Summer thermal structure and anticyclonic circulation of Lake Erie

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[1] In most thermally stratified lakes, the summer thermocline has the shape of a "dome", with a shallower depth offshore than nearshore. This configuration is accompanied by a lake-wide cyclonic circulation. Lake-wide observations of subsurface temperature in central Lake Erie revealed an atypical "depressed" or "bowl-shaped" thermocline in late summer, with a deeper thermocline in the middle of the lake and a shallower thermocline nearshore. Currents measured in the central basin when the bowl-shaped thermocline was observed were anticyclonic, forming a single basin-wide gyre. It is suggested that the unusual bowl-shaped thermocline is the result of Ekman pumping driven by anticyclonic vorticity in surface winds. The bowl-shaped thermocline can lead to greater hypoxia in bottom waters and negative effects on biota by reducing the hypolimnetic volume.
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1. Introduction

[2] The seasonal thermocline in lakes and oceans is a region of strong vertical gradients of temperature located immediately below the surface mixed layer. In large temperate lakes it separates warm surface waters from cold bottom waters with top-to-bottom summer temperature differences of 10–15°C [*Boyce et al.*, 1989]. The depth and strength of the thermocline determine the distribution and magnitude of vertical turbulent fluxes that in turn influence a variety of ecological processes in lakes. One of the extreme examples is late summer hypoxia/anoxia in the central basin of Lake Erie [*Burns et al.*, 2005].

[3] Filtered of transient events, the summer thermocline has largely the shape of a dome in most large thermally stratified lakes (horizontal size exceeding internal Rossby radius), with a shallower depth offshore than nearshore [*Church*, 1945; *Tikhomirov*, 1982; *Simons and Schertzer*, 1987]. The nearshore-offshore temperature gradients which begin to form in 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] that emphasizes downward advection of heat in nearshore areas during coastal downwellings. More recently, numerical model results showed that a zero heat flux at a sloping lake boundary (the fact first pointed out by *Phillips* [1970] and *Wunsch* [1970]) leads to bending isotherms at the bottom and generates a dome-shaped thermocline as well [*Schwab et al.*, 1995]. Observations in lakes showed that a dome-shaped thermocline is typically accompanied by geostrophic cyclonic circulation [*Csanady*, 1977].

[4] Early analytical models showed that in an idealized flat-bottom homogeneous basin circulation is determined by the horizontal shear in the wind field [*Shtokman*, 1941]. In particular, a wind field with a cyclonic curl generates a single gyre cyclonic circulation in a circular lake, and if stratification is present it is accompanied by a domed thermocline [*Csanady*, 1968]. Bathymetry effects profoundly modify circulation patterns in lakes [*Shtokman*, 1953; *Weenink*, 1958]. A spatially uniform wind generates a circulation pattern consisting of two counter-rotating gyres [*Birchfield*, 1967; *Csanady*, 1973; *Bennett*, 1974] shaped by the individual lake bottom topography in realistic settings [*Rao and Murty*, 1970]. At the same time, introduction of vorticity in the wind field can again cause one gyre to become dominant or actually cover the whole lake [*Birchfield*, 1967; *Pickett and Rao*, 1977; *Schwab and Beletsky*, 2003].

[5] It is well known that wind vorticity can change the shape of the thermocline in oceans through the vertical motions generated by the divergence of Ekman transport, i.e., Ekman pumping mechanism [*Gill*, 1982]. Wind stress curl is ubiquitous in the world ocean causing horizontal motions ranging from basin-scale gyres to regional gyres comparable in size to individual Great Lakes [*Hofmann et al.*, 1981] and associated vertical motions. Although references to Ekman pumping in physical limnology are rare, the presence of substantial wind stress curl over many lakes implies that a similar mechanism is likely to be at work in lakes as well. In particular, a cyclonic wind generates near-surface divergence (and surface level depression) in the mid-lake region, which will cause mid-lake upwelling and result in a dome-shaped thermocline. As the surface level and isotherms become tilted in the process, horizontal pressure gradients develop and give rise to a cyclonic circulation in geostrophic equilibrium with the density field. For an anticyclonic wind the opposite is true. Mid-lake near-surface convergence (and surface level elevation) and resulting downwelling leads to a depressed or bowl-shaped thermocline accompanied by anticyclonic circulation.

