Coastal Boundary Layer Characteristics during Summer Stratification in Lake Ontario

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ABSTRACT

Simultaneous measurements of Eulerian and Lagrangian currents along the north shore of Lake Ontario are analyzed to provide the mean flow properties and horizontal turbulent exchange characteristics in the coastal boundary layer (CBL). The summer coastal boundary layer is characterized by a frictional boundary layer (FBL) of a width of ~3 km, 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 an inertial boundary layer (IBL), 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 mean subsurface westward currents associated with downwelling events are typically stronger in comparison to weak eastward flow during upwelling. Further, upwelling events are characterized by reduced low frequency motion (>1 day) and significant near-inertial (~17 h) currents. The width of the CBL decreases during upwelling and increases during downwelling. Internal waves generated by baroclinic seiches during these events have periods from 11 to 17 hours. The near-surface horizontal exchange coefficients calculated from Lagrangian measurements are higher than those from subsurface Eulerian values. Upwelling events show that the turbulent kinetic energy is higher than mean flow kinetic energy (MKE) in the CBL, and cross-shore turbulent exchange increases in the IBL. During downwelling the alongshore exchange coefficients are higher in the FBL, whereas cross-shore exchanges are higher in the IBL. Downwelling events are also characterized by increased contribution from the MKE rather than the turbulent kinetic energy.

1. Introduction

Coastal zones are areas of intense biological, chemical, and geological processing of materials arriving from both 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 1972) or the inner shelf (Lentz 1995). The significant features of the coastal zone are across-shelf exchange and strong along-shore parallel currents. Large enclosed and rotating basins like the Great Lakes are subjected to many of the same forcings as coastal oceans and serve as an example for understanding the complicated coastal ocean dynamics. The lakes are also easier to study than the coastal ocean because they are smaller and do not have salinity effects and tides (Csanady 1982; Beletsky et al. 1997). The Great Lakes manifest into two distinct flow environments: an open lake environment and a coastal environment. The main differences 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.

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. 1989). During the unstratified period (Nov–Jun), 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 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 nearshore bathymetry, and is typically of the order of 5–10 km, hence, within the coastal boundary layer (Murthy and Dunbar 1981). 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 Poincaré wave and the internal Kelvin wave. Poincaré waves are a basinwide response with oscillations in the thermocline across the entire lake with anticyclonic phase propagation. On the other hand, internal Kelvin waves are a coastally trapped response of the thermocline that progresses cyclonically around the lake. The Rossby radius of deformation, 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 the 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 (Csanady and Scott 1980). Further, upwelling and downwelling events have also been cited as some of the important mechanisms for onshore and offshore transport of sediment (Lee and Hawley 1998). Observational and theoretical studies of coastal upwelling and downwelling for deciphering physical dynamics near a coast were carried out in several coastal regions (Smith 1981; Brink et al. 1980; Winant et al. 1987; Allen et al. 1995; Allen and Newberger 1996). 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 (Blanton 1975; Csanady 1982; Simons and Schertzer 1989; Beletsky et al. 1997). However, the elucidation of the role of physical processes during these episodes in the distribution of geologically and biologically important materials in the coastal zones of the Great Lakes has not been attempted in great detail, mainly due to the lack of detailed time series measurements.

The purpose of this paper is to provide 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. These data records are analyzed to identify the characteristics of mean and fluctuating currents and temperature during upwelling and downwelling cycles. This study uses near-surface drifter observations along with moored current meter statistics in the coastal zone of Lake Ontario. A quantitative analysis of dynamical balances and exchange characteristics for upwelling and downwelling events would enhance the understanding of horizontal exchange processes in the coastal zone. The remainder of this paper is divided into five sections. The next section gives a brief description of data and methods followed by mean circulation and exchange characteristics of the summer regime obtained from Eulerian measurements. The detailed flow and structure of the coastal boundary layer during upwelling and downwelling events are discussed in section 4, followed by a section on the calculation of Lagrangian and Eulerian exchange coefficients during these episodes. The last section gives a brief summary and conclusions of this study.

2. Data and methods

The data consists of Eulerian time series of water temperature and currents (speed and direction) obtained from an array of six SACM Brown current meters moored at a depth of 10 m off Darlington Nuclear Generating Station on the north shore of Lake Ontario (Fig. 1). At this coastal site the bathymetry gently slopes from a depth of 11 m at the innermost mooring to 87.5 m 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 temperature data from 1 July 1990 (Julian day 218) to 30 September 1990 (Julian day 273) for this analysis. The coordinate system used is such that the x axis is parallel to the shore and the y axis is pointed offshore along the instrument array. 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 shoreline (80° from north). Figure 1 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 north shore 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 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 \( \tau = \rho_a C_d |W| \), where \( \rho_a = 1.2 \) kg m\(^{-3}\) is the air density, \( C_d \) is a constant drag coefficient of \( 1.3 \times 10^{-3} \) 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 the alongshore direction being aligned with the general orientation of the north shore (80° from north) of Lake Ontario.

The current data were supplemented by six Lagrangian drifter experiments conducted along a line on the north shore of Lake Ontario during the period of May 1990 to October 1990. Seven to eight drifters were used in each experiment with drogues set at 3.5-m depth and were tracked using service Argos navigation. The drag area ratio for the Hermes Electronics drifters was estimated to be approximately 20:1 indicating that the velocity error due to wind drag is minimal (Niiler et al. 1995). There were on average 10 to 12 positional fixes per day per buoy. Out of the six experiments, two were...
chosen to study upwelling and downwelling characteristics. Each experiment lasted for a period of 8–10 days. In order to resolve the currents into shore parallel and perpendicular directions, the position time series was first converted to a velocity time series, in the form \((S, \theta)\), where \(S\) is the speed in centimeters per second and \(\theta\) is the instantaneous direction in degrees measured from north. The velocity field was then resolved into alongshore and cross-shore components.

### 3. Summer regime

In order to delineate parameters characteristic of transport and exchange processes, it is necessary to isolate the mean flow from the time series data. Numerical filtering techniques developed by Graham (1963) and extensively applied to the analysis of large lakes by Simons (1974) were used to define the mean flow and fluctuations. The filter was designed on the basis of typical kinetic energy spectra constructed from 92 days of hourly current meter data from the six coastal chain current meter stations.

Typical plots of kinetic energy spectra of alongshore and cross-shore components along the coastal chain moorings are plotted in Figs. 2a and 2b. 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 h (0.04–0.03 cph). The dominant peak near 17 h (0.058 cph) corresponds to the near-inertial period of Lake Ontario and increases offshore. The near-inertial oscillations are a characteristic feature of summer stratification and are observed to be intermittent. The spectral minimum at 24–30 h is a characteristic feature of energy transfer from a large-scale lakewide
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 (18–24 h) 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–Väisälä frequency turbulent eddies are intermingled with near-inertial internal waves and the motions in this range are generally classified as mesoscale turbulent motions (Nihoul 1980). The time series of mean (filtered) currents shows that alongshore currents were dominant at all six stations, and cross-shore velocities account for less than 10% of all subsurface current intensities in the first 10 km from shore (Fig. 3). 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
Low-pass filtered hourly averaged alongshore and cross-shore components of current velocity at all coastal chain stations.

Flow in the low-frequency band accounts for more than 95% of the total kinetic energy, indicating the shore-parallel nature of currents.

We have next examined the response of currents to wind forcing. The coherence between alongshore and cross-shore winds with alongshore currents was calculated for all stations. Examples of coherence plots at stations 2 and 6 are shown in Figs. 2c and 2d. Significant response