Lake Erie using linked hydrodynamic and ecological models (http://sitemaker.umich.edu/ecoforelake.erie/home). The data for hydrodynamic model validation were collected as part of the US-Canada IFYLE (International Field Years on Lake Erie) program [*Hawley et al*., 2006] from an array of moorings deployed mostly in the central basin in areas 20–25 m deep in 2005. More limited field measurements were also conducted in 2004 and 2007. A particular emphasis was put into understanding the dynamics and evolution of the summer thermocline—a region of strong vertical gradients of temperature separating surface waters (epilimnion) from bottom waters (hypolimnion). Analysis of IFYLE data revealed anticyclonic circulation and a bowl-shaped thermocline in the central basin driven by anticyclonic wind vorticity [*Beletsky et al*., 2012]. On the other hand, historic water temperature data supported by limited current observations [*Hamblin*, 1971; *Mortimer*, 1987], showed that in the deeper eastern basin, the thermocline is dome-shaped, suggesting a cyclonic circulation due to geostrophy. This indicates that baroclinic mechanisms may be dominant in deeper parts of the lake.

[6] In most large thermally stratified lakes, the summer thermocline has the shape of a "dome," with shallower depth offshore than nearshore [*Church*, 1945; *Tikhomirov*, 1982; *Simons and Schertzer*, 1987]. The nearshore-offshore temperature gradients that begin to form in the spring and persist through the end of summer were previously explained by a differential heating mechanism [*Forel*, 1901; *Monismith et al*., 1990] where shallow areas warm faster than the deep ones, and also by the heat transport divergence mechanism [*Csanady*, 1977]. More recently, numerical model results [*Schwab et al*., 1995] showed that a zero heat flux at a sloping lake boundary leads to curved isotherms at the bottom and generates a dome-shaped thermocline.

[7] Another potentially important mechanism for dome-shaped thermoclines is related to Ekman transport in cyclonic surface winds. *Ragotzkie and Bratnick* [1965] hypothesized that upwelling of cold water in the center portion of Lake Superior is due to the divergence of surface Ekman transport (i.e., Ekman pumping), a phenomenon well known in oceanography [*Gill*, 1982]. More recently, *Bennington et al*. [2010] showed that cyclonic wind curl in Lake Superior produced enhanced thermally driven cyclonic circulation and should have also contributed to formation of a dome-shaped thermocline (working in concert with other dome-shape producing mechanisms). *Saylor* [1994] suggested that Ekman pumping in the bottom boundary layer generated by a cyclonic flow from above would produce mid-lake upwelling that would support dome-shaped thermocline.

[8] In addition to modifying thermocline shape through vertical motions, wind stress curl is also a major factor that governs geophysical flows [*Gill*, 1982], causing horizontal motions ranging from basin-scale oceanic gyres [*Hakkinen and Rhines*, 2009] to regional gyres comparable in size to individual Great Lakes [*Hofmann et al*., 1981]. In the coastal ocean, wind stress curl has an important effect on upwellings and mesoscale dynamics [*Huthnance*, 2002; *Fennel and Lass*, 2007]. In limnology, the importance of wind stress curl was first stressed in research in high-altitude lakes where large spatial inhomogeneity in the wind field can be generated by local orography [*Endoh*, 1986; *Strub and Powell*, 1986; *Lemmin and DAdamo*, 1996]. Recent research in the Great Lakes showed that wind stress curl is a major factor there as well, becoming dominant in winter when considerable vorticity in the wind field is present [*Schwab and Beletsky*, 2003]. The situation gets more complicated in the summer when wind curl becomes smaller but baroclinic effects increase due to developing stratification. On the other hand, spatially variable lake surface temperature affects the wind stress field and lake circulation. In particular, *Emery and Csanady* [1973] suggested that cyclonic wind stress curl due to stability dependent drag on the surface would lead the

cyclonic circulation in the lake even in the case of horizontally uniform wind. Model results in Lake Michigan however showed that this effect (or effect of wind vorticity) is less important in driving lake circulation in summer than baroclinic effects [*Schwab and Beletsky*, 2003].

[9] IFYLE observations showed that anticyclonic wind stress vorticity generates anticyclonic circulation and bowl-shaped thermocline in the central basin [*Beletsky et al.*, 2012]. It is not clear however if the same kind of circulation and thermocline is possible in the eastern basin, especially in its deeper areas where the effect of wind stress curl is opposed by mechanisms that produce dome-shape thermocline and cyclonic circulation. Hydrodynamic modeling conducted in the ECOFORE program provided us with opportunity to explore this question in some detail. In this paper, we use model results for summer 2005 (supplemented by 2004 and 2007 results) to examine some features of circulation and thermocline in the three basins of Lake Erie. A previous application of the model in Lake Michigan [*Beletsky and Schwab*, 2001] was successful in reproducing its dome-shaped thermocline and cyclonic circulation, but in order to model Lake Erie hypoxia accurately, we also need to verify that that the model reproduces the bowl-shaped thermocline and associated anticyclonic circulation, and to explore their persistence in summer. An additional motivation is to provide a comprehensive description of lake-wide circulation and thermal structure on a monthly to seasonal time scales, thoroughly validated by lake-wide, high spatial resolution observations.

[10] The main goals of this paper are: (1) to determine and explain summer (May to October) circulation and thermal structure in Lake Erie in all three basins of the lake, (2) to test the hydrodynamic model with available temperature and current observations, and (3) to provide the physical background information needed for ecological modeling. The paper is organized as follows. The hydrodynamic model is described in section 2, meteorological data are presented in section 3, model results are analyzed and compared with observations in sections 4 and 5, respectively, circulation mechanisms are discussed in section 6, and discussion and conclusions are presented in section 7.

2. Lake Erie Numerical Model

[11] A three-dimensional hydrodynamic model was used to calculate circulation and thermal structure in Lake Erie. The model is based on the Princeton Ocean Model (POM) [*Blumberg and Mellor*, 1987], which is a three-dimensional, primitive equation, hydrostatic, finite-difference model. The model uses time-dependent wind stress and heat flux forcing at the surface, free-slip lateral boundary conditions, and quadratic bottom friction. The drag coefficient in the bottom friction formulation is spatially variable. It is calculated based on the assumption of a logarithmic bottom boundary layer using depth-dependent bottom roughness that varies from 0.1 cm in deep water to 1 cm in shallow water. Horizontal diffusion is calculated with a Smagorinsky eddy parameterization (with a multiplier of 0.1) to give a greater mixing coefficient near strong horizontal gradients. The Princeton Ocean Model employs a terrain-following vertical coordinate system (sigma coordinate). The equations are written in flux form, and the finite differencing is done on an Arakawa-C grid using a control volume formalism. The finite differencing scheme is second order and centered in space and time (leapfrog).

[12] The hydrodynamic model of Lake Erie has 21 sigma levels uniformly distributed with depth (this translates into about 1 m resolution in most of the central basin and 3 m resolution in the deepest part of the eastern basin) and a uniform horizontal grid size of 2 km. Vertical and horizontal resolution was chosen based on previous model applications to other lakes and also computational demands of the ecological model that runs at the same resolution as the hydrodynamic model. We found that thermal structure results in the deep eastern basin are sensitive to the horizontal Prandtl number, so we used a value of 10 to keep deep waters in the eastern basin sufficiently cold throughout summer. We also modified the short wave radiation model used in POM (after *Paulson and Simpson* [1977]) in accordance with results of *Mccormick and Meadows* [1988] obtained for Lake Erie. The incoming short-wave radiation is split 55/45 between infrared and visual bands with extinction coefficients of 2.85 m^{-1} and 0.28 m^{-1}, respectively.

