Encyclopedia of Earth Sciences Series
Encyclopedia of Lakes and Reservoirs
Springer Science+Business Media B.V. 2012
10.1007/978-1-4020-4410-6_264
Lars Bengtsson, Reginald W. Herschy and Rhodes W. Fairbridge

Laurentian Great Lakes, Interaction of Coastal and Offshore Waters

Yerubandi R. Rao[1] and **David J. Schwab**[2]

(1) Environment Canada, National Water Research Institute, Canada Center for Inland Waters, 867 Lakeshore Road, Burlington, ON, Canada

(2) Great Lakes Environmental Research Laboratory, 2205 Commonwealth Blvd, Ann Arbor, MI 48105, USA

Yerubandi R. Rao (Corresponding author)
Email: Ram.Yerubandi@ec.gc.ca

David J. Schwab
Email: david.schwab@noaa.gov

Without Abstract

Introduction

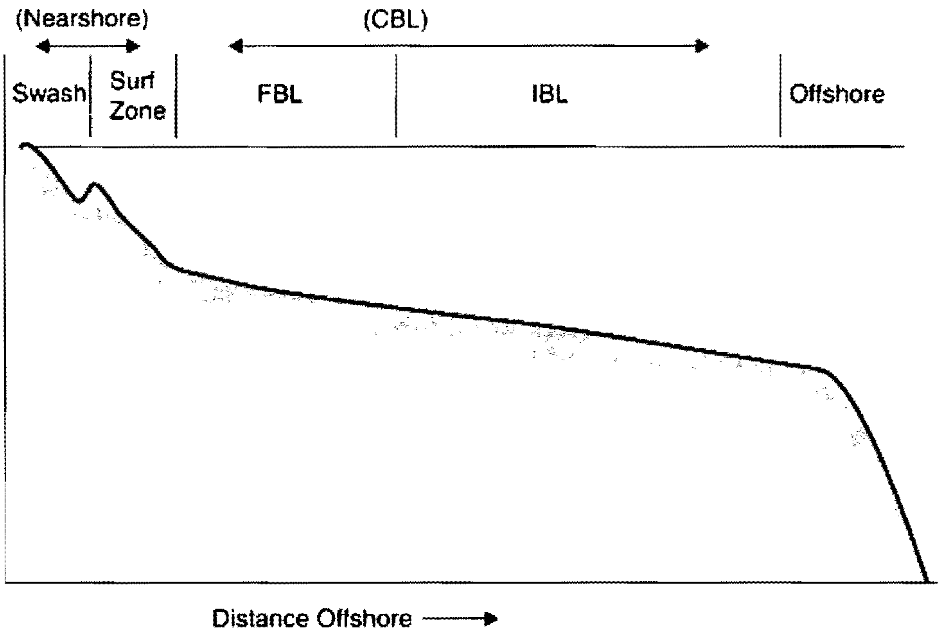
The Laurentian Great Lakes represent an extensive, interconnected aquatic system dominated by its coastal nature. While the lakes are large enough to be significantly influenced by the earth's rotation, they are at the same time closed basins to be strongly influenced by coastal processes (Csanady, 1984). Nowhere is an understanding of how physical, geological, chemical, and biological processes interact in a coastal system more important to a body of water than the Great Lakes. Several factors combine to create complex hydrodynamics in coastal systems, and the associated physical transport and dispersal processes of the resulting coastal flow field are equally complex. Physical transport processes are often the dominant factor in mediating geochemical and biological processes in the coastal environment. Thus, it is critically important to have a thorough understanding of the coastal physical processes responsible for the distribution of chemical and biological species in this zone. However, the coastal regions are not isolated but are coupled with mid-lake waters by exchanges involving transport of materials, momentum, and energy.

This review will focus on several mechanisms that contribute to the alongshore and cross-shore transport of material. These are (1) wave-driven processes, (2) coastal boundary layer processes including upwelling and downwelling flows, (3) episodic events such as storms, (4) the thermal bar, and (5) river plumes.

Subregions of the coastal zone

The first characteristic feature of coastal waters is their shallow depth, typically 0–20 m, compared with lake-average depths of 60–150 m except Lake Erie. The nearshore or coastal zone in the Great Lakes is defined as the zone that begins at the shoreline or the lakeward edge of coastal wetlands and extends offshore to the depth where the thermocline typically intersects with the lake bed in late summer or early fall (Rao and Schwab, *2007*). This delineation also includes the surf and swash zones in the littoral zone. Because of shallow depths in the coastal zone, currents near the bottom are often much larger than in deeper areas. Bottom friction plays a significant role in nearshore dynamics. The presence of the shoreline acts as a lateral constraint on water movements, tending to divert currents so that they flow nearly parallel to the shoreline. The shoreline also causes surface slopes to develop, which in turn affect water movements. The influx of freshwater runoff from the land affects the density of the coastal water. For a similar heat flux through the sea surface, the shallower water near the coast undergoes larger changes in temperature than deeper water. Because of these effects, coastal waters of the Great Lakes exhibit large horizontal gradients of density, often associated with changes in currents. The Great Lakes also undergo a complete cycle of isothermal to vertically stratified conditions in a year. The thermal structure in the Great Lakes generally depends on the season because of the large annual variation of surface heat fluxes (Boyce et al., *1989*). During the unstratified period, storm action is the most important forcing, as higher wind speeds and the absence of stratification allow the wind forcing to penetrate deeper into the water column. In summer and fall most of the lakes are stratified with a distinct thermocline in the upper 20–30 m (Boyce et al., *1989*).