[6] While cyclonic circulations are abundant in lakes and marginal seas [*Emery and Csanady*, 1973; *Laval et al.*,

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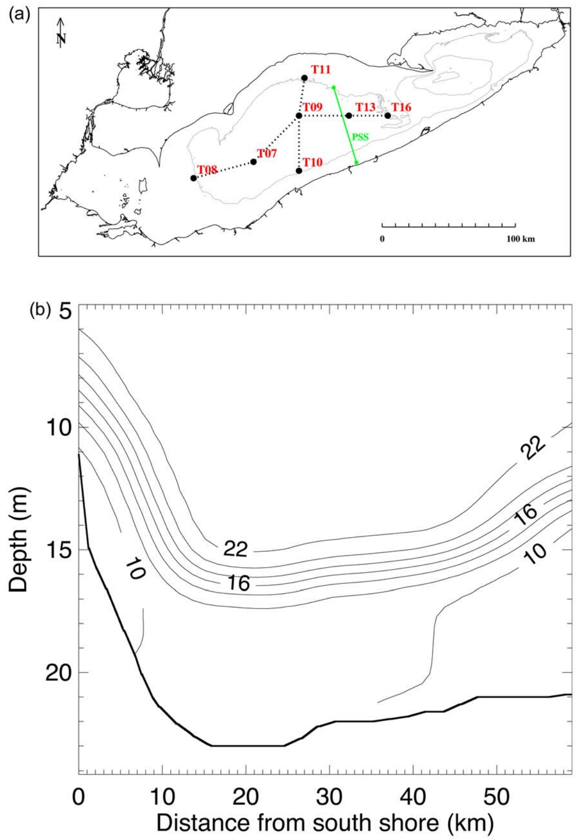

Figure 1. (a) Lake bathymetry and mooring locations. Isobaths shown every 20 m. Thermistor mooring location is shown with filled circles, PSS transect is shown in green. (b) Temperature observed at PSS transect on July 9, 2005.

2005; *Beletsky and Schwab*, 2008], anticyclonic motions rarely dominate basin-scale circulation [*Strub and Powell*, 1986] and appear primarily as regional gyres [*Beletsky et al.*, 1999; *Rueda et al.*, 2005; *Shimizu et al.*, 2007]. Even more rare are observations of thermocline depressions linked to anticyclonic gyres [*Endoh and Okumura*, 1993].

[7] In this paper we present a comprehensive set of long-term measurements in Lake Erie. High spatial resolution (both vertical and horizontal) temperature observations are used to objectively map the 3D summer thermocline structure for the first time. The maps reveal a persistent basin-wide bowl-shaped thermocline accompanied by anticyclonic circulation. This shape is counter to the conventional notion that large stratified lakes have cyclonic circulation and a domed thermocline. Analysis of vorticity in the surface winds suggested Ekman pumping as a likely mechanism for the generation of this unusual thermocline shape.

2. Data and Methods

[8] Lake Erie is one of the smaller Great Lakes but is still sufficiently large for its thermocline to feel rotational effects in summer (internal Rossby radius of about 5 km). It is about 400 km long, 90 km wide and 64 m deep, and has 3 distinct basins [*Bolsenga and Herdendorf*, 1993]: a shallow western basin, a deep eastern basin and a relatively flat central basin (mean depth 18.5 m, maximum depth 25 m) which is the largest and of most interest to this study (Figure 1a). High spatial resolution temperature observations were collected in summer 2005 (and on a smaller scale in 2007) in the course of a multi-disciplinary US-Canada experiment [*Hawley et al.*, 2006] from an array of moorings deployed in the central basin every 30–50 km in areas 20–25 m deep (Figure 1a and Table 1). The primary goal of the physical measurement program was to accurately map the evolution of a 3D thermocline and its effects on central basin hypoxia.