3. Forcing Functions and Model Initialization

[13] The model is forced by momentum and heat flux at the surface and tributary flow represented as current vectors at river mouths. The latter were obtained from the Advanced Hydrologic Prediction System (AHPS) [*Gronewold et al.*, 2011] for 21 major tributaries and two outflows (Welland Canal and Niagara River); the list of tributaries used by the model is presented elsewhere [*Schwab et al.*, 2009]. The Niagara River flow was balanced on an hourly time scale to have net zero accumulation of water in the basin since the seasonal cycle of lake level is not modeled here (evaporation and precipitation are assumed to balance each other in this approach).

[14] Hourly observations of air temperature, dew point, and cloud cover at NWS and Environment Canada stations around the lake and at one NOAA and two Environment Canada buoys were interpolated to the hydrodynamic model grid and used to calculate surface heat and momentum fluxes as described in *Beletsky and Schwab* [2001] and *Beletsky et al*. [2003]. Previously, we used observed winds to drive the model but we found that for Lake Erie the winds produced by a mesoscale atmospheric model were superior to observed winds in reproducing both the observed thermocline shape and type of circulation pattern in the central basin. This supports (although on a more dramatic scale) the conclusion of a winter circulation model for Lake Michigan where high-resolution atmospheric model winds were superior to interpolated winds [*Beletsky et al.*, 2003]. Replacing the winds only and keeping the rest of the observed meteorological data also helps to elucidate the crucial role of wind in forming the bowl-shaped thermocline and anticyclonic circulation in summer.

[15] The 3 hourly winds were obtained from a regional version of the Global Environmental Multiscale (GEM) model, which is being run for operational forecast in North America. The GEM model central domain has a uniform resolution of 15 km covering all of North America and adjacent oceans. The regional forecasts system is run at the Canadian Meteorological Centre (CMC) twice a day for a

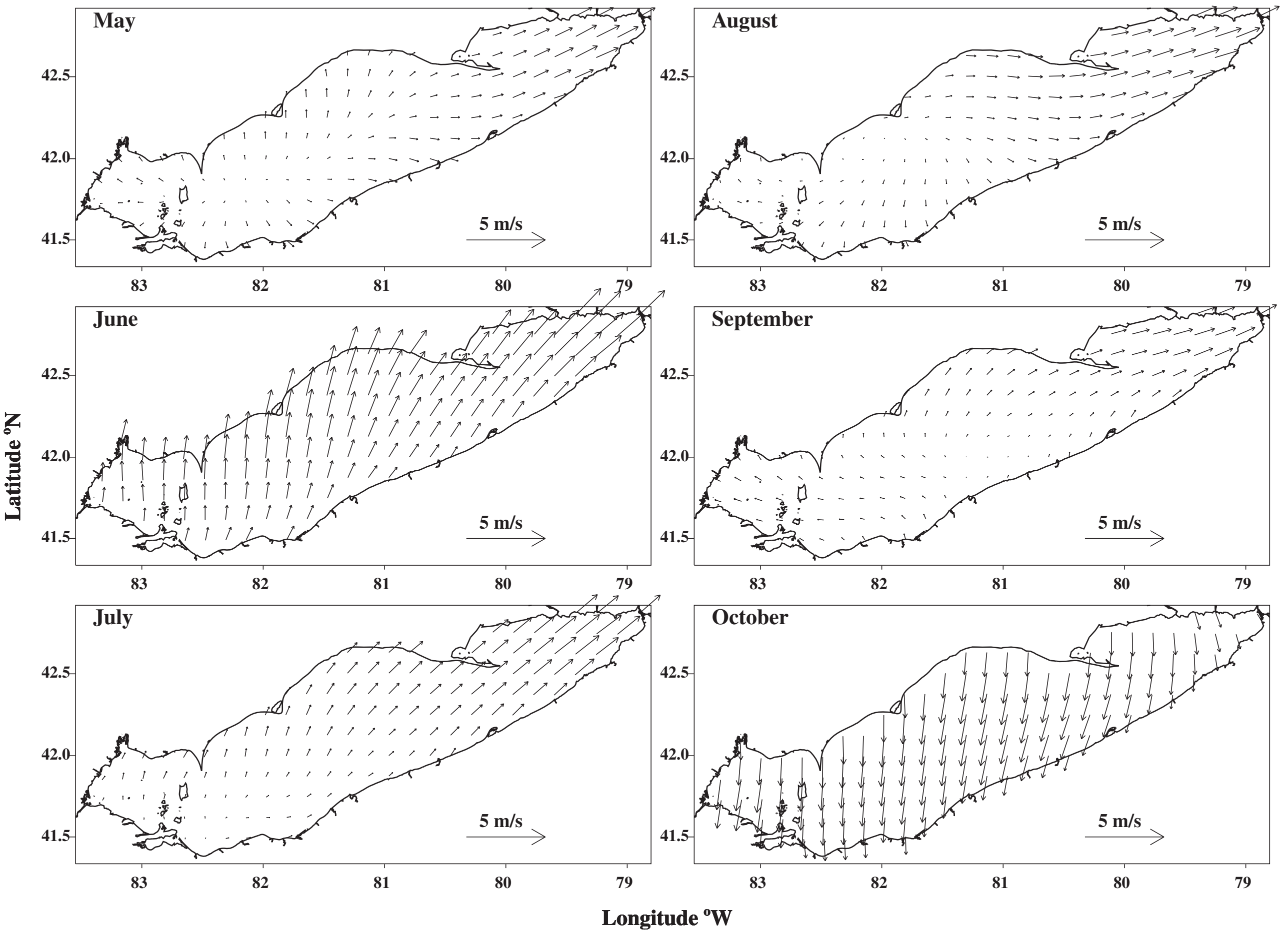

Figure 2. Spatial plots of monthly averaged winds (GEM) in 2005.

48 h forecast. Although the forecast system does not include lakes explicitly, surface temperatures obtained from weather buoys and remote sensing data from satellite are assimilated at 12 h cycles [*Mailhot et al*., 2006]. Analysis of modeled winds shows that during the May to October period they were largely from west to east, with anticyclonic vorticity visible over the central basin in August to September (Figure 2).

[16] The hydrodynamic model was initialized on 1 January 2004 for a continuous 2 year (2004–2005) run and again on 1 January 2007 using satellite lake surface temperature observations made available through Great Lakes CoastWatch Node (http://coastwatch.glerl.noaa.gov) and zero currents (cold start). Although the model does not have an ice component, this has a negligible effect on the model results during the period of interest (May to October). *Wang et al*. [2010] showed that in a relatively shallow lake the thermal effects disappear quickly (after about 2 months), so even May temperature calculations are impacted rather weakly and the ice effect disappears entirely throughout late spring-summer.

4. Model Results

4.1. Thermal Structure

[17] At the end of winter, the lake is well mixed both vertically and horizontally with temperatures normally below temperature of maximum density (about 4°C). As heating intensifies in the spring, the temperature rises above 4°C in the shallow areas first, and weak nearshore-offshore gradients begin to form in April. This also leads to a persistent temperature gradient between warmer shallow western basin water (which remains fully mixed most of the time) and the rest of the lake [*Schertzer et al*., 1987]. At the same time, during this spring warming period most of the lake is only weakly stratified (as seen for instance in the May plot of Figure 3a). In the central basin the thermocline begins to form in June and becomes sharper and deeper in July and especially in August. The thermocline eventually intersects the bottom in the eastern part of the central basin in September, while the thickness of the remaining hypolimnetic areas reduces dramatically, to only about 5 m or less. In October, the central basin becomes fully mixed again while week stratification persists in the eastern basin, where the mixed layer grows to 30 m. Stratification finally disappears in the eastern basin in November (not shown).