Horizontal spatial scales of coastal physical processes can range from 10 m in nearshore areas for surface gravity waves to hundreds of kilometers for large-scale wind-driven flows. The flow regimes of the coastal zone are not all uniform from nearshore to offshore waters but vary appreciably as water depth changes. For convenience, the coastal zone can be divided into three regimes, namely, (1) the nearshore area consisting of swash and surf zones, (2) the frictional and inertial boundary layers, together known as coastal boundary layer (CBL), and (3) the open lake (Figure 1). In the open lake the momentum imparted by the wind stress is balanced by the Coriolis force, frictional forces are small, and wave-induced bottom agitation is minimal. In contrast, the frictional boundary layer (FBL) is dominated by bottom friction and lateral friction. At around 3 km from shore an outer boundary layer, known as the inertial boundary layer (IBL) develops due to the adjustment of inertial oscillations to shore-parallel flow (Rao and Murthy, *2001*). Wave run-up and breaking waves are dominant sources of mean flows within the swash and surf zones.



Laurentian Great Lakes, Interaction of Coastal and Offshore Waters, Figure 1 Schematic diagram of the subregions of the coastal zone (Source: Rao and Schwab, 2007).

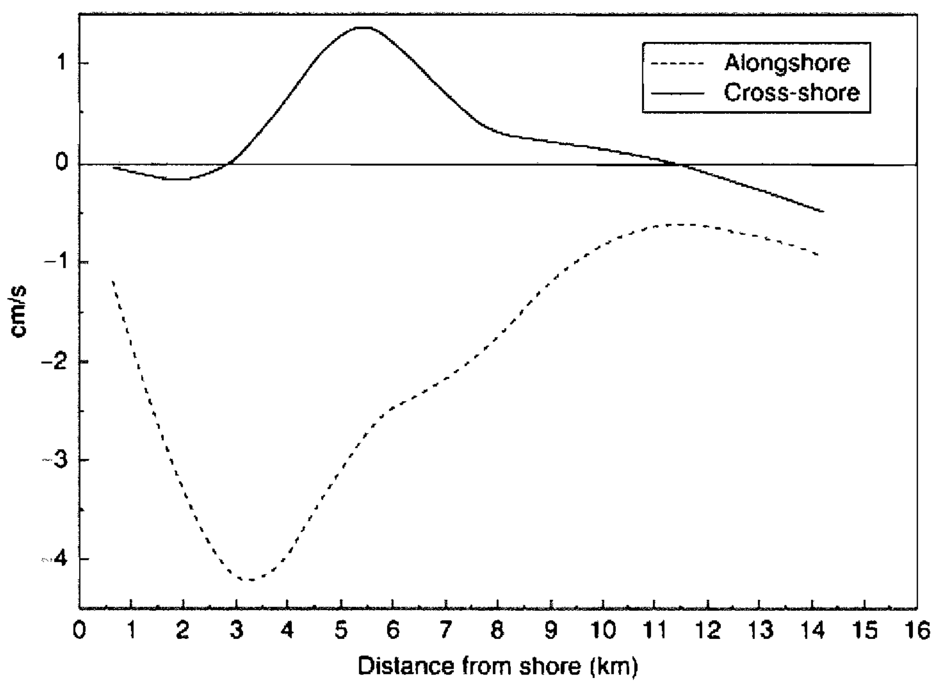
Wave-driven processes

The wind excites surface waves that create hazardous conditions for recreation and navigation and are also the main cause for shoreline erosion. The most common wind directions over the Great Lakes region are south-westerly to westerly, but in a climate which is extremely variable from day to day, winds from other directions are quite frequent, and strong spells of easterly or north-easterly winds are not unusual. As wind-generated waves propagate from deeper water toward the shore, wave orbital motions must adjust to the shallower water depths, modifying the wave kinematics. Therefore, the greatest effect of wind waves occurs in the surf and swash zones. Inputs of storm runoff, combined sewer overflows, and streams occur in this zone. The swash zone with wave run-up and run-down on a beach forms the boundary between the surf zone and the backshore. It also determines the landward boundary of the area affected by the wave action. The surf zone is the area of water between the swash zone and the seaward side of breaking waves. The width of the surf zone is very small compared to the total width of the coastal boundary layer. In contrast to other regimes in the coastal zone, the surf zone is severely constrained laterally; therefore the geostrophic effects (steady currents sustained by a balance between the pressure gradient force and the Coriolis force) are negligible. Circulation is driven almost exclusively by forces resulting from the dissipation of breaking waves. The net onshore transport of water by wave action in the breaker zone, the lateral transport inside the breaker zone by longshore currents, and the