[9] In 2005, each mooring had a string of thermistors spaced every 1–2 meters vertically from 1 m below the surface to the bottom from late April through mid-October. In 2007, instruments were placed only below 11 m depth, mooring T16 was not occupied, and observations lasted only until the second half of September. Water temperature measurements were made using a combination of Brancker TR-1000, Onset Tidbit, and Seabird SBE39 temperature sensors. Single point observations were made every 30 minutes. The Brancker and Onset sensors have an accuracy of 0.05°C and 0.2°C respectively and a time constant of approximately 5 minutes. The Seabird sensors have an accuracy of 0.002°C and a time constant of 5 seconds.

[10] High spatial frequency temperature profiles (at ~ 600 m intervals) along the north-south transect (Figure 1a) were obtained with a Plankton Survey System (PSS), a suite of instruments including an OS200 CTD (Ocean Sciences, San Diego), that was raised and lowered at 0.1 m s^{-1} from 1 m below the surface to 1–2 m above the bottom as it was towed at 2–2.5 m s^{-1} alongside our research vessel [*Vanderploeg et al.*, 2009].

[11] Current velocity measurements were made in 2005 only, with 300, 600, or 1200 kHz broad band Acoustic Doppler Current Profilers (ADCP) manufactured by RD Instruments. The profilers were mounted looking upward in gimbaled bottom mounts with the sensor head 0.5 meters above the bottom. Data was collected in 20 minute ensembles using 1 m bins.

[12] The 3-hourly winds were obtained from regional version of Global Environmental Multi-scale (GEM) model, which has been proven to provide reliable winds over the Great Lakes [*Huang et al.*, 2010] at 15 km resolution.

3. Results

[13] Some of the PSS nearshore-offshore transects revealed the unusual bowl-shaped thermocline in the central basin (Figure 1b) with thermocline depth dropping up to

Table 1. Observations of Temperature (T) and Current Velocity (C) Used in the Analysis

Station	Parameter	Latitude (°N)	Longitude (°W)	Depth (m)	Observation Period
5	C	41.670	82.630	12.0	06/01/2005 – 10/27/2005
6	C	41.710	81.720	21.5	06/21/2005 – 10/14/2005
7	T, C	41.940	81.660	24.5	05/06/2005 – 10/26/2005
8	T	41.830	82.200	20.1	04/21/2005 – 10/17/2005
9	T	42.250	81.250	22.6	04/20/2005 – 10/18/2005
10	T	41.880	81.250	21.2	04/20/2005 – 10/18/2005
11	T	42.500	81.200	20.2	04/20/2005 – 10/18/2005
13	T, C	42.250	80.800	21.5	05/05/2005 – 10/28/2005
14	C	42.435	80.400	12.2	05/20/2005 – 10/20/2005
15	C	42.156	80.292	22.7	05/19/2005 – 10/19/2005
16	T, C	42.250	80.450	21.8	04/28/2005 – 10/19/2005

8 meters from nearshore to the middle of the lake. On July 9, 2005 temperature decreased from 22° to 12°C across the thermocline producing a strong vertical temperature gradient about 3° C m^{-1} for a typical mid-summer thickness of 3 meters [*Schertzer et al.*, 1987].

[14] Analysis of temperature measurements at the 2005 moorings confirmed the persistence of an atypical bowl-shaped thermocline in summer on a basin-wide scale. To track the long-term evolution of thermocline, each temperature record was low-pass filtered, mainly to remove near-inertial oscillations, i.e., Poincare waves with 18 h period for Lake Erie latitude of 42° N [*Rao et al.*, 2008]. Internal Kelvin waves have not been observed in the central basin, and moorings were nevertheless located outside of their potential impact area. The resulting vertical temperature profile at each mooring was then objectively analyzed to determine thermocline position (its top and bottom depth). To accomplish that, each hourly temperature profile was fitted in a least squared sense with a 3-layer structure: fully mixed upper and bottom layers, and linearly decreasing temperature in between, as described by *Beletsky at al.* [2006]. The resulting positions of the thermocline's top and bottom were averaged over 10 day periods and plotted in Figure 2a for the August-September period (days 210–269) when the bowl-shaped thermocline was most pronounced.