[18] In the central basin, a characteristic bowl-shaped thermocline begins to form first in July (although a weaker bowl-shaped thermocline is seen in the eastern part in June) and becomes especially pronounced in August to September. The shape of this bowl is not symmetric as the thermocline is tilted toward the east, which is likely a reflection of the prevailing westerly component in surface winds. Interestingly enough, a weak doming of the hypolimnion exists

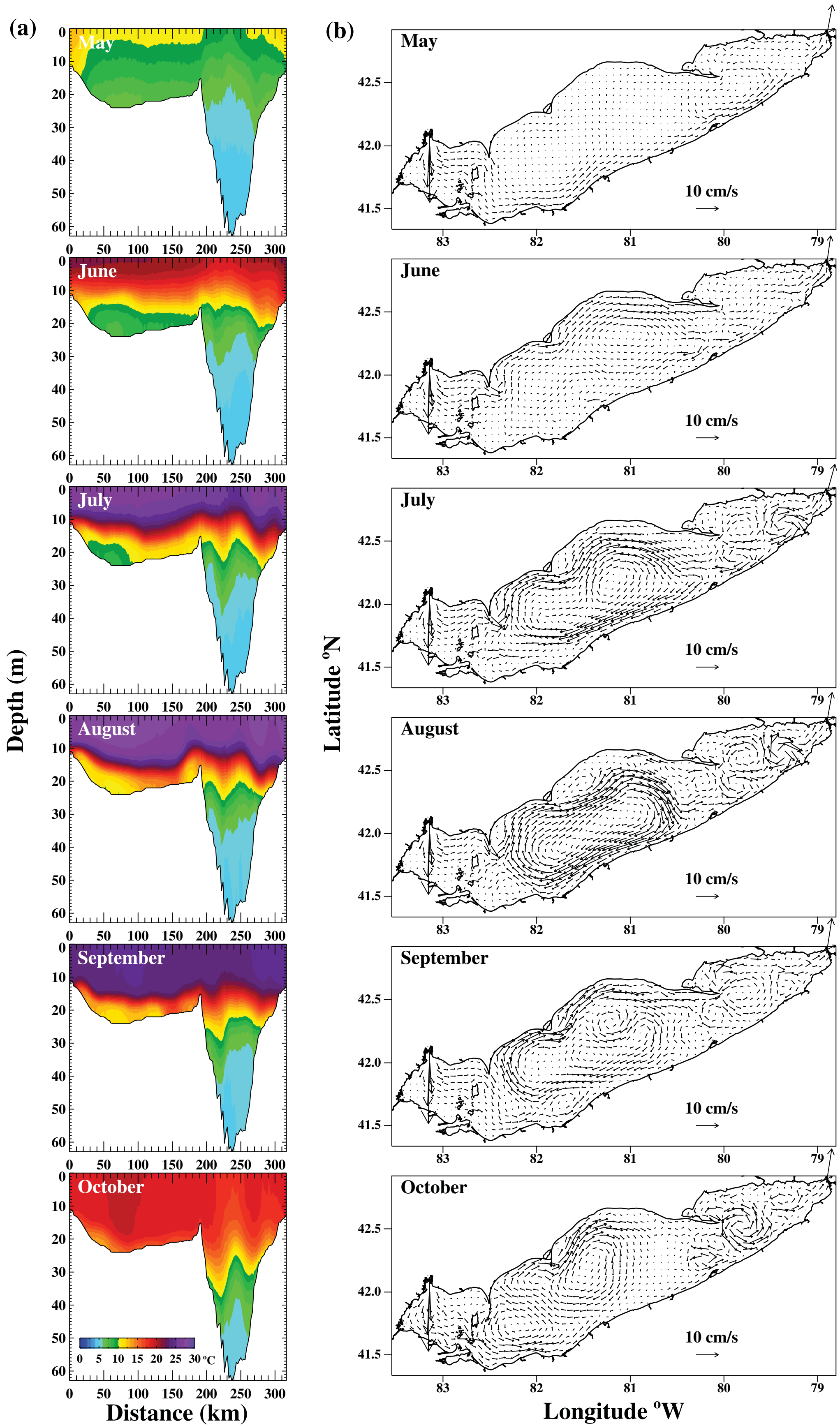

Figure 3. Monthly averaged (a) temperature and (b) depth-averaged currents in 2005. Base model run.

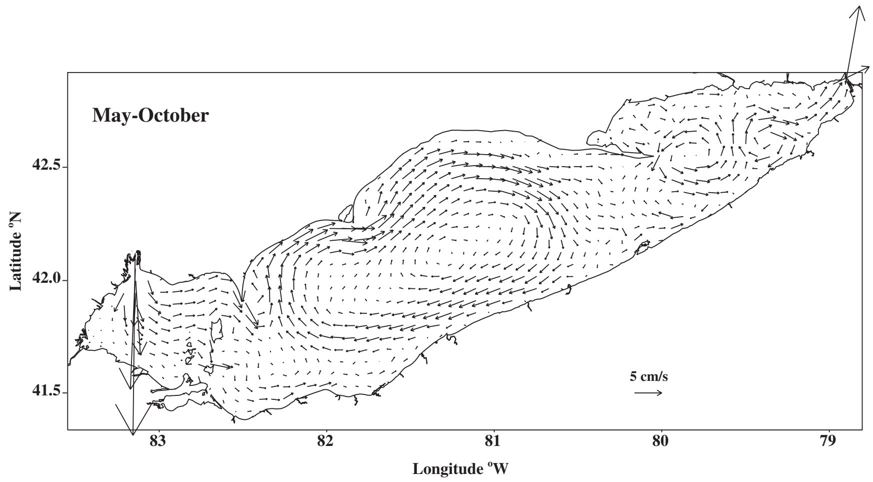

Figure 4. May to October 2005 depth-averaged currents.

in the deepest area of the central basin. At the same time, the thermocline of the eastern basin (which has a pronounced conic bathymetry) has a pronounced dome shape in its deep part that resembles that of Lake Michigan [*Beletsky and Schwab*, 2001] and other large lakes [*Schwab et al*., 1995].

4.2. Circulation

[19] Large-scale circulation exhibits significant variability during the stratified period (May to October). It is rather weak in May, with depth-averaged currents reaching only a few cm/s (Figure 3b) but currents pick up in speed and large-scale anticyclonic circulation develops in the central basin in June and becomes especially strong in July to September. This anticyclonic circulation is in geostrophic balance with the bowl-shaped thermocline. Circulation in the opposite direction (cyclonic) develops during June to October in the deep part of the eastern basin, this time in geostrophic balance with a dome-shaped thermocline. In shallow parts of the eastern basin, small-scale anticyclonic gyres are present near the northern shore, and larger and stronger anticyclonic gyres hug the southern shore. Monthly circulation in the western basin is primarily from west to east, with flow concentrated in the northern half of the basin during May to September and shifting to the southern half in October. In some months (i.e., in June), an anticyclonic gyre is present north of Toledo (as was described by *Hamblin* [1971]).

[20] Averaging currents on a seasonal time scale (May to October) produces rather organized, mostly isobath-following circulation patterns (Figure 4). In the western basin, a broad west-east flow is driven by the large discharge(5300 m^3 s^{-1}) of the Detroit River [*Bolsenga and Herdendorf*, 1993]. In the central basin large-scale anticyclonic circulation prevails, with the exception of a small cyclonic gyre in the Sandusky basin (south of buoy 45005). Cyclonic circulation occurs in the deepest part of the eastern basin, while anticyclonic gyres occur in the shallower areas. There is a broad northeast flow in the easternmost part of the lake that accelerates in the vicinity of Buffalo, where lake waters enter the Niagara River.

5. Model Validation

[21] Observations traditionally available for model validation in the Great Lakes are those of water level and surface temperature, but since extensive temperature and current measurements were made in the central basin in 2005 (see Figure 1 for locations), we focus our model validation efforts on this year. Each temperature mooring had a string of thermistors spaced every 1–2 m vertically from 1 m below the surface to the bottom from late April through mid-October. Current velocity measurements were made at several moorings with 300, 600, or 1200 kHz broadband acoustic Doppler current profilers. Details of the observations can be found on the IFYLE website (http://www.glerl.noaa.gov/ifyle).

