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Environnement Canada

Coastal Physical Processes in the Great Lakes

By:

Yerubandi R. Rao

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Coastal Physical Processes in the Great Lakes

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Abstract

Inland Seas and Large Lake Systems are subjected to many of the same forcing as coastal oceans and serve as model basins for understanding the complex coastal ocean dynamics. They are also somewhat simpler to study than the coastal oceans since they are enclosed and large enough to include the Coriolis forcing. In large lake systems such as the North American Great Lakes the absence of salinity and tidal forcing simplifies the dynamics even further. The coastal zone dynamics is complex and highly variable, where interrelated biological, chemical, geological and physical processes are occurring simultaneously and is strongly influenced by the climatic conditions. An understanding of the coastal physical processes is essential to develop science based integrated management of coastal oceans. With this broad objective in mind systematic monitoring and modeling studies of the North American Great Lakes have been carried out for well over three decades. Coastal zone studies of the Great Lakes included long time series current measurements from a network of self recording current meters, satellite tracked drifters, synoptic hydrographic surveys, tracer dispersion experiments and meteorology. These studies have provided long time series climatological data base and systematic analysis of this data base has revealed an array of complexities and variability in water movements ranging from predominant shore parallel currents to near-inertial oscillations, episodes of current stagnation, current reversals, and thermal fronts such as spring thermal bar and summer upwelling. However, certain flow regimes appear to be highly correlated with prevailing meteorological conditions and repeat themselves with some regularity at any given coastal station. These coastal flow regimes include coastal boundary layer, coastal upwelling, coastally trapped waves and scale dependent turbulent exchange. These complex coastal physical processes are parameterized and incorporated in coastal transport and dispersion models. Case studies of the application of the climatological data base and coastal models will be presented to manage waste disposal operations from land based sources such as municipal outfalls and industrial discharges including waste heat from thermonuclear power plants.

NWRI RESEARCH SUMMARY

Plain language title

Physical processes in the Great Lakes

What is the problem and what do scientists already know about it?

This overview paper describes some aspects of the physical and dynamical processes in the North American Great Lakes. North American Great Lakes with horizontal scales of hundreds of kilometers and depth scales of hundreds of meters behave much like inland seas and exhibit physical and dynamical processes characteristic of the coastal oceans. However, these characteristics are determined by the facts that the Great Lakes basins are enclosed, horizontal dimensions are larger than the vertical dimensions, and the principal source of mechanical energy is the wind. We describe the aspects of both advection and diffusion based on physical experiments.

Why did NWRI do this study?

Circulation and coastal exchange processes in the Great Lakes are being studied by NWRI scientists for more than 30 years. These studies provided several original contributions on the dynamics of the coastal physical processes. Ram Yerubandi was invited to present an overview of the coastal physical processes a lead talk in 2nd CSCE conference in Toronto. The main results will be published in the conference proceedings.

What were the results?

We have observed an array of complexities in coastal currents that vary in magnitude, time and space. The coastal currents shows large scale features due to the meteorological forcing, and meso-scale circulations due earth's rotation, topography etc. Superimposed on this large-scale circulation, coastal currents exhibit episodic events of shorter duration (typically 2-3 days) such as upwelling/downwelling, strong alongshore coastal jets and weaker stagnation currents interspersed with reversals. Coastal circulation features introduce a wide range of nearshore/offshore exchange processes. These studies also indicate turbulent exchange exchanges during mean summer conditions as well as variability during certain episodic events.

How will these results be used?

The results will be used to improve the nearshore environmental monitoring/modeling and assessment of the Great Lakes.

Who were our main partners in the study?

Several organizatons were involved at many stages notably Ontario Hydro, Ontario Ministry of Enviroment, NOAA, NSF, etc.