[15] Similar to the PSS observations in July, the thermocline thickness in August-September varied between 2 and 3 m. During days 210–219 in 2005 (Figure 2a), the thermocline deepened by 4 m from the westernmost mooring, T08, to the central mooring, T09 (from about 13 to 17 m), and then rose by 2 m at easternmost mooring T16. The north-south transect showed the same bowl-shaped pattern but a smaller depth change (from 1 m at the south-center moorings to 3 m for the north-center moorings). 10 days later, the thermocline downwelled at T09 to 18 m which resulted in a west-center thermocline depth difference of about 6.5 m and an east-center depth difference of about 3 m. Although thermocline depth differences became somewhat smaller in later periods, the bowl shape persisted until the end of September in both west-east and north-south directions. From early August to late September thermocline depth gradually increased in time everywhere, and the thermocline was getting very close to the lake's bottom in September. The shape of this bowl was not symmetric. On average, the northern side was tilted more upward than the south side (3.8 m versus 1.8 m) and the west side was tilted more upward than the east side (5.3 m versus 2.3 m).

[16] In 2007, the bowl-shaped thermocline was observed in the central basin of Lake Erie again, but only in August (not shown). There was a 2 m difference in thermocline depth between both west-center and east-center moorings, so the bowl was more symmetric in the west-east direction in 2007 than in 2005 but its mid-lake depression was less pronounced. Interestingly, the deepest thermocline location shifted west in 2007, from mooring T09 to mooring T07.

[17] Long-term current measurements showed rather uniform velocity profiles in the upper layer (which occupied about 2/3 of the water column due to a deep thermocline in August-September 2005 as seen in Figure 2a) with very small velocities below the thermocline. Although observations in the northern part of the central basin are lacking, available data indicate a single gyre anticyclonic circulation pattern during August-September (Figure 2b). This type of circulation is rather unusual for the Great Lakes [*Beletsky et al.*, 1999] but was actually observed in Lake Erie before [*Saylor and Miller*, 1987]. Since wind curl is an effective source of vorticity in lakes [*Schwab and Beletsky*, 2003], this finding prompted a detailed investigation of the wind field during the period of study.

[18] Wind data analysis showed that although winds were omni-directional during August-September 2005, anti-cyclonic (negative) vorticity was present most of the time (Figure 3) and was apparently impacting circulation patterns in Lake Erie while the temperature field must be affected through the Ekman pumping mechanism as well. Anticyclonic circulation covered the whole central basin and current speed (water column averaged) was strongest during the first half of August (days 210–229) when anti-cyclonic vorticity in the wind field was strongest (Figure 3). During the next 10 days (230–239) wind vorticity became cyclonic (positive). Consequently, the area covered by anti-cyclonic circulation decreased along with decrease in the average current speed as the new wind pattern was generating a cyclonic circulation opposing the existing anticyclonic one. The bowl-shaped thermocline became less pronounced during the day 230–239 period as well, especially in the north-south section. In the next 30 days, wind vorticity became anti-cyclonic again (Figure 3) and the anticyclonic circulation expanded correspondingly, covering most of the basin again. The bowl-shaped thermocline became more pronounced in the north-south direction as well.

[19] The magnitude of vertical motions caused by the Ekman pumping is proportional to the wind stress curl [*Gill*, 1982]. Using the same wind data we calculated wind stress (assuming neutral stability of atmospheric boundary layer) and estimated the Ekman pumping velocity (i.e., wind stress curl divided by the Coriolis parameter and water density). The average wind stress curl in August–September 2005 was about -10^{-7} N m^{-3} (negative) which gives an Ekman pumping velocity of about 10^{-6} m s^{-1} resulting in thermocline deepening of 1 m every 10 days. This compares well with the presented temperature observations and thus makes Ekman pumping a likely mechanism for supporting this unusual shape of a thermocline.