5.1. Water Level

[22] Modeled water levels were compared to observed ones at eight water level gauges around the lake (results for Toledo and Buffalo are presented in Figure 5). Accurate

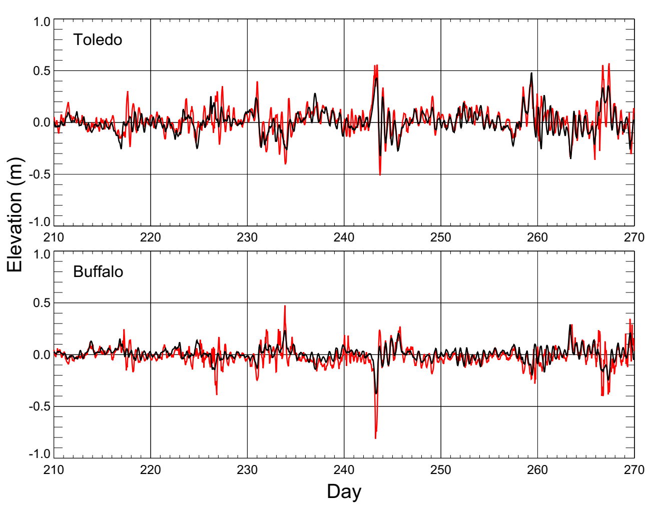

Figure 5. Modeled (black) versus observed (red) water levels at (top) Toledo and (bottom) Buffalo from August to September 2005.

modeling of water level fluctuations is an important test because it is an indicator of the accuracy of wind fields used to drive the model. Although GEM has proven to provide reliable meteorological data over Lake Ontario [*Huang et al.*, 2010], we tested water level fluctuations driven by GEM winds on Lake Erie again because of the important implications for circulation modeling. Water levels were modeled reasonably well with RMS error varying between 4 (Toledo) and 10 cm (Buffalo). The model reproduced seiching well (seen for instance as “aftershocks” following a surge due to a strong wind event on day 243). The 14 h oscillation period corresponds to the first mode longitudinal seiche [*Platzman and Rao*, 1964]. The model usually underestimated the amplitude of water level fluctuations, including the surge amplitude at both Toledo and Buffalo during the event on day 243 (when the percentage error reached 50%). This is a result of an underestimated wind speed in GEM that may also lead to reduced surface momentum and heat fluxes, which in turn affect lake surface temperature, Ekman pumping, and horizontal currents. In particular, comparison of GEM winds with observations at the meteorological buoys showed that the model underestimated wind stress by 8–20% during August to September, and up to 28% during the strongest wind event.

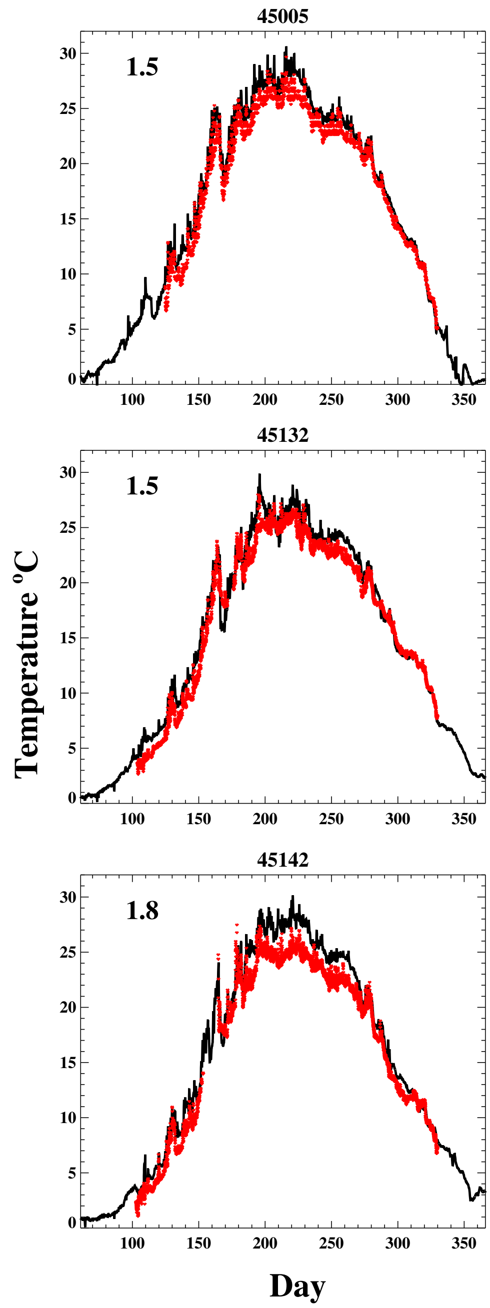

Figure 6. Modeled (black) versus observed (red) surface water temperature at meteorological buoys in 2005. RMSE is shown in top left corner.

5.2. Temperature

[23] Observations of surface water temperature at the three meteorological buoys in the central and eastern basins were used to validate the model during April to November 2005. Both the seasonal cycle and the synoptic variations of temperature are well simulated by the model (Figure 6), although the model produces a slight warm bias of about 1°C (likely related to a reduced wind speed in GEM). The RMS error varied between 1.5 and 1.8°C, which is consistent with previous modeling results for Lake Michigan [*Beletsky et al.*, 2006]. The RMS errors at meteorological buoys during 2004 and 2007 model runs were comparable to that of 2005 but were slightly higher, varying between 1.7 and 2.0°C.

[24] Subsurface measurements of temperature at the deepest mooring in the central basin (T07, Figure 1) provided additional information for model validation. The model reproduces the general evolution of the thermocline at this location reasonably well (Figure 7) but several deficiencies are evident. First, the modeled thermocline is too diffuse, not a surprising fact considering similar issues in previous POM applications to other lakes [*Beletsky and Schwab*, 2001]. Second, the mixing event on day 243 that resulted in a 5 m deepening of the thermocline is barely reproduced by the model (this is likely a result of weaker winds produced by the atmospheric model during this event). And third, total destratification (lake turn over in the fall) at this site (which occurred on day 273) was delayed in the model by about 2 weeks (although the modeled thermocline did deepen significantly during this event and almost complete mixing occurred). Similar findings of excessive thermocline diffusion and somewhat delayed destratification were also found in model simulations in 2004 and 2007 (not shown).

[25] Quantitative modeling of vertical thermal structure is a challenging problem in strongly stratified large lakes [*Beletsky et al.*, 2006]. Lake Erie is a particularly difficult lake to model not only because its thermocline is one of the sharpest in of all the Great Lakes but also because its thermal structure is very sensitive to wind vorticity. As expected, maximum model errors occurred in the thermocline at and below 15 m. In 2005, model errors were comparable but slightly higher (RMSE between 0.7°C and 4.8°C) than those in a previously used 1-D model [*Rucinski et al.*, 2010], except for nearsurface and nearbottom areas. While some of the discrepancies can be attributed to the diffuse model thermocline (this may be due to several reasons, including numerical diffusion, penetrative short-wave radiation specification, internal waves unresolved by 2 km grid, etc.), we want to draw attention here to the error in

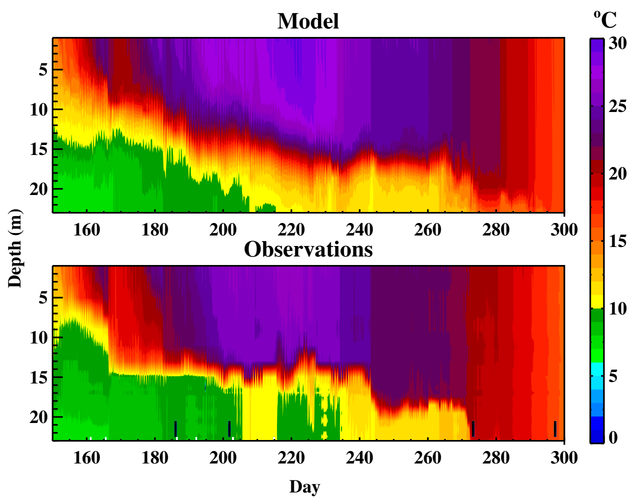

Figure 7. (top) Modeled versus (bottom) observed water temperature at T07 in 2005.

the vertical location (displacement) of the thermocline. The model results showed a high sensitivity of the thermocline shape in the central basin to spatial details of the wind field (which can produce either too much or too little Ekman pumping). This may lead to large displacement errors (in addition to errors caused by an excessively diffuse model thermocline). Considering the particularly sharp thermocline that develops in Lake Erie by the end of summer [*Schertzer et al.*, 1987], inaccuracies in the wind field can easily misplace the thermocline in the model at any particular location, although its overall shape can still be correct.