Les processus physiques littoraux dans les Grands Lacs

Yerubandi R. Rao

Résumé

Les mers continentales et les grands réseaux de lacs sont soumis aux mêmes forces que les eaux côtières et peuvent donc servir de modèles pour comprendre la dynamique complexe de ces dernières. Ils sont aussi plus faciles à étudier que les eaux côtières, puisqu'ils sont fermés et assez grands pour être soumis à la force de Coriolis. Dans les grands réseaux de lacs, comme les Grands Lacs d'Amérique du Nord, l'absence de salinité et de marées simplifie encore plus la dynamique. La dynamique de la zone côtière est complexe et très variable. Elle est marquée par une simultanéité de processus biologiques, chimiques, géologiques et physiques interdépendants et une forte influence des conditions climatiques. L'élaboration d'une gestion intégrée et scientifique des eaux côtières dépend de notre compréhension des processus physiques côtiers. C'est dans cette perspective générale qu'on mène depuis plus de trente ans un large éventail d'études de surveillance et de modélisation systématiques des Grands Lacs d'Amérique du Nord. Les études des eaux littorales des Grands Lacs portent sur des mesures à long terme du courant à l'aide de courantomètres autoenregistreurs, de bouées dérivantes suivies par satellites, de relevés hydrographiques synoptiques, d'expériences sur la dispersion de traceurs et de relevés météorologiques. Ces études ont permis d'élaborer une base de données climatologiques à long terme. L'analyse systématique de ces données a révélé une série de complexités et de variations dans la circulation de l'eau : des courants prédominants parallèles à la rive, des oscillations quasi inertielles, des épisodes de stagnation du courant, des renversements du courant et des fronts thermiques comme une barrière thermique printanière ou une remontée d'eau estivale. Toutefois, certains régimes d'écoulement semblent fortement corrélés avec les conditions météorologiques prévalentes et se répètent avec une certaine régularité dans une station littorale. Les principaux régimes de ce type sont la couche limite littorale, la remontée littorale, les vagues piégées et l'échange turbulent à dépendance scalaire. Ces processus physiques complexes sont paramétrés et incorporés à des modèles de transport et de dispersion le long des côtes. On présentera des études de cas portant sur l'utilisation de la base de données climatologiques et des modèles côtiers pour la gestion de l'élimination des déchets de source terrestre, comme les rejets des émissaires municipaux et des industries, y compris la chaleur résiduelle des centrales électriques thermonucléaires.

Sommaire des recherches de l'INRE

Titre en langage clair

Les processus physiques dans les Grands Lacs

Quel est le problème et que savent les chercheurs à ce sujet?

Le présent aperçu décrit certains aspects des processus physiques et dynamiques dans les Grands Lacs d'Amérique du Nord. Les Grands Lacs, avec des dimensions horizontales de centaines de kilomètres et des profondeurs de centaines de mètres, se comportent comme des mers continentales et présentent des processus dynamiques et physiques caractéristiques des eaux côtières. Toutefois, ces caractéristiques dépendent du fait que les bassins des Grands Lacs sont fermés, que leurs dimensions horizontales sont plus grandes que leurs dimensions verticales et que le vent constitue la principale source d'énergie mécanique. Nous décrivons les différents aspects de l'advection et de la diffusion en nous basant sur des expériences physiques.

Pourquoi l'INRE a-t-il effectué cette étude?

Les chercheurs de l'INRE étudient les processus littoraux de circulation et d'échange dans les Grands Lacs depuis plus de 30 ans. Ces études ont fourni de nombreuses contributions originales sur la dynamique des processus physiques littoraux. Ram Yerubandi a été invité à présenter un aperçu des processus physiques littoraux dans une des grandes communications de la 2^{e} conférence spécialisée du congrès de la SCGC à Toronto. Les principaux résultats seront publiés dans les actes du congrès.

Quels sont les résultats?

Nous avons observé une série de complexités dans les courants littoraux, qui varient en importance dans le temps et dans l'espace. Les courants littoraux présentent des caractéristiques à grande échelle dues au forçage météorologique et des circulations à méso-échelle causées par la rotation de la Terre, la topographie et d'autres facteurs. À ce grand régime de circulation se superposent des événements épisodiques de courte durée (habituellement de 2 à 3 jours), comme les remontées et les plongées, de forts courants jets littoraux et des courants de stagnation plus faibles interrompus par des inversions de courant. Les caractéristiques de la circulation littorale sont à l'origine d'un grand nombre de processus d'échange entre les eaux du rivage et celles du large. Ces études indiquent aussi la présence d'échanges turbulents pendant les conditions estivales moyennes et une variabilité lors de certains événements épisodiques.

Comment ces résultats seront-ils utilisés?

Les résultats serviront à améliorer la surveillance et la modélisation de l'environnement littoral et l'évaluation des Grands Lacs.

Quels étaient nos principaux partenaires dans cette étude?

Plusieurs organismes ont participé à diverses étapes : Ontario Hydro, le ministère de l'Environnement de l'Ontario, la NOAA, la NSF, etc.

2nd CSCE Specialty Conference on Coastal, Estuary and Offshore Engineering
2e Conférence spécialisée sur le génie côtier, des estuaires et de l'offshore

Toronto, Ontario, Canada
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COASTAL PHYSICAL PROCESSES IN THE GREAT LAKES

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ABSTRACT: The large enclosed and rotating basins like large lakes are subjected to many of the same forcings as coastal oceans and serve as an example for understanding the complicated coastal ocean dynamics. Coastal zone climatological studies of Great lakes included long time series current measurements from a network of self recording current meters, GPS-satellite tracked Lagrangian drifters, ADCP moorings and transects, temperature measurements from fixed thermistor chains and synoptic surveys, dye dispersion experiments and local wind history. From these studies an extensive climatological data base has been developed for coastal management of the Great Lakes. The present article describes spring thermal bar circulation and its effect in inhibiting the horizontal mixing in Lake Ontario. It also provides a brief overview of summer circulation and impact of episodic events like upwelling/downwelling on the coastal circulation.