4. Discussion

[20] The persistence of the bowl-shaped thermocline over a long period of time (two months in 2005 and over one month in 2007) was probably enhanced by low energy dissipation due to very low current speeds in the bottom layer. Estimated spin down time [*Greenspan and Howard*, 1963] for a barotropic basin with a depth of 20 m and vertical viscosity of 10^{-4} m^2 s^{-1} [*Rao et al.*, 2008] is about 3 days and does not depend on the sense of rotation. In a stratified basin, the spin down time becomes longer because the area that responds to friction becomes bottom-trapped without appreciably affecting the upper layers [*Holton*, 1965; *St-Maurice and Veronis*, 1975], so it is thus possible that once established during a favorable wind event, the bowl-shaped thermocline and (geostrophically balanced) anticyclonic circulation would last for a considerable time without requiring additional supply of energy. Unusual anticyclonic circulation in central Lake Erie is most likely explained by its higher sensitivity to the wind curl due to the

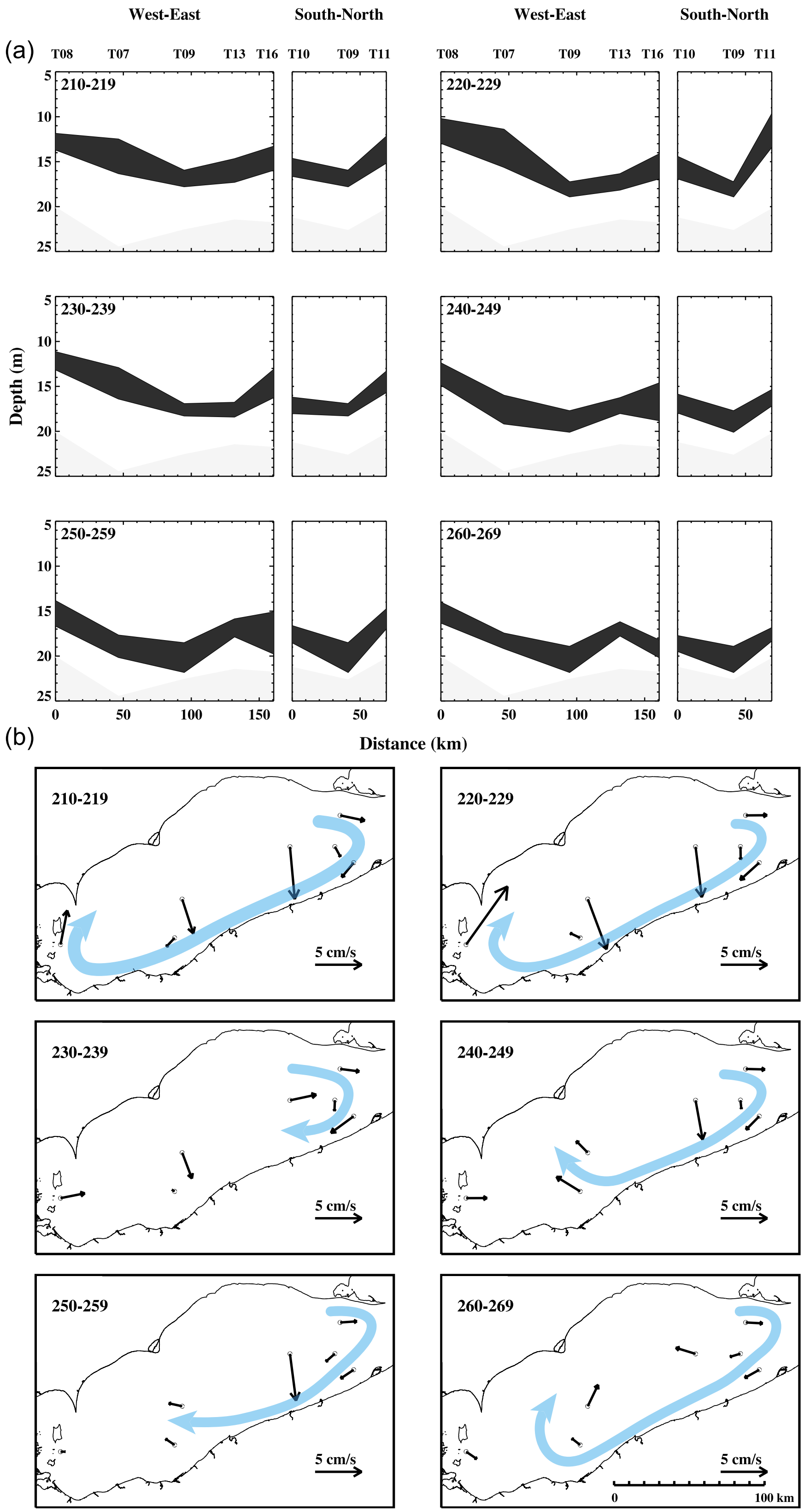

Figure 2. (a) Bowl-shaped thermocline profile. Objectively analyzed, 10-day averaged thermocline profile observed in Lake Erie at west-east and south-north transects (see Figure 1 for mooring location and text for details) in 2005. Time period is shown in the upper left corner of each panel. Thermocline is represented by a black shading, bottom topography by a grey shading. (b) Anticyclonic circulation patterns. 10-day averaged, water column averaged observed currents in Lake Erie. Time period is shown in the upper left corner of each panel. ADCP mooring locations are given in Table 1.

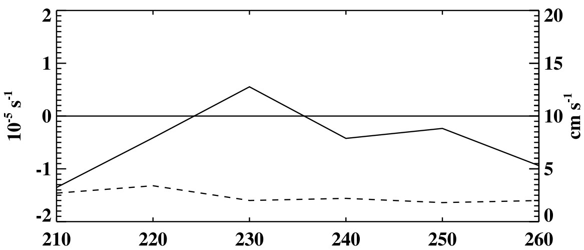

Figure 3. Anticyclonic wind vorticity (solid line). 10-day averaged, lake averaged wind vorticity over Lake Erie derived from atmospheric model winds during six 10-day periods (days 210–269) in 2005. Lake-averaged current speed is shown by a dotted line.

flat bottom geometry, but when sufficient wind vorticity is present, other large lakes are likely to experience a similar Ekman pumping mechanism working in summer as well: one suspect case is the southern Lake Michigan anticyclonic circulation in August 1999 presented by *Beletsky et al.* [2006].