[26] The relatively high density of moorings in the central basin (Figure 1) allowed additional validation of monthly temperatures along a longitudinal transect (likely the first of its kind in the Great Lakes). Monthly averaged observed temperatures are presented in Figure 8a, while model results are shown in Figure 8b. Both modeled and observed temperatures show weakly stratified conditions in May (although the model exhibits slightly stronger stratification). In June, the model still predicts a bit sharper thermocline than seen in observations, with a shape (traditional dome) similar to observations near the deepest spot. In July, the observations show a very sharp thermocline forming in the lake. The modeled thermocline is slightly shallower and more diffuse, and the thermocline depression is somewhat more pronounced than in the observations. The model matches the thermocline position very well in August, and nicely reproduces (if somewhat exaggerated) the thermocline erosion near the bottom in the eastern part of the central basin. In September, the modeled hypolimnion is somewhat thicker than the observed one and bowl shape is slightly less pronounced, which is most probably an indication of a too-weak Ekman pumping produced by GEM winds during that month. The overall conclusion from the temperature transect validation is that while in general the model does a good job of describing the shape of the thermocline and its depth, there are inevitable discrepancies due to both numerical diffusion and displacement errors due to Ekman pumping. This makes it difficult to match the thermocline position at any particular location.

5.3. Currents

[27] Modeled circulation patterns were first compared with observations in the central basin during the hypoxia period (August to September), during which the bowl-shaped thermocline was most pronounced. The model shows large-scale anticyclonic circulation covering the whole basin (Figure 9a) with the exception of a small cyclonic gyre in the Sandusky basin. The observations (which cover only the southern part of the basin) support the model

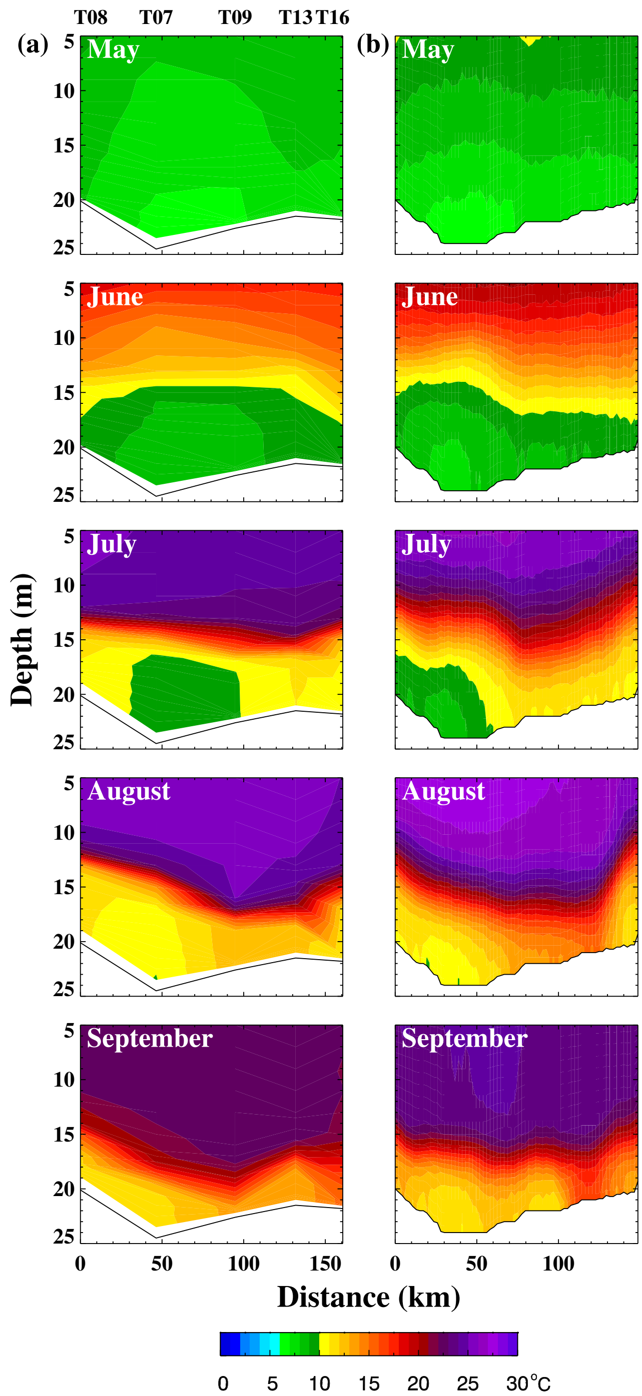

Figure 8. Monthly averaged (a) observed and (b) modeled temperature at west-east transect in 2005.

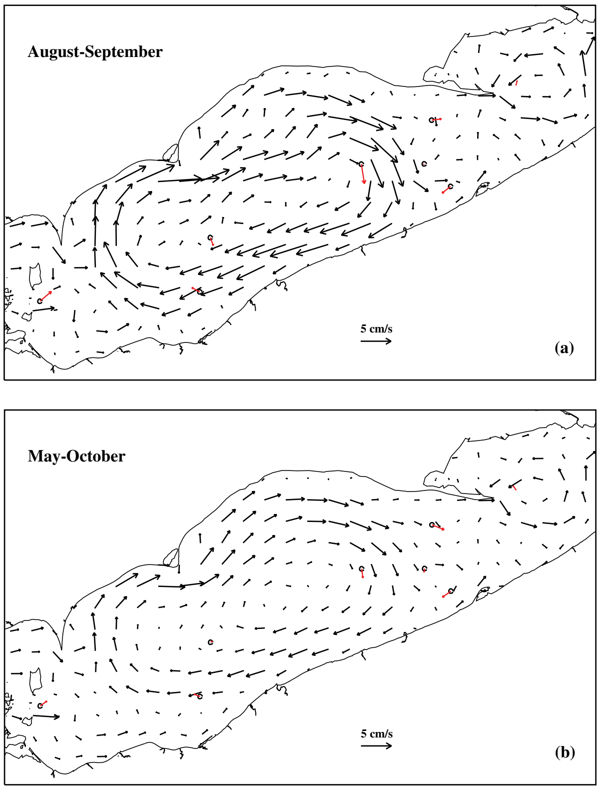

Figure 9. (a) August to September depth-averaged modeled currents and (b) May to October depth-averaged modeled currents in 2005. Observations are shown in red.

results. On the other hand, currents observed in the deep part of the eastern basin (mooring C12) were much smaller and opposite to model results. One possible explanation is that actual anticyclonic wind vorticity was stronger than in GEM and the anticyclonic gyre southwest of C12 covered a larger area. Another possibility is that local dynamics were not well resolved by the model with present horizontal resolution (2 km). This area is characterized by extremely steep bathymetry and is only 10 km east of the Long Point which could have a major influence on local currents.