1. INTRODUCTION

The Laurentian Great Lakes, between 41°N and 49°N and 76°W and 92°W, on the international boundary between Canada and the United States, contain a fifth of the Earth's freshwater, a thermal mass sufficient to locally moderate the cool climate to a semi-maritime climate. With horizontal scales of hundreds of kilometers, depth scales of 100 m, and a well-developed seasonal thermal stratification in the summer, the Great Lakes basins are host to many of the physical phenomena associated with the coastal oceans or inland seas. The Great Lakes are also easier to study than oceans because they are smaller and do not have salinity effects and tides. Closed nature of the Great Lakes basins provided an excellent opportunity to study the Great Lakes systems as model oceans (Csanady, 1982). The Great Lakes manifest into two distinct flow environments: an open lake environment and a coastal environment. The main difference between these regions is that the momentum imparted by the wind stress is balanced by bottom friction inshore, while it is balanced by the Coriolis force offshore. Coastal zones are areas of intense biological, chemical and geological processing of materials arriving from both the terrestrial and offshore zones. Details of the transport and pathways of material entering to the coastal environment are dictated by complex coastal currents and forcing functions in a distinct inshore region known as the coastal boundary layer. Csanady (1982) described the flow structure within the coastal boundary layer. Subsequently, Murthy and Dunbar (1980) and Rao and Murthy (2001a) developed a climatology of flow and turbulent exchanges in this region of the Great Lakes.

The thermal structure and circulation in the Great Lakes generally depends on the season because of the large annual variation of surface fluxes (Boyce et al. 1986). During early spring, the temperature in a large temperate lake is more or less constant and below 4°C (temperature of maximum density). As the spring heating proceeds, the water is heated convectively, leading to a faster increase of temperature in shallow areas compared to deeper waters. When the temperature reaches 4°C, a stable stratification develops at the shore. Between this region and deep part of the lake that still experiences convection and a temperature below 4°C, there is a zone of sinking water in the vicinity of a temperature corresponding to maximum density. This zone is referred to as thermal bar. In summer and fall there is a distinct thermocline in the upper 30 m in most of the lakes, which makes them stratified. During this period of stratification, significant wind events will cause upwelling and downwelling of the thermocline along the shore. The scale of the offshore distance over which these events takes place depends on the wind stress and near shore bathymetry, and is typically of the order of 5-10 km, hence, within the coastal boundary layer. During the unstratified period (November-June), 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.

The purpose of this paper is to provide a description of the structure of flow within the coastal zone during the spring and summer regimes in Lake Ontario. The experimental data collected during the spring of 2003 offer the opportunity to carry out a detailed analysis of circulation and mixing during the spring thermal bar in the lake. The Eulerian data collected during 1990 and 1996-97 have been used for studying the summer circulation and turbulent exchange processes in Lake Ontario.

2.0 SPRING REGIME

There have been a number of field investigations of the thermal bar in the Great Lakes and other large lakes (Rodgers 1968; Thikhomirov 1963; Malm et al. 1994). The thermal bar phenomenon regularly occurs in the Great Lakes, and first reported by Rodgers (1968) in Lake Ontario. These studies confirmed the general features of the temperature distribution in the thermal bar zone. 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 4°C isotherm, where 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. Csanady (1974) argued that this double cell circulation during the thermal bar may actually promote the horizontal mixing of nearshore and offshore waters, rather than inhibiting it. However, Gbah and Murthy (1998) showed that the horizontal exchange coefficients are in fact reduced near the thermal bar zone. Their observations of circulation are limited to only one sub-surface (10-m) level, therefore the vertical distribution of horizontal exchanges is not available during the thermal bar period. In addition to horizontal mixing, the numerical studies have also shown the variability of vertical mixing from stably-stratified coastal areas to the deeper convective areas, with enhanced mixing near 4°C isotherm. The effect of winds on the circulation during the thermal bar is found to be very important in numerical studies, which need to be verified from systematic field experiments. It is therefore particularly important to be able to analyze the experimental evidence in detail to determine the importance of exchange processes and the overall circulation during the thermal bar period.

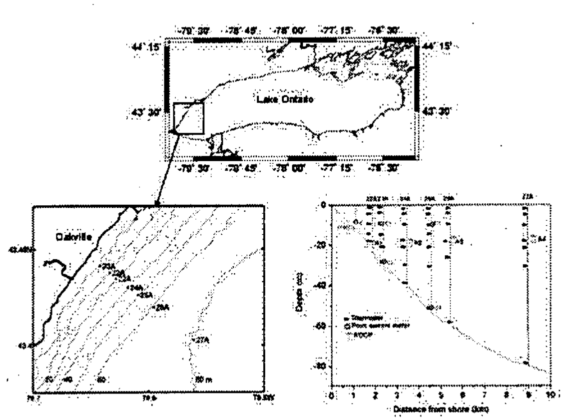

Figure 1: Map of Lake Ontario with experimental setup, local bathymetry and instrument configuration.