[21] Ecological implications of the bowl-shaped thermocline discovery should be significant for large shallow basins. In the case of central Lake Erie, a 5 m increase in thermocline depth due to a depressed thermocline means a significant reduction of the hypolimnion (bottom layer) thickness which is typically less than 10 m in mid-summer. Of particular interest will be the impact of the bowl-shaped thermocline on mid-lake hypoxia/anoxia which forms in Lake Erie in September (and related biogeochemical processes) when strong stratification still exists but the thermocline gets very close to the lake's bottom. When present in late summer over a period of one month or longer, a significantly deeper thermocline coupled with the intrinsic sediment oxygen demand will result in lower oxygen concentration in the hypolimnion that will affect health and behavior of fish, plankton, and benthos [*Vanderploeg et al.*, 2009]. Another concern raised by these findings is that long term studies of hypoxia which rely on 1D models using profiles taken at the lake center do not include the Ekman pumping effect.

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References

Beletsky, D., and D. Schwab (2008), Climatological circulation in Lake Michigan, *Geophys. Res. Lett.*, *35*, L21604, doi:10.1029/2008GL035773.

Beletsky, D., J. H. Saylor, and D. J. Schwab (1999), Mean circulation in the Great Lakes, *J. Great Lakes Res.*, *25*(1), 78–93, doi:10.1016/S0380-1330(99)70718-5.

Beletsky, D., D. Schwab, and M. McCormick (2006), Modeling the 1998–2003 summer circulation and thermal structure in Lake Michigan, *J. Geophys. Res.*, *111*, C10010, doi:10.1029/2005JC003222.

Bennett, J. R. (1974), Dynamics of wind-driven lake currents, *J. Phys. Oceanogr.*, *4*(3), 400–414, doi:10.1175/1520-0485(1974)004<0400:OTDOWD>2.0.CO;2.

Birchfield, G. E. (1967), Horizontal transport in a rotating basin of parabolic depth profile, *J. Geophys. Res.*, *72*(24), 6155–6163, doi:10.1029/JZ072i024p06155.

Bolsenga, S. J., and C. E. Herdendorf (1993), *Lake Erie and Lake St. Clair Handbook*, 467 pp., Wayne State Univ. Press, Detroit, Mich.

Boyce, F. M., M. A. Donelan, P. F. Hamblin, C. R. Murthy, and T. J. Simons (1989), Thermal structure and circulation in the Great Lakes, *Atmos. Ocean*, *27*(4), 607–642, doi:10.1080/07055900.1989.9649358.