[28] On a seasonal time scale (May to October), the model again shows an anticyclonic pattern in the central basin, in agreement with the anticyclonic circulation in the observations (Figure 9b). The model also reproduced a reduction in seasonal current speed compared with the August to September mean. Note that some of the observed currents are averaged on a somewhat shorter time scale than in the model because they were only observed for 4 or 5 months, so the comparison is somewhat qualitative on the 6 month time scale. In the eastern basin, currents observed at C12 were still smaller than in the model but the model matched their direction better than in August to September. It is interesting to note that observed currents were almost perpendicular to the isobaths. This is unusual for the Great Lakes where long-term currents tend to follow local bathymetry [*Beletsky et al.*, 1999] and is probably due to some peculiarities of hydrodynamics in the vicinity of Long Point. Nevertheless, the overall successful model

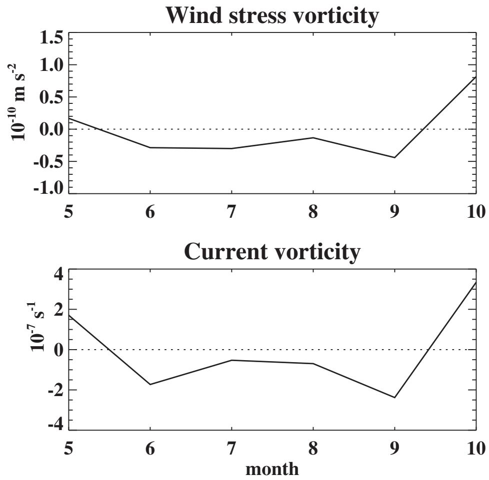

Figure 10. (top) Wind stress vorticity versus (bottom) depth-average current vorticity in May to October 2005.

validation provides confidence in the model results when they are used to drive ecological models on long time scales.

6. Circulation Mechanisms

[29] Comparison with data showed that model reasonably accurately reproduced lake hydrodynamics in the area most densely covered by observations (e.g., the model captured both a bowl-shaped thermocline and anticyclonic circulation in the central basin), and this gives confidence in model results for the lake overall. Model results showed that overall lake circulation was anticyclonic (with the exception of a cyclonic gyre occupying the deepest portion of the eastern basin). Lake-average current vorticity closely followed vorticity in the wind stress (Figure 10) which was negative (anticyclonic) during the summer months (June to September), which shows sensitivity of circulation patterns in Lake Erie to the wind vorticity.

[30] We conducted several sensitivity studies in both baroclinic and barotropic settings to further investigate the link between wind vorticity, circulation pattern, and thermocline shape using a variety of forcings (Table 1). In the first series of tests, we focused on the central basin and ran the model for a period of time limited to 60 days (this duration is sufficient to demonstrate some important tendencies in evolution of the thermocline and circulation). Tributary flows were neglected in order to isolate wind effects most accurately. We began with a model run (case S1) starting

Table 1. Summary of 2005 Model Runs

Run	Duration (days)	Tributaries	Surface Fluxes
Base	365	Yes	Momentum, heat
S1	60	No	None
S2	60	No	Momentum only
S3	365	Yes	Momentum, heat
S4	365	Yes	Momentum, heat
S5 (barotropic)	365	Yes	Momentum only
S6 (observed wind)	365	Yes	Momentum, heat

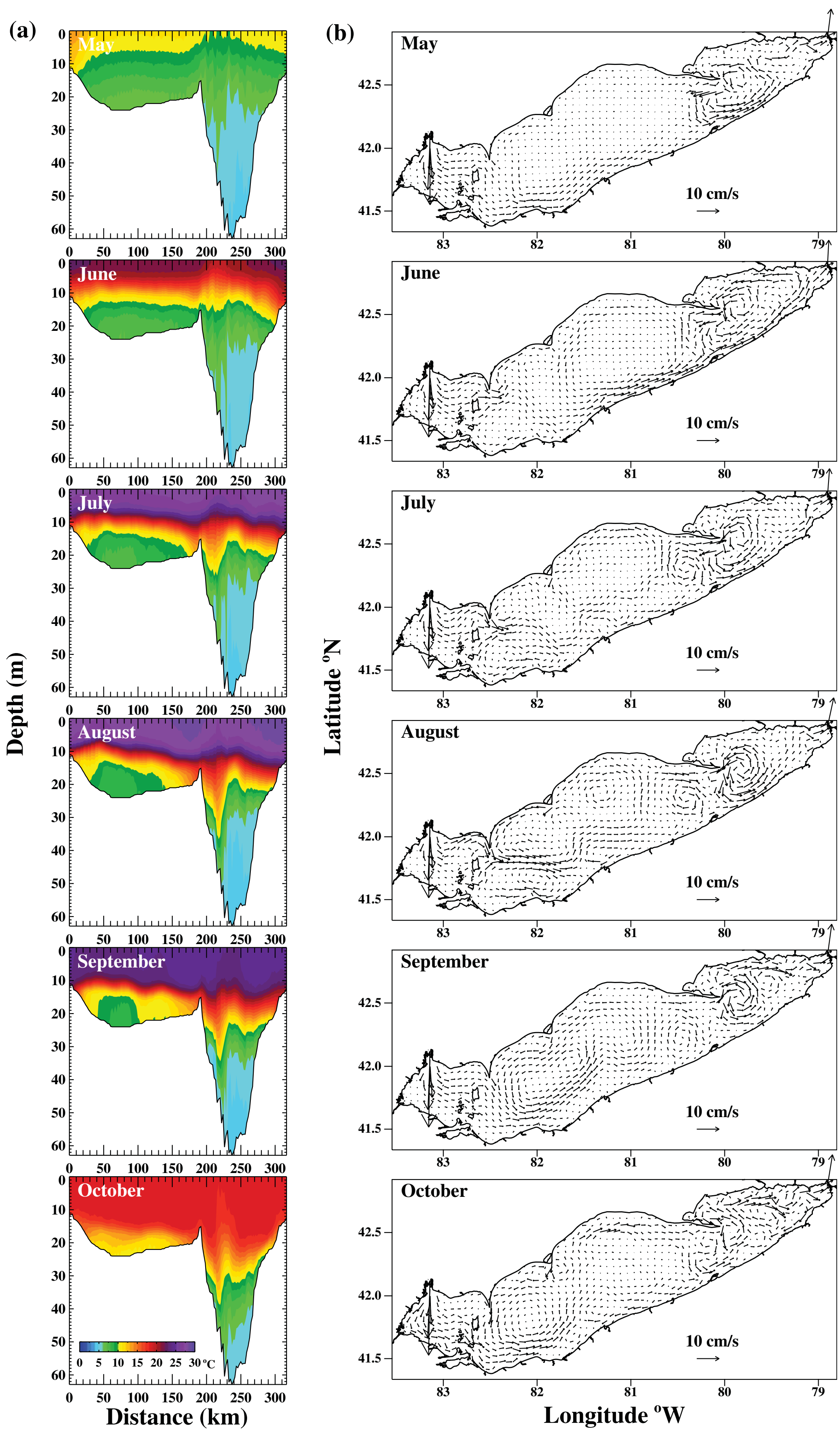

Figure 11. Monthly averaged (a) temperature and (b) depth-averaged currents. Model run with spatially uniform winds.