Because of these concerns and the renewed issue of abundant Cladophora *Sp* fouling beaches each summer in Lake Ontario, an elaborate experiment has been conducted in Lake Ontario during the spring of 2003 (Rao et al. 2004). The data obtained from this experiment offers the opportunity to carry out a detailed analysis of circulation and mixing during the spring thermal bar in Lake Ontario. The measurements for obtaining currents, winds, and temperatures consisted of Eulerian measurements during the spring of 2003. As part of the field program, current meter and thermistor moorings were deployed at a cross-section off Oakville in the western end of Lake Ontario (Figure 1). The local bathymetry has a gentle slope with depths ranging from 10 m at 0.9 km to 80 m at 8.9 km from the shore. The mooring setup was designed to capture the onshore-offshore flow structure at fixed points along an axis, which is more or less perpendicular to the local shore line. Three broadband and one narrowband RDI Acoustic Doppler Current Profilers (ADCP) provided vertical profiles of horizontal currents during this period. The ADCP located at 21 m water depth (22A) was mounted at the bottom facing up. The rest of the ADCPs were installed at a depth of 15-16 m below the surface on stable sub-surface floats facing up. Measured vertical resolution was set at 1-m bin interval. In addition to ADCPs, single point current meters (Nobska-MAVS) at sub-surface (10 m) and 1 m above the bottom were deployed at two locations. Water temperature data were obtained from six moorings with thermistors deployed at 5 m intervals in the epilimnion, and at a lesser frequency (10 m) in the bottom waters. Apart from this water temperature was also obtained from the current meters and the ADCP instrument location at the bottom.

A land based meteorological station at the western end of the lake provided the wind and radiation data from day 119 (29 April) to 171 (20 June). The daily averaged heat flux ranged from – 98.3 W m^{-2} to 221 W m^{-2} during the spring. The wind data from Toronto island airport which is around 20 km from the experimental site has been substituted for the missing data. The wind measurements showed peaks of over 10 m s^{-1} during the early part of spring, usually associated with easterly storms. The winds were moderate during the rest of the experimental period. The experiment also consisted of several weekly surveys measuring the water quality parameters from a research vessel during the thermal bar evolution. Each survey consisted of measuring temperature, conductivity and chlorophyll at nine stations in the same cross-section off Oakville using an YSI water quality profiler in the experimental region. The duration of a typical survey could be about 3- 4 hours.

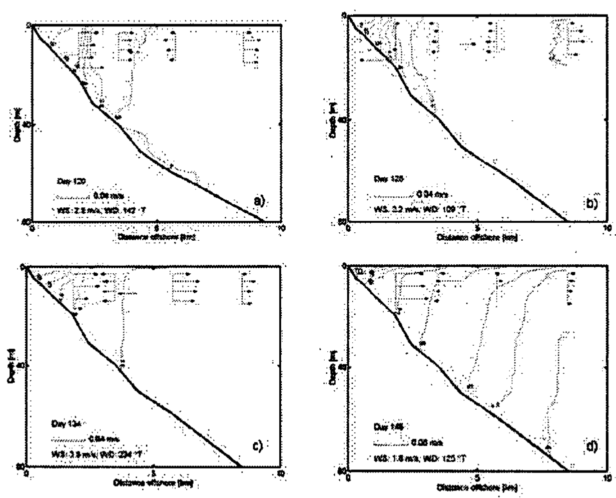

Figure 2: Measured temperature (in °C) distributions along the cross-section off Oakville from vessel surveys on (a) 30 April (day 120), (b) 8 May (day 128), (c) 14 May (day 134), and (d) 26 May (day 146).

Figures 2a to 2d show the temperature structure for day 120 (30 April), day 128 (8 May), day 134 (14 May) and day 146 (26 May), respectively. The corresponding wind speed and direction averaged over the survey period are inserted in the plots. The mean cross-shore currents (averaged over each survey) were plotted at selected depths. By day 120, the thermal bar is well-developed, and 4°C isotherm was present at 2.2 km from the shore. Weak stratification was noticed in the nearshore zone. As observed by Rodgers (1968) the horizontal temperature gradients near 4°C isotherm were large compared to the regions away from it. This could be due to the mixing associated with downwelling circulation in the vicinity of the thermal bar. The mean cross-shore currents on days 128 and 134 indicate that the currents were converging near 4°C isotherm in the surface levels. However, on day 120 the cross-shore currents flowed in the offshore direction near the thermal bar region. The thermal bar was stationary in this area for the next two weeks, which can be observed from the 4°C isotherm on day 134. The temperature structure of the nearshore zone shows that the westerly storm from day 132 to 133 caused coastal upwelling. This can be clearly seen from the reduction of nearshore temperatures by 1°C, and tilting of the isotherms between 4 and 5°C. The westerly storm and the subsequent calm weather with positive heat flux have significantly increased the speed of progression of the thermal bar to the deeper regions, which can be evidenced by the survey on day 146. The 4°C isotherm can be traced at about 8 km from the shore. A stable stratification developed in the nearshore zone.