Burns, N. M., D. C. Rockwell, P. E. Bertram, D. M. Dolan, and J. J. H. Ciborowski (2005), Trends in temperature, Secchi depth, and dissolved oxygen depletion rates in the central basin of Lake Erie, 1983–2002, *J. Great Lakes Res.*, *31*(2), 35–49, doi:10.1016/S0380-1330(05)70303-8.

Church, P. E. (1945), *The Annual Temperature Cycle of Lake Michigan. II. Spring Warming and Summer Stationary Periods*, *Misc. Rep.*, vol. 18, 100 pp., Univ. of Chicago Press, Chicago, Ill.

Csanady, G. T. (1968), Wind-driven summer circulation in Great Lakes, *J. Geophys. Res.*, *73*(8), 2579–2589, doi:10.1029/JB073i008p02579.

Csanady, G. T. (1973), Wind-induced barotropic motions in long lakes, *J. Phys. Oceanogr.*, *3*, 429–438, doi:10.1175/1520-0485(1973)003<0429:WIBMIL>2.0.CO;2.

Csanady, G. T. (1977), Cyclonic mean circulation of large lakes, *Proc. Natl. Acad. Sci. U. S. A.*, *74*(6), 2204–2208, doi:10.1073/pnas.74.6.2204.

Emery, K. O., and G. T. Csanady (1973), Surface circulation of lakes and nearly land-locked seas, *Proc. Natl. Acad. Sci. U. S. A.*, *70*(1), 93–97, doi:10.1073/pnas.70.1.93.

Endoh, S., and Y. Okumura (1993), Gyre system in Lake Biwa derived from recent current measurements, *Jpn. J. Limnol.*, *54*(3), 191–197, doi:10.3739/rikusui.54.191.

Forel, F. A. (1901), Etudes thermique des lacs du nord de l'Europe, *Arch. Sci. Phys. Nat.*, *4*(12), 35–55.

Gill, A. E. (1982), *Atmosphere-Ocean Dynamics*, 666 pp., Academic, New York.

Greenspan, H. P., and L. N. Howard (1963), On the time-dependent motion of a rotating fluid, *J. Fluid Mech.*, *17*(03), 385–404, doi:10.1017/S0022112063001415.

Hawley, N., T. Johengen, R. Yerubandi, S. Ruberg, D. Beletsky, S. Ludsin, B. J. Eadie, D. J. Schwab, T. Croley, and S. Brandt (2006), Lake Erie hypoxia prompts Canada-U.S. study, *Eos Trans. AGU*, *87*(32), 313–319, doi:10.1029/2006EO320001.

Hofmann, E. E., A. J. Busalacchi, and J. J. Obrien (1981), Wind generation of the Costa Rica dome, *Science*, *214*(4520), 552–554, doi:10.1126/science.214.4520.552.

Holton, J. R. (1965), Influence of viscous boundary layers on transient motions in a stratified rotating fluid. Part I, *J. Atmos. Sci.*, *22*(4), 402–411, doi:10.1175/1520-0469(1965)022<0402:TIOVBL>2.0.CO;2.

Huang, A., Y. R. Rao, and Y. Lu (2010), Evaluation of a 3-D hydrodynamic model and atmospheric forecast forcing using observations in Lake Ontario, *J. Geophys. Res.*, *115*, C02004, doi:10.1029/2009JC005601.

Laval, B. E., J. Imberger, and A. N. Findikakis (2005), Dynamics of a large tropical lake: Lake Maracaibo, *Aquat. Sci.*, *67*(3), 337–349.

Monismith, S. G., J. Imberger, and M. L. Morison (1990), Convective motions in the sidearm of a small reservoir, *Limnol. Oceanogr.*, *35*(8), 1676–1702, doi:10.4319/lo.1990.35.8.1676.

Phillips, O. M. (1970), On flows induced by diffusion in a stably stratified fluid, *Deep Sea Res.*, *17*(3), 435–443.

Pickett, R. L., and D. B. Rao (1977), One- and two-gyre circulations in homogeneous lakes, *Int. Field Year Great Lakes Bull.*, *19*, 45–49.