seaward return of the flow through the surf zone by rip currents constitute a nearshore circulation system. Wave-generated currents, which transport beach material, are an important factor in the beach stability. The direction of littoral drift is determined by the angle of wave approach and associated longshore currents, and is particularly critical during periods of high lake levels. The predominant direction of the littoral drift depends on non-storm waves that contain much more total energy than is contained in storm waves of shorter duration. Wave-generated currents carry some particles along the bottom as bed load, while other particles are carried some height above the bottom as suspended load.

The coastal boundary layer

The coastal boundary layer is the region between the wave-breaking zone and the open lake where frictional forces and the steering affect of the shore are dominant processes. The prime driving force of circulation in this zone is again the wind; however, the effects of stratification can become very important during the summer period. The wind action on coastal waters rapidly generates flow predominantly parallel to the coast. When a steady wind blows across a lake, the equilibrium condition of the water surface is a depression along the upwind end and an increase of elevation (storm surge) along the downwind end of the lake. Surface seiche, which is the oscillatory response of the lake surface after wind cessation, can also have a significant impact on the nearshore circulation in some of the Great Lakes. When a steady wind over the homogeneous lake pushes water downwind, the water level rises, and the resultant pressure gradient causes a return flow in the deeper parts of the lake forming two counter-rotating gyres.

Winds at mid-latitudes are usually quite variable, rarely displaying significant persistence for more than a day. Under these circumstances the transient properties of coastal currents are often of greater practical importance than the steady state for constant wind. These transient properties depend on the frequency of weather cycles. A particularly notable feature of coastal currents in the Great Lakes is the presence of inertial oscillations during the stratified period. At the latitude of the Great Lakes the inertial period is close to 17 h. Although these oscillations are more like an organized flow, because of their oscillatory nature they can be viewed as large-scale fluctuations and as such contribute to dispersal processes in the coastal zone. In the coastal zone, these types of rotary motions are modified since the particle velocities perpendicular to the coast must vanish at the shoreline. Consequently, there is an adjustment zone, typically 5–10 km wide often referred to as the coastal boundary layer (Figure 2).



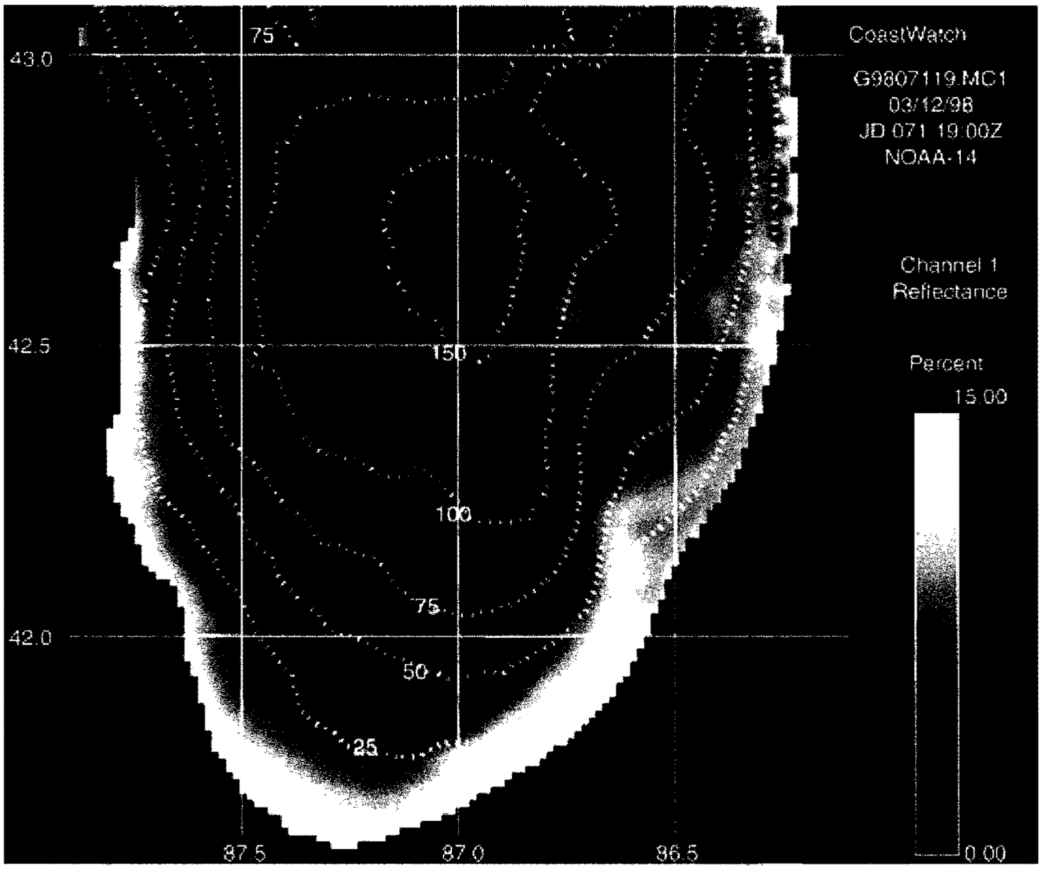
Laurentian Great Lakes, Interaction of Coastal and Offshore Waters, Figure 2 Mean alongshore and cross-shore components of currents (Source: Rao and Murthy, 2001).