From the temperature observations the progression rate of the thermal bar can be estimated as the ratio of bar displacement from one mooring location to the other. The observed progression speed of the thermal bar indicates an initial slow phase (0.5 cm/s) and a later fast phase (2 - 2.5 cm/s). This two phase propagation of the thermal bar was also observed in the laboratory experiments of Elliott and Elliott (1970). This relatively slow propagation of the thermal bar in the early phase was attributed to the inertia of the existing flow.

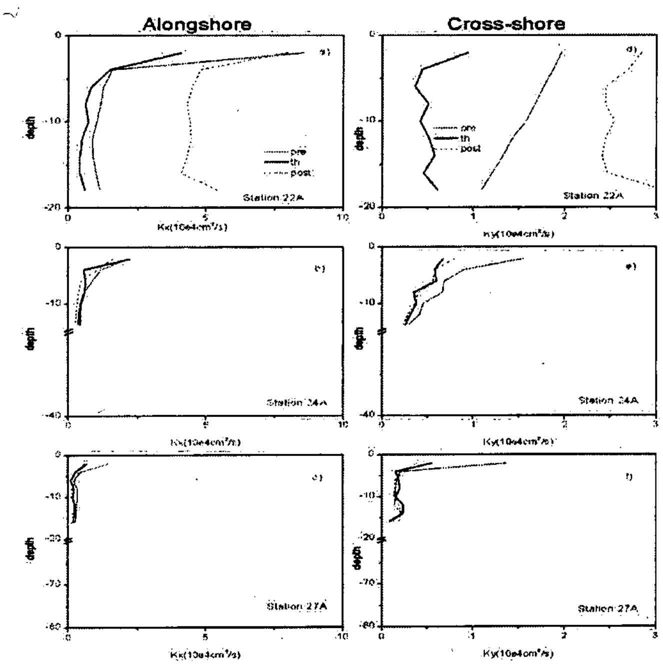

Figure 3: The depth variation of horizontal exchange coefficients during the pre-thermal bar, thermal bar and post-thermal bar episodes at stations a) 22A, b) 24A, and c) 27A.

In order to estimate the vertical structure of horizontal exchange coefficients, we use current velocity data obtained from the ADCP stations considered for the mean flow. The earlier study by Gbah and Murthy (1998) showed that during the thermal bar period a low-pass filter of 8-14 hours revealed short term fluctuations responsible for horizontal mixing. Typical plots of kinetic energy spectra of along-shore and cross-shore components (figures not shown) showed that the spectral energy levels at high frequency (>0.125 cph) are rather low (5% of total energy), and roughly indicate the turbulent fluctuations. Therefore, the time series of filtered (>8 h) flow values $\bar{u}(t)$ and $\bar{v}(t)$ are subtracted from the observed hourly values $u(t)$ and $v(t)$ to obtain the fluctuations $u'(t)$ and $v'(t)$. By following Taylor's (1921) analysis a relationship has been developed between the horizontal exchange coefficient and the Eulerian current fluctuations in Lake Ontario (Rao and Murthy 2001b). In their study, the horizontal exchange coefficients in terms of Eulerian statistics were written as $K_x = \beta \overline{u'^2} \tau$, $K_y = \beta \overline{u'^2} \tau$ where $\tau = \int_0^\infty R(\tau) d\tau$ is the Eulerian integral time scale, and $R(\tau)$ is the Eulerian auto-correlation coefficient and $\beta = 1.4$. As described in that study the horizontal exchange coefficients obtained from this method is a reasonable estimate as our primary goal is not the precise quantification of the exchange coefficient but an estimate of horizontal mixing. Also, from a practical point of view, seasonal climatological characteristics of horizontal exchange coefficients during spring and its variability during the thermal bar progression can be established from a long time series of current profiles under actual meteorological conditions. In contrast to earlier studies, as described in mean flow calculations we obtain the exchange coefficients exclusively associated with the immediate area of the bar by considering the time series data at each ADCP station as the bar advances from this location. This approach is more effective because it considers the dynamic nature of the bar.