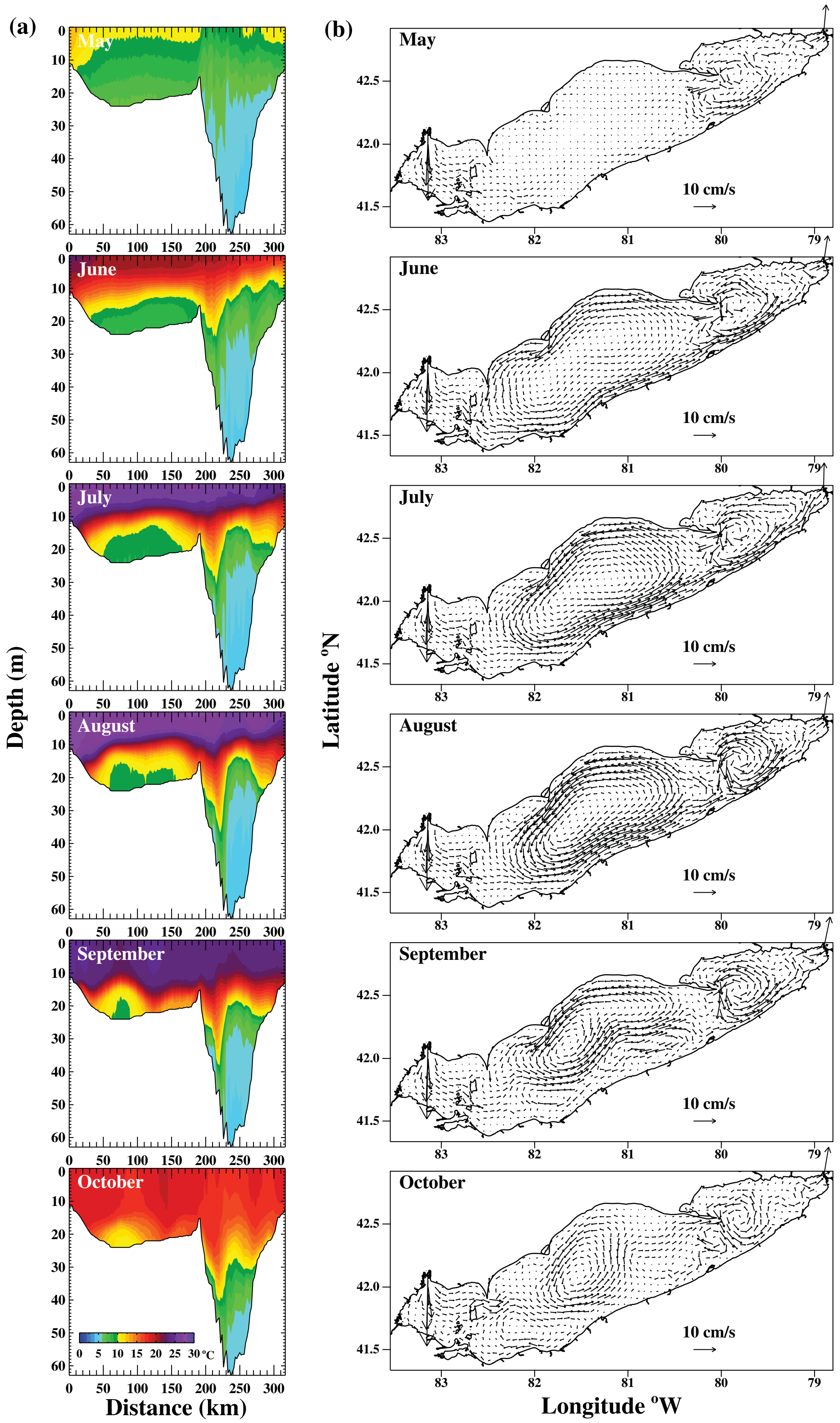

Figure 12. Monthly averaged (a) temperature and (b) depth-averaged currents. Model run with reversed wind direction.

with a flat thermocline (located between 11 and 13 meters) derived from central basin temperature observations on day 210, 2005. The model was run with zero wind and heat flux to allow the thermocline to adjust at lake slopes to boundary conditions of zero heat flux similar to the *Schwab et al.* [1995] experiment, but using actual lake bathymetry. The resulting circulation was cyclonic (with maximum speeds of a few cm/s) with a matching dome-shaped thermocline, in line with findings from idealized basin cases [*Schwab et al*., 1995]. Next the model was run with the same initial conditions for a similar 60 day period driven by the August to September GEM winds but still keeping zero heat flux (run S2). As a result of the added wind forcing the circulation reversed to anticyclonic, and the modeled thermocline exhibited a pronounced bowl-shaped profile (in both east-west and northsouth directions) with a mid-lake depression of about 2–3 m. Mirroring the depression of the thermocline in the central basin, the surface level was elevated in the mid-lake. This supports the idea that near surface convergence due to Ekman drift leads to mid-lake downwelling.

[31] We next conducted a set of experiments for the full year that included tributary flows to further elucidate factors affecting circulation and thermocline location in different basins of the lake. In the first experiment (run S3), we eliminated wind vorticity by running the model with spatially uniform (lake average) winds while all other input fields and model parameters were kept unchanged. Thermocline retained its dome shape in the eastern basin. Circulation in shallow parts of the eastern basin switched from anticyclonic to cyclonic during months when thermocline doming was most pronounced (June to August), while currents and thermocline in the deeper part did not change qualitatively, but showed an increase in current speed. At the same time, there was a dramatic change in circulation, shape, and thickness of the thermocline in the central basin (Figure 11a). Thermocline shape changed to that of a dome clearly seen from July to September, resembling the one observed in the 60 day thermocline adjustment case. Whereas the dome-shaped thermocline was a result of sloping bottom effect in the thermocline adjustment case, because of nonzero heat flux in run S3 additional mechanisms may also play a role in producing a dome-shaped thermocline [*Csanady*, 1977; *Monismith et al*., 1990]. This thermocline transformation in the central basin was accompanied by a circulation reversal, which became mostly cyclonic (Figure 11b). Another important effect of eliminating anticyclonic vorticity in the wind field was an increased hypolimnion thickness in the central basin and an extension of the stratification period to October. Conversely, this finding also shows that the presence of anticyclonic vorticity in the wind field leads to thinning of the hypolimnion in the central basin and earlier destratification in the fall, which has important implications for lake ecology.

[32] In the next experiment (run S4), we reversed the wind direction which changed overall wind vorticity from anticyclonic to cyclonic (and reversed overall thermocline tilt in the lake compared to the base run). In this case, a dome-shaped thermocline was observed in both central and eastern basins, however the doming was much more pronounced (Figure 12a) than in the uniform wind case due to Ekman pumping. Stratification in the central basin also lasted longer than in the base case run but hypolimnion area shrank relative to the uniform wind case, probably because of intensified mixing near the bottom. Circulation became stronger and even more cyclonic (Figure 12b) compared to the uniform wind case. In fact, in most months practically the whole lake is covered by cyclonic circulation. The main reason for stronger circulation is that reversed wind forcing provided cyclonic vorticity, which worked in concert with density-driven cyclonic circulation mechanisms in the lake.

[33] The results of sensitivity studies showed that long-term circulation in the central basin is more variable than circulation in the western and eastern basins. To better understand importance of various circulation mechanisms in each basin it is useful to recall findings of previous numerical studies of lake circulation and the thermocline. Circulation in the Great Lakes on monthly and longer time scales is affected mostly by two factors: wind stress vorticity and baroclinic effects [*Schwab and Beletsky*, 2003], with baroclinic effects being especially important in summer [*Schwab and Beletsky*, 2003; *Bennington et al*., 2010]. For example, in Lake Michigan cyclonic circulation driven by density gradients prevails in summer in deeper offshore areas while shallow nearshore areas are occupied by anticyclonic circulation driven by wind [*Beletsky and Schwab*, 2008]. In Lake Erie, all of the central basin is shallow (less than 25 m), so when sufficient anticyclonic wind vorticity is present, its circulation becomes anticyclonic as well, overwhelming density-driven cyclonic circulation and completely modifying the density field in the process.