During the stratified season significant wind events cause upwelling and downwelling of the thermocline along the shore and within the CBL. If the coast is to the left of the prevailing winds, the wind-induced Ekman transport will be away from the coast in the surface layer and upwelling occurs near the coast. During this period an onshore and upslope transport occurs at some depth below the surface. On the other hand, if the coast is to the right of the wind, downwelling occurs. The transport in the surface layer is toward the coast, and offshore transport occurs below the surface layer. The changeovers from upwelling to downwelling regimes and vice versa are of particular interest to nearshore biology and chemistry studies. The offshore distance scale over which these events take place depends on the wind stress and nearshore bathymetry (Csanady, 1984) and is known as the Rossby radius of deformation (typically of the order of 3–5 km). In this zone a balance exists between wind stress, Coriolis force, and internal pressure gradient. A typical changeover from upwelling to downwelling is accompanied by marked changes in the thermal structure in this zone in a period of 4–5 days, exposing the zone to either epilimnetic water or hypolimnetic water depending upon the situation. Upwelling and downwelling have the potential to produce large onshore-offshore transport of material.

During the stratified season in the Great Lakes two types of internal waves often occur after a strong wind event: Poincaré waves and internal Kelvin waves. Poincaré waves are the near-inertial period basin-wide oscillations of the thermocline characterized by anticyclonic phase propagation. These waves were first observed in the Great Lakes by analyzing temperature observations at municipal water intakes for cities around Lake Michigan (Mortimer, 1963). On the other hand, internal Kelvin waves are coastally trapped oscillations of the thermocline that progress cyclonically around the lake with a phase speed of 0.5 m/s (Beletsky et al., 1997). During periods of calm or weak meteorological conditions, coastal currents are usually weak. Experiments conducted on the Great Lakes showed that significant mass exchange between the CBL and offshore waters takes place during episodic events and the current reversals associated with the propagation of internal Kelvin waves. Complex patterns of cross-shore transport have been observed in upwelling systems including the Great Lakes.

Episodic events in Great Lakes

Circulation in the Great Lakes is also highly episodic with the most energetic currents and waves occurring during the strongest storms. During fall and winter seasons, the higher wind speeds and the absence of the thermocline allow the effects of wind action to penetrate deeper into the water column. In the Great Lakes, the gradients of many biogeochemically important materials are considerably higher in the offshore direction than in the alongshore direction. In the presence of these large gradients, cross-isobath circulation is a primary mechanism for the exchange of material between nearshore and offshore waters. Spring and fall storms can create a nearshore zone of turbid water up to 10 km wide which sometimes encompasses a significant portion of the lake's coastal zone (Figure 3). Much of the resuspended material consists of fine-grained silty clay that can remain in suspension for several weeks after a storm. The total estimated amount of material resuspended during a large event can be comparable to the total annual load (erosion, atmospheric deposition, and tributary input) of fine-grained material to the entire basin.