Rao, D. B., and T. S. Murty (1970), Calculation of the steady state wind-driven circulations in Lake Ontario, *Meteorol. Atmos. Phys.*, *19*, 195–210.

Rao, Y. R., N. Hawley, M. N. Charlton, and W. M. Schertzer (2008), Physical processes and hypoxia in the central basin of Lake Erie, *Limnol. Oceanogr.*, *53*(5), 2007–2020, doi:10.4319/lo.2008.53.5.2007.

Rueda, F. J., S. G. Schladow, S. G. Monismith, and M. T. Stacey (2005), On the effects of topography on wind and the generation of currents in a large multi-basin lake, *Hydrobiologia*, *532*, 139–151, doi:10.1007/s10750-004-9522-4.

Saylor, J. H., and G. S. Miller (1987), Studies of large-scale currents in Lake Erie, 1979–80, *J. Great Lakes Res.*, *13*(4), 487–514, doi:10.1016/S0380-1330(87)71668-2.

Schertzer, W. M., J. H. Saylor, F. M. Boyce, D. G. Robertson, and F. Rosa (1987), Seasonal thermal cycle of Lake Erie, *J. Great Lakes Res.*, *13*(4), 468–486, doi:10.1016/S0380-1330(87)71667-0.

Schwab, D. J., and D. Beletsky (2003), Relative effects of wind stress curl, topography, and stratification on large-scale circulation in Lake Michigan, *J. Geophys. Res.*, *108*(C2), 3044, doi:10.1029/2001JC001066.

Schwab, D. J., W. P. O'Connor, and G. L. Mellor (1995), On the net cyclonic circulation in large stratified lakes, *J. Phys. Oceanogr.*, *25*(6), 1516–1520, doi:10.1175/1520-0485(1995)025<1516:OTNCCI>2.0.CO;2.

Shimizu, K., J. Imberger, and M. Kumagai (2007), Horizontal structure and excitation of primary motions in a strongly stratified lake, *Limnol. Oceanogr.*, *52*(6), 2641–2655, doi:10.4319/lo.2007.52.6.2641.

Shtokman, V. B. (1941), Storm surge and horizontal circulation in a shallow enclosed sea [in Russian], *Izv. Akad. Nauk SSSR Ser. Geogr. Geofiz.*, *1*, 69–89.

Shtokman, V. B. (1953), Effects of bottom topography and horizontal wind shear on horizontal circulation in a shallow sea or reservoir [in Russian], *Meteorol. Hydrol.*, *8*, 16–22.

Simons, T. J., and W. M. Schertzer (1987), Stratification, currents, and upwelling in Lake Ontario, summer 1982, *Can. J. Fish. Aquat. Sci.*, *44*(12), 2047–2058, doi:10.1139/f87-254.

St-Maurice, J.-P., and G. Veronis (1975), A multi-scaling analysis of spin-up problem, *J. Fluid Mech.*, *68*, 417–445, doi:10.1017/S0022112075001747.

Strub, P. T., and T. M. Powell (1986), Wind-driven surface transport in stratified closed basins: Direct versus residual circulations, *J. Geophys. Res.*, *91*(C7), 8497–8508, doi:10.1029/JC091iC07p08497.

Tikhomirov, A. I. (1982), *Thermal Regime of Large Lakes* [in Russian], 232 pp., Nauka, Leningrad, Russia.

Vanderploeg, H. A., S. A. Ludsin, S. A. Ruberg, T. O. Hook, S. A. Pothoven, S. B. Brandt, G. A. Lang, J. R. Liebig, and J. F. Cavaletto (2009), Hypoxia affects spatial distributions and overlap of pelagic fish, zooplankton, and phytoplankton in Lake Erie, *J. Exp. Mar. Biol. Ecol.*, *381*, S92–S107, doi:10.1016/j.jembe.2009.07.027.

Weenink, M. P. H. (1958), *A Theory and Method of Calculation of Wind Effects on Sea Levels in a Partly-Enclosed Sea*, *Meded. Verh.*, vol. 73, 111 pp., R. Neth. Meteorol. Inst., De Bilt.

Wunsch, C. (1970), On oceanic boundary mixing, *Deep Sea Res.*, *17*(2), 293–301.

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