[34] Long-term circulation in both the western basin and in the deep part of the eastern basin is rather stable, but for different reasons. The shallow western basin has no permanent stratification and its circulation, a broad west-east flow, is determined by a strong hydraulic flow due to large tributary inflows reshaped to some extent by wind (in an additional model run, removal of hydraulic flow led to a completely different flow pattern consisting of several gyres and much weaker circulation). Wind contribution is demonstrated by stronger currents in the northern half of the basin in May to September (Figure 3b), when winds with southerly component prevailed while in October, when winds switched to northerly, currents in the southern half of the basin became stronger. In addition, because the western basin is smaller than the other two basins, the effect of spatial wind gradients is less significant there. Inspection of circulation patterns in runs with and without wind vorticity (Figure 3b versus Figure 11b) revealed essentially the same results.

[35] The deeper portion of the eastern basin of Lake Erie can be likened to that of southern Lake Michigan (although smaller and only half that deep) because isobaths are fairly concentric and bottom slope is very pronounced. Model results show that available anticyclonic wind vorticity was not strong enough to overwhelm density-driven cyclonic circulation in its deepest part (in the barotropic run S5 with uniform density an anticyclonic wind-driven circulation does exists in the eastern basin). To prove that cyclonic circulation is not due to interbasin flow we conducted model run where the eastern basin was cut off from the rest of the lake and no tributary flow existed. The cyclonic circulation

remained essentially the same, which proves that it is generated by basin-scale processes. Therefore, the stability of cyclonic circulation of the deeper part of the eastern basin is due to baroclinic effects.

7. Discussion and Conclusions

[36] Because of significant ecological implications, it is important to examine the persistence of the bowl-shaped thermocline and anticyclonic circulation in the central basin. Analysis of data published in the last 40 years (based on systematic temperature surveys and long-term current measurements) revealed a compelling list of evidence showing that this configuration is indeed rather typical for the central basin. *Hamblin* [1971] presented observations showing anticyclonic circulation in 1963 and a bowl-shaped thermocline in 1967. *Simons* [1976] presented 1970 observations showing bowl-shaped thermoclines in both the central and eastern basins and observed an anticyclonic circulation pattern in July to August. Long-term current observations in 2005 are consistent with the mean anticyclonic summer circulation pattern derived previously by *Beletsky et al*. [1999], using the 1979 data collected by *Saylor and Miller* [1987], although in 2005 the anticyclonic circulation covered the whole basin (as in 1970) while in 1979 there was a smaller cyclonic gyre in its westernmost part. In some years, persistent dome-shaped thermocline was observed. Temperature surveys in 1978 showed a dome-shaped thermocline throughout summer [*Saylor and Miller*, 1985]. Although this case is an important indication of interannual variability, we nevertheless found more cases showing the opposite—a bowl-shaped thermocline in the central basin. Quite remarkably, the bowl-shaped thermocline of the central basin has never received proper recognition (unlike the traditional dome-shaped thermocline of the eastern basin), and to the best of our knowledge was never explained until recently [*Beletsky et al*., 2012]. In fact, *Simons* [1976], whose model used temperature fields obtained from observations (and showed good agreement with anticyclonic current observations) wrote that "our computations do not establish why thermocline likes to adopt this particular configuration."

[37] The anticyclonic circulation pattern in the central basin, accompanied by a basin-wide bowl-shaped thermocline, was also seen in our 2004 and 2007 model results (not shown) and also in two out of three more recent years we are currently modeling in an on-going project. Model results reported by *Dupont et al*. [2012] showed an anticyclonic circulation pattern in 2006 as well (their model was driven by GEM 15 km winds). Therefore, based on available observations and modeling, it seems that the anticyclonic circulation/bowl-shaped thermocline configuration is rather typical for the central basin. At the same time, recent hydrodynamic models of Lake Erie that used either observed winds [*Schwab et al*., 2009; *Fujisaki et al*., 2012, 2013] or relatively coarse-resolution (36 km) atmospheric model winds [*Bai et al*., 2013] produced quite different thermocline and circulation patterns in the central basin. *Schwab et al*. [2009] and *Fujisaki et al*. [2013] presented a two-gyre circulation pattern, with anticyclonic gyre occupying roughly the north and eastern parts of the central basin while cyclonic gyre occupied the south and western parts. Circulation presented by *Bai et al*. [2013] also shows a two-gyre pattern but the line separating the northern anticyclonic and southern cyclonic gyres runs parallel to the longitudinal axes of the lake. Regardless of gyre position in either model, when only half of the basin (or less) is covered by an anticyclonic circulation, the area occupied by a bowl-shaped thermocline is substantially reduced, which has important implications for water quality modeling.

[38] The high sensitivity of central basin circulation and thermal structure to wind vorticity prompted an additional comparison of the base model run with one that uses observed winds. Using observed (interpolated) winds was a standard choice for most POM applications to Lake Michigan [*Beletsky and Schwab*, 2001], and we subsequently employed the same approach in Lake Erie modeling, starting with *Schwab et al*. [2009]. Nevertheless, because of potential important implications for modeling of Lake Erie summer hydrodynamics and transport processes (especially in hypoxia prone central basin) the choice of wind required a reassessment.

[39] Model run with observed winds (run S6) conducted for 2005 produced a dome-shaped thermocline and cyclonic circulation in the central basin (not shown), contrary to observations of temperature and currents presented in Figures 8 and 9. The reason behind this discrepancy turned out to be the overall cyclonic vorticity of the wind stress, which is opposite to the anticyclonic wind stress vorticity in the GEM wind (base) case. The simplest explanation of this deficiency in the observed winds is that the interpolated wind fields are biased by winds at the land-based stations (the meteorological buoys are located rather close to the lake shore). As a result, this primarily geometric approach apparently misses important details in spatial wind structure over the lake, and in particular over the central basin, which is the largest. In this regard, GEM holds an important advantage since it does account for physics of lake-atmosphere interactions to some extent through lake surface temperature assimilation during the forecasting cycle.

[40] Similar to 2005, model runs for 2004 and 2007 driven by observed winds (which exhibited overall cyclonic vorticity) produced cyclonic circulation and a dome-shaped thermocline in the central basin as well. This contradicts results from the corresponding 2004 and 2007 runs with GEM winds (which were mostly anticyclonic). While the configuration and density of temperature observations in 2004 were not sufficient to determine the shape of the thermocline, they were detailed enough in 2007 to show a bowl-shaped thermocline in the central basin in August, qualitatively confirming GEM-based model results. At the same time, GEM winds produced an exaggerated bowl-shaped thermocline. Therefore, while observation-based wind fields may not always be suitable for central basin hydrodynamic modeling in summer, there is still room for improvement with modeled winds as well. In fact, a more systematic investigation of medium and high-resolution wind fields from a variety of operational atmospheric models is highly desirable in view of their impact on the quality of circulation and thermal structure modeling in Lake Erie (and other lakes). In that regard, a comprehensive data set of temperature and current observations obtained in IFYLE (especially in 2005) can be very useful in testing various wind fields that drive hydrodynamic models.

[41] The presented results do not automatically invalidate hydrodynamic modeling that uses observed winds (especially when model is validated with direct current observations), but in fact may shed more light on the nature of discrepancies with observations. For example, previous research in Lake Michigan showed that summer circulation was modeled less accurately than winter circulation [*Beletsky and Schwab*, 2001; *Beletsky et al*., 2006] and inaccuracy in wind field can be one of the main reasons. Circulation modeling in shallow areas of other basins can be prone to the same errors. Lake Erie, with its large and shallow central basin certainly is a case where particular attention needs to be paid to the choice of wind because its circulation is so sensitive to changes in wind vorticity. While use of winds produced by high-resolution meteorological models would be a desirable development, we also want to stress the need for improved coverage of over-lake wind observations—more meteorological buoys are needed. The central basin of Lake Erie is one of the places where this information will be of great importance not only for improvements in hydrodynamic modeling but also for understanding of its recurring hypoxia as well.

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