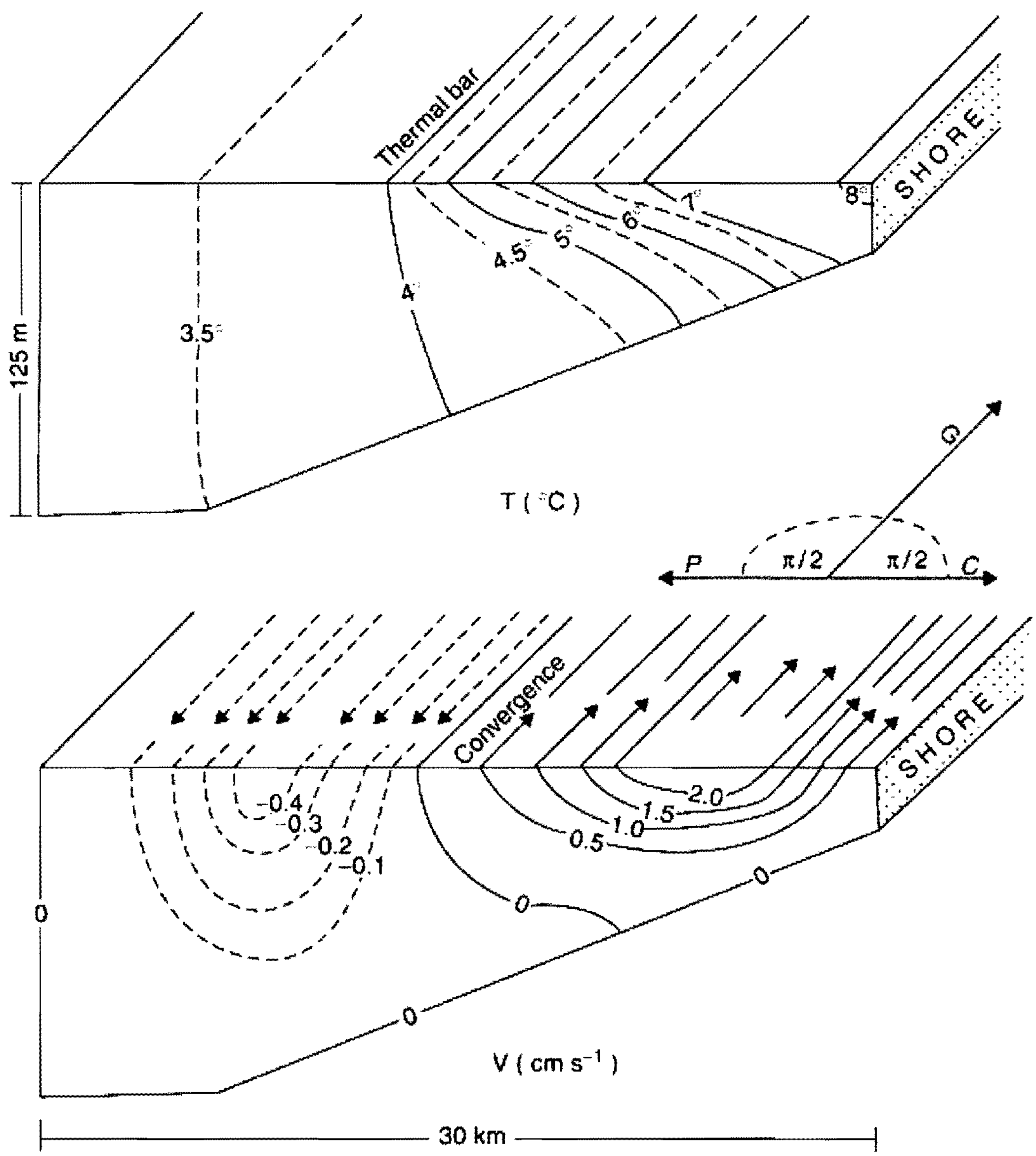


Laurentian Great Lakes, Interaction of Coastal and Offshore Waters, Figure 3 Satellite picture showing reflectance during a winter storm in Lake Michigan.

In the case represented in Figure 3, it was observed that in the shallow waters of the southern basin of Lake Michigan, the water near the coasts moves in the direction of the wind toward the south, while return flow occurs in the deeper parts of the lake. This process forms two counter-rotating closed gyres, a cyclonic gyre to the right of the wind and an anticyclonic gyre to the left. These gyres are one of the important mechanisms for nearshore-offshore transport in the Great Lakes since they generate an area of intense offshore flow where they converge at the downward end of the lake. The mean and fluctuating coastal currents in southeastern Lake Michigan were studied during the winter and early spring during the three field years of the Episodic Events Great Lakes Experiment (EEGLE). The winter-spring currents in this region are quite depth-independent, and the vortex mode identified earlier in offshore waters is also evident in the data from these coastal waters. The net seasonal currents during the winter season flow predominantly alongshore and toward the north. Time varying alongshore circulation is more closely tied to the alongshore component of the wind. The net offshore transport appears to be a result of the combination of wind-forced two-gyre circulation, Ekman veering of bottom boundary layer currents, and the topographic steering. However, the interannual variability of current speeds and magnitudes seems to be caused mainly by variability of surface wind forcing. The intermittent episodic circulation influenced by northerly storms causes significant asymmetry in the mean circulation pattern. There is also significant variability of circulation from one storm to another. The alongshore currents were initially driven by strong northerly wind pulses, but subsequently reverse direction as the forcing stops. The two-gyre circulation seems to be an important mechanism for the relaxation of currents as well as the offshore transport in the southern Lake Michigan. Direct wind-forced offshore transport was also observed in some regions.