Figures 3a to 3f shows significant variability of horizontal exchange coefficients in the water column. It is clear from this figure that the horizontal exchange coefficients are not isotropic over the depth in the coastal areas, but becomes nearly isotropic in the offshore areas. In the shallow depths the alongshore exchange coefficients (K_x) were higher in the surface layer (8.0×10^4 cm^2 s^{-1}) in comparison to sub-surface values (1 to 5×10^4 cm^2 s^{-1}) during both pre-and post thermal bar period. The magnitude of alongshore and cross-shore exchange coefficients considerably decreased during the thermal bar. However, at the mid-depth and offshore stations the thermal bar has not shown significant impact on alongshore exchange coefficients. The cross-shore exchange coefficients reduced slightly during the thermal bar and post-thermal bar periods at the mid-depth station. However, at the deeper station the impact of the thermal bar in reducing the cross-shore exchange coefficients is confined close to the surface. In general the horizontal exchange coefficients are higher in the nearshore areas compared to the deeper regions. The general range of cross-shore exchange coefficients (0.1 to 0.6×10^4 cm^2 s^{-1}) during the thermal bar period is comparable to the previous study by Gbah and Murthy (1998). Low values of horizontal exchange coefficients during the thermal bar compared to pre and post-thermal bar periods support the hypothesis that the thermal bar plays an important role in suppressing the horizontal mixing.

3.0 SUMMER REGIME

By middle of June a continuous thermocline is usually established in Lake Ontario, at an equilibrium depth of between 10 and 20m. Long waves of near-inertial period usually distort this into an irregular surface, the shore-zone edges of which show more persistent upwelling and downwelling of the thermocline. Much as in the spring, a nearshore band of 10 km wide becomes a unique kind of coastal boundary layer in which mid-lake motions adjust to the presence of the shores (Rao and Murthy, 2001). In the coastal upwelling zone a near balance exists between wind stress, Coriolis force and internal pressure gradient. However, as the wind subsides two types of waves are established: the Poincare′ wave and the internal Kelvin wave. Poincare′ waves are basin wide response with oscillations in the thermocline across the entire lake with anti-cyclonic phase propagation. On the other hand, internal Kelvin waves are coastally trapped response of the thermocline that progresses cyclonically around the lake. The Rossby radius of deformation which is typically of the order of 3-5 km in the Great Lakes is the e-folding scale for the amplitude of this wave as a function of distance from shore.

Past studies on the mean summer circulation in the coastal zone of Lake Ontario were based on daily transect data collected during the International Field Year on Great Lakes (IFYGL) in 1972. Although some important features of mean flow pattern were explained using this data and simple equilibrium models, many discrepancies were observed between model results and measurements owing to transient upwelling and downwelling events during summer. In the Great Lakes the coastal upwelling and downwelling induced by local winds and propagation of these events as internal Kelvin waves have also been studied by using both field data and numerical models. Rao and Murthy (2001) provided a description of the structure of flow within the coastal boundary layer during the summer regime in Lake Ontario using simultaneous Eulerian and Lagrangian currents.

The data consists of Eulerian time series of water temperature and currents obtained from an array of 6 SACM Brown current meters moored at a depth of 10 m off Darlington Nuclear Generating Station on the north shore of Lake Ontario (Fig. 4). At this coastal site the bathymetry gently slopes from a depth of 11m at the innermost mooring to 87.5m at the outermost. The coastal chain was deployed perpendicular to the local bathymetry and extended to 14.3 km offshore. The sampling rate of the current data was 30 minutes, except at the second mooring from the shore where the rate was 36 minutes. We have obtained current and

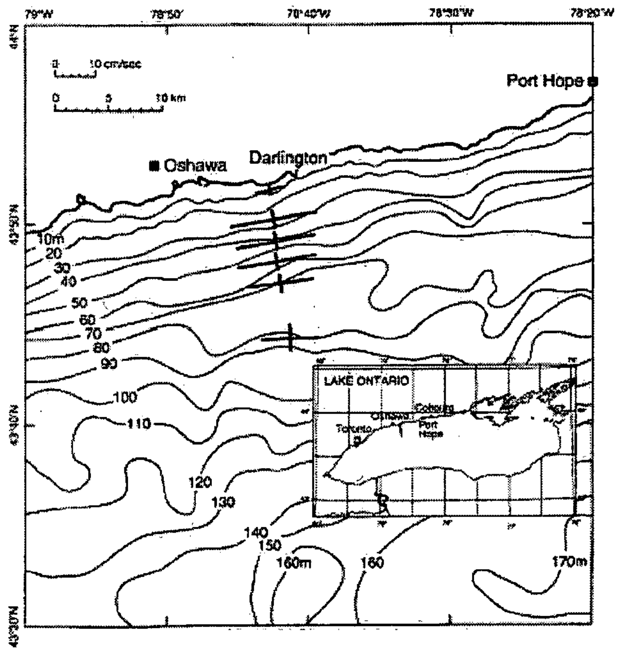

Figure 4 : Map of Lake Ontario showing the experimental location, local bathmetry and flow ellipses.

temperature data from 1 July 1990 (Day 181) to 30 September 1990 (Day 273) for this analysis. The time series is first hourly averaged, then the east and north velocities are resolved into shore parallel and shore perpendicular components after aligning to the local shore line (80° from north). Figure 4 also shows flow ellipses in the alongshore and cross-shore directions for all current meters. This gives an estimate of predominant movements of water along the northshore of Lake Ontario. The experiment also contained temperature survey component along the coastal chain stations.