The thermal bar

The thermal bar is a downwelling plume of freshwater at the temperature of maximum density (4°C), and is formed in temperate lakes in spring and fall when waters on either side of the 4°C isotherm mix (Figure 4). The density-induced horizontal circulation in large temperate lakes of the northern hemisphere is counter-clockwise in the stably stratified nearshore region, and clockwise in the deep water region. The secondary circulation, perpendicular to the primary one, consists of two circulation cells, one on each side of the 4°C isotherm, where coastal and offshore waters mix and descend. This two-cell thermal bar circulation is important because of its role in inhibiting the horizontal exchange of water between the nearshore and offshore regions. The thermal bar can significantly affect the flow and thermal characteristics of the Great Lakes and may have significant influence on their ecological functioning. This effect is extremely important because a proper understanding of an ecosystem's interaction with the hydrodynamics is required to determine optimum nutrient loadings to the lake.



Laurentian Great Lakes, Interaction of Coastal and Offshore Waters, Figure 4 Schematic diagram of the spring thermal bar (From Henderson-Sellers, 1984).

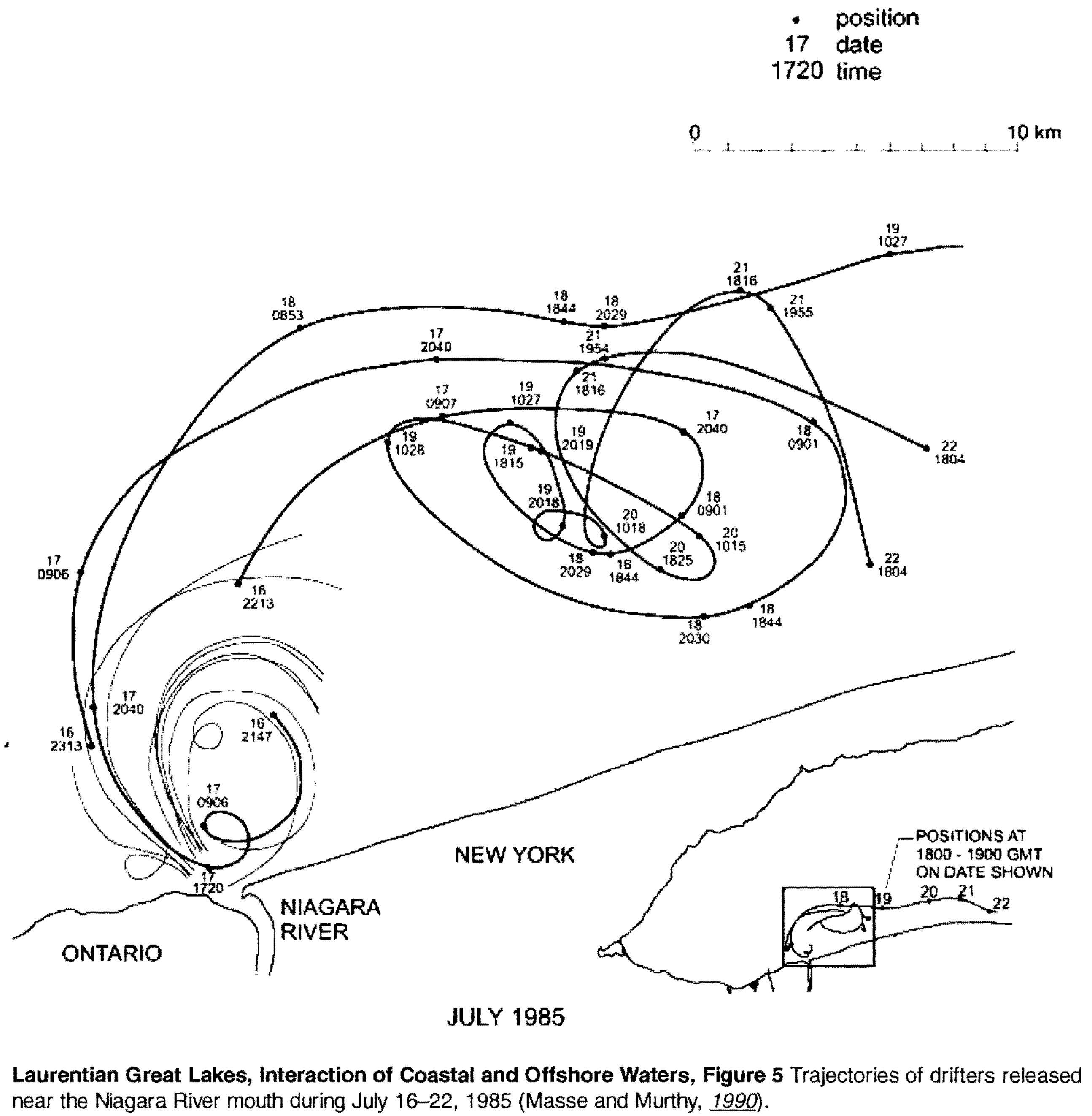
In the 2003 Lake Ontario experiment, the coastal circulation was mainly influenced by the alongshore winds. One of the interesting observations in this experiment is that the thermal bar was stationary for several days. Although mean cross-shore flow decreased during the thermal bar period, the flow was depth-dependent. In general, theoretical models overestimated the progression rate of the thermal bar during the early phase. In the later phase, the models that incorporated the effect of horizontal heat flux in the thermal bar region were able to predict the significant increase in the progression rate. This study concluded that the effect of wind on the thermal bar seems to be an important feature and the models have to incorporate this effect. Also, the horizontal turbulent exchange parameters showed non-isotropic conditions in the shallow stably stratified region. The alongshore horizontal exchange coefficients were higher than cross-shore exchange coefficients. During the thermal bar period, the magnitude of both alongshore and cross-shore exchange coefficients decreased when the bar was in the nearshore zone and from mid-depth onward the thermal bar has not shown any impact on alongshore exchange coefficients, but cross-shore exchanges decreased marginally. Some studies suggest that the lateral current shear between the nearshore and the thermal bar region could be an important factor in maintaining the horizontal exchanges in the deeper waters. The vertical exchange coefficients observed during the thermal bar are comparable to the high values observed during significant upwelling episodes in Lake Ontario. The high values in the water column were due to the convective mixing during the thermal bar. During the evolution of the spring thermal bar, the vertical mixing decreased considerably in the nearshore regions under stable stratification, whereas, the high vertical mixing levels continued in the offshore region for a longer period.

River plumes

Discharge from rivers contains sediments, nutrient, and pollutant loads that can have significant adverse impacts on water quality near the river mouth in the receiving lake. Horizontal mixing and dispersion of a river plume in shallow receiving basins are key processes which affect the distribution and fate of water-borne material. The mixing of river plumes has been widely studied in the past few decades using numerical models. Obviously, the effects of buoyant forces on plume transport in a lake are much weaker compared to the oceanographic settings, even though both the positively and negatively (Masse and Murthy, 1990) buoyant river plume were observed in large lakes due to temperature differences and particle concentrations of river discharges.

Water-quality analyses of the Niagara River have shown high concentrations of toxic chemicals that are introduced by the river plume into Lake Ontario. Much research has been conducted to investigate the dynamics of the Niagara River inflow into Lake Ontario. The nearshore thermal structure is altered significantly by the inflow, the warmer Niagara River plume extends beyond the river mouth in excess of 10 km, after which it eventually mixes with the ambient lake water. The vertical extent of the Niagara River plume can be 8–10 m, with the warmer inflowing water developing a frontal structure as it enters the lake. The gradient across the thermal front depends on the time of year and therefore on the difference between the temperature of the inflowing water and the ambient lake temperatures.

Prevailing wind conditions and lake circulation patterns determine the spread of the Niagara River plume in Lake Ontario. In most circumstances, a plume develops from the Niagara River mouth and tends to extend eastward along the south shore of the lake. In the initial phase, horizontal velocities from the Niagara River mouth are reduced significantly, and the river water is vertically well mixed over the shallow bar area. Beyond this initial phase, the river plume is deflected in response to lakewide circulation and the prevailing winds. In the transition phase, a large clockwise eddy between 10 and 12 km in diameter is formed to the east of the Niagara River mouth. The eddy appears often and lasts for a few days. From a water-quality standpoint, river outflow that is entrained into this zone of low net transport is effectively isolated from the mixing effects of the main shore-parallel currents. Consequently, this nearshore area can be a zone in which fine particulate material is deposited (Figure 5).



Laurentian Great Lakes, Interaction of Coastal and Offshore Waters, Figure 5 Trajectories of drifters released near the Niagara River mouth during July 16–22, 1985 (Masse and Murthy, 1990).

Cross-references

Circulation Processes in Lakes

Great Lake Processes: Thermal Structure, Circulation and Turbulent Diffusion Processes

Great Lakes, North America

Hydrodynamics and Circulation of Fjords

Ladoga Lake and Onego Lake (Lakes Ladozhskoye and Onezhskoye)

Mixing in Lakes

Thermal Regime of Lakes

Water Exchange Between Littoral Zone and Open Lake Water

Bibliography

Beletsky, D., O'Connor, W. P., Schwab, D. J., and Dietrich, D. E., 1997. Numerical simulation of internal Kelvin waves and coastal upwelling fronts. *Journal of Physical Oceanography*, **27**, 1197–1215.