A land based tower at Toronto Island airport provided hourly wind speeds and directions from 1 July 1990 to 30 September 1990. In the absence of offshore meteorological measurements the winds at this island station are taken as representative of forcing during this period. The vector wind stress was estimated as $\tau = \rho_a C_d |W| W$, where $\rho_a = 1.2$ kg m^{-3} is the air density, C_d is a constant drag coefficient of $1.3*10^{-3}$ and W is the wind velocity. Here the direction of the wind stress points toward the reference. The stresses were also decomposed into alongshore and cross-shore components with alongshore direction being aligned with the general orientation of the north shore (80° from north) of Lake Ontario.

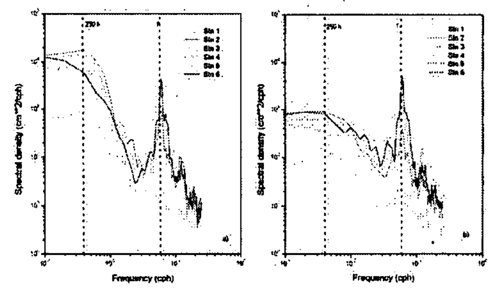

Figure 5: Kinetic energy spectra of a) alongshore and b) cross-shore components of current velocity at coastal chain moorings, here, f is the inertial period

Typical plots of kinetic energy spectra of along-shore and cross-shore components along the coastal chain moorings are plotted in figure 5a and 5b, respectively. The energy spectra were characterized by a flat peak around 10-12 days (0.0041-0.0034 cph) and a spectral minimum around 24-30 hours (0.04 - 0.03 cph). The dominant peak near 17 hr (0.058 cph) corresponds to the near-inertial period of Lake Ontario and increases offshore. The near-inertial oscillations are characteristic feature of summer stratification and are observed to be intermittent. The spectral minimum at 24 to 30 hours is a characteristic feature of energy transfer from large scale lake wide circulation to small scale oscillations. The period corresponding to the spectral minimum can be used as a transition between mean flow and fluctuations. The low-pass filter with a cutoff frequency of 0.055 - 0.041 cph (18 to 24 hr) leaves all high frequency oscillations including inertial oscillations in the fluctuating part. Although near-inertial 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, hence, they are included in fluctuating turbulent currents (Murthy and Dunbar 1981). Also in the range of frequencies between Coriolis frequency and maximum Brunt-vaisala frequency turbulent eddies are intermingled with near-inertial internal waves and the motions in this range are generally classified as meso-scale turbulent motions. The nearshore stations (within 3.5 km from shore) show that alongshore currents were dominated by low frequency motion (> 3 days) more than offshore stations. The kinetic energy of the alongshore flow in the low frequency band accounts for more than 95% of the total kinetic energy, indicating the shore-parallel nature of currents.

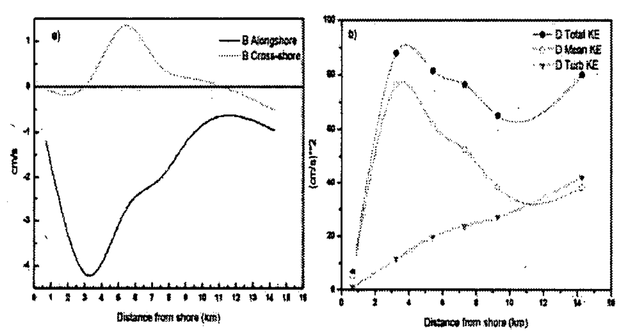

Figure 6: a) Mean alongshore and cross-shore currents b) components of kinetic energy (total, mean flow and turbulent with distance during summer regime.

Figure 6a shows the variation of mean cross-shore and alongshore current components with distance from shore. The cross-shore velocity increased with offshore and peaked at 5 km from shore. The mean alongshore currents were toward the west and peaked at a distance of 3 km from shore. The observed westward mean flow of 3 to 4 cms^{-1} was consistent with earlier observations of mean cyclonic circulation in large lakes. Csanady (1982) attributed this flow to the persistence of domed thermocline in summer due to the influence of prevailing winds. Presence of this domed thermocline in coastal waters is evidence of adjustment to geostrophic equilibrium provided by cyclonic circulation with mean surface flow of 3-4 cms^{-1}. Figure 6b shows components of kinetic energy (total, mean and fluctuations) as a function of offshore distance. The mean flow kinetic energy (MKE) dominates within 8-10 km from the shore. Fluctuating kinetic energy or turbulent kinetic energy (TKE) increases with offshore distance, as near-inertial oscillations become dominant offshore. In summer the MKE increases offshore to a peak at about 3 km from shore then decreases further offshore. Murthy and Dunbar (1981) characterized this flow regime, where total kinetic energy or mean currents increases to a peak as the frictional boundary layer (FBL). Within this zone the currents are influenced by bottom and shore friction. Beyond 3 km, due to the adjustment of inertial oscillations to shore parallel flow an outer boundary layer develops, known as the inertial boundary layer (IBL). The total (FBL+IBL) forms the coastal boundary layer (CBL). In defining the width of the IBL previous studies used the distance where the inertial oscillations dominate the shore parallel flow. Alternatively, the CBL width can be simply taken as the distance where the TKE contributes maximum to the total kinetic energy. During the summer stratification in Lake Ontario the width of the CBL as determined here was around 10 km.

As discussed in the previous section, the horizontal exchange coefficients were obtained by Eulerian measurements during the two episodic events in summer season (Table 1). In the first experiment during which significant upwelling occurred, the statistics show that alongshore exchange coefficients (K_x) were slightly higher than cross-shore components (K_y) in the first 5.5 km from the shore, *i.e* in the FBL. The cross-shore components reached a peak at around 6-7 km from shore and remained steady outside the CBL. These results indicate that momentum transfers occur in the longshore direction in the FBL and cross-shore transfers may dominate in the IBL. The cross-shore exchange coefficients in the surface levels were lesser than sub-surface values in the IBL. During the second experiment that is favored by downwelling circulation the alongshore components were higher in the CBL, and outside the CBL the cross-shore exchanges were dominant. The turbulent momentum exchanges were rather small in the FBL, but significantly increased in the IBL.

Table 1: Alongshore (K_x) and cross-shore (K_y) eddy diffusivities from Eulerian and Lagrangian measurements during upwelling and downwelling cycles.

Station/ Distance from shore (km)	$K_{x(E)}$ X 10^5 cm^2s^{-1}	$K_{y(E)}$ X 10^5 cm^2s^{-1}
Upwelling		
1 /0.68	0.277	0.864
2 /3.24	10.36	6.173
3 /5.42	26.98	16.78
4 /7.30	16.62	20.38
5 /9.28	19.26	20.42
6 /14.2	24.30	20.33
Downwelling		
1 /0.68	1.010	0.652
2 /3.24	7.161	4.197
3 /5.42	30.97	21.55
4 /7.30	31.16	28.42
5 /9.28	37.03	41.57
6 /14.2	60.09	72.37

4.0 DISCUSSION

The present article describes spring thermal bar circulation and its effect in inhibiting the horizontal mixing in Lake Ontario. It also provides a brief overview of summer circulation and impact of episodic events like upwelling/downwelling on the coastal circulation. The observed circulation within a zone between the shore and the thermal bar is predominantly shore-parallel, and towards the west (i.e., counter-clockwise). The flow away from the thermal bar to offshore showed clockwise circulation on a few occasions. The coastal circulation is mainly influenced by the alongshore winds. Although mean cross-shore flow reduced during the thermal bar, it appears that it is depth-dependent. The horizontal turbulent exchange parameters show 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 still within the mid-depth (<40 m). In contrast to an earlier study (Gbah and Murthy, 1998) from mid-depth onwards the thermal bar has not shown any impact on alongshore exchange coefficients, but cross-shore exchanges decreased marginally. Although this supports the hypothesis that the thermal bar plays an important role in suppressing the horizontal mixing in the shallow depths, its impact is not that significant in deep offshore areas. 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 summer coastal boundary layer is characterized by a frictional boundary layer (FBL) of a width of ~3km, in which shore and bottom friction affects the flow. In this regime the currents are predominantly shore parallel and persistent. The outer boundary layer also called as an inertial boundary layer (IBL) which is typically of the order of 5-6 km wide, is a consequence of the adjustment of inertial oscillations to the lateral boundary. During the summer season within the CBL, the current motions are associated with thermocline displacements. The eastward (westward) wind stress causes thermocline elevation (depression) causing upwelling (downwelling). The turbulent exchange coefficients shows that during upwelling episodes, although alongshore coefficients were comparable to summer values, the cross-shore components increased, particularly in the IBL regime. It has been observed that lateral current shears are important in the FBL. This could be an important factor in the dispersion of material entered into lake waters.

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