Boyce, F. M., Donelan, M. A., Hamblin, P. F., Murthy, C. R., and Simons, T. J., 1989. Thermal structure and circulation in the great lakes, atomsphere. *Ocean*, **27**, 607–642.

Csanady, G. T., 1984. *Circulation in the Coastal Ocean*. Boston: D. Reidel, p. 279.

Henderson-Sellers, B., 1984. *Engineering Limnology*. London: Pitman Advanced Publishing Program.

Masse, A. K., and Murthy, C. R., 1990. Observations of the Niagara River thermal plume (Lake Ontario, North America). *Journal of Geophysical Research*, **95**, 16097–16109.

Mortimer, C. H., 1963. *Frotiers in physical limnology with particular reference to long waves in rotating basins*. Great lakes Div. Publ, Univ of Michigan, vol. 10, pp. 9–42.

Rao, Y. R., and Murthy, C. R., 2001. Coastal boundary layer characteristics during summer stratification in Lake Ontario. *Journal of Physical Oceanography*, **31**, 1088–1104.

Rao, Y. R., and Schwab, D. J., 2007. Transport and mixing between the coastal and offshore waters in the Great Lakes: a review. *The Journal of Great Lakes Research*, **33**(1), 202–218.

Encyclopedia of Earth Sciences Series

ENCYCLOPEDIA OF LAKES AND RESERVOIRS

Volume Editors

Lars Bengtsson is professor in Water Resources Engineering at Lund University, Sweden. He was previously professor of hydrology at Uppsala University and Luleå Technical University and visiting professor in the USA, Canada and Hungary. He is and has been editorial board member of a large number of scientific journals. He has published more that 100 papers in international peer-reviewed journals. He specializes in physical processes in lakes and rivers and cold climate hydrology.

Reginald Walter Herschy is a British consultant in hydrology dealing mainly with rivers, lakes and reservoirs. His work has taken him to Ireland, China, India, South Africa, Lesotho, Kenya, USA, Canada and South America. He was formerly with the UK Government for many years as head of hydrometry in England and Wales. He is the author of some 60 technical papers on hydrology and meteorological satellites and several books. He is co-editor with the late Professor Rhodes Fairbridge of the Encyclopedia of Hydrology and Water Resources.

Editorial Board

Aims of the Series

The *Encyclopedia of Earth Sciences Series* provides comprehensive and authoritative coverage of all the main areas in the Earth Sciences. Each volume comprises a focused and carefully chosen collection of contributions from leading names in the subject, with copious illustrations and reference lists.

These books represent one of the world's leading resources for the Earth Sciences community. Previous volumes are being updated and new works published so that the volumes will continue to be essential reading for all professional earth scientists, geologists, geophysicists, climatologists, and oceanographers as well as for teachers and students. See the back of this volume for a current list of titles in the *Encyclopedia of Earth Sciences Series*. Go to http://www.springerlink.com/reference-works/ to visit the "Earth Sciences Series" online.

About the Series Editor

Professor Charles W. Finkl has edited and/or contributed to more than eight volumes in the Encyclopedia of Earth Sciences Series. For the past 25 years he has been the Executive Director of the Coastal Education & Research Foundation and Editor-in-Chief of the international *Journal of Coastal Research*. In addition to these duties, he is Professor at Florida Atlantic University in Boca Raton, Florida, USA. He is a graduate of the University of Western Australia (Perth) and previously worked for a wholly owned Australian subsidiary of the International Nickel Company of Canada (INCO). During his career, he acquired field experience in Australia; the Caribbean; South America; SW Pacific islands; southern Africa; Western Europe; and the Pacific Northwest, Midwest, and Southeast USA.

Founding Series Editor

Professor Rhodes W. Fairbridge (deceased) has edited more than 24 Encyclopedias in the Earth Sciences Series. During his career he has worked as a petroleum geologist in the Middle East, been a WW II intelligence officer in the SW Pacific and led expeditions to the Sahara, Arctic Canada, Arctic Scandinavia, Brazil and New Guinea. He was Emeritus Professor of Geology at Columbia University and was affiliated with the Goddard Institute for Space Studies.

ENCYCLOPEDIA OF EARTH SCIENCES SERIES

ENCYCLOPEDIA *of* LAKES AND RESERVOIRS

edited by

LARS BENGTSSON
Lund University
Sweden

REGINALD W. HERSCHY
UK

RHODES W. FAIRBRIDGE

Springer

Library of Congress Control Number: 2012939385

ISBN: 978-1-4020-5616-1
This publication is available also as:
Electronic publication under ISBN 978-1-4020-4410-6 and
Print and electronic bundle under ISBN 978-1-4020-5617-8

Springer Dordrecht, Heidelberg, New York, London

Printed on acid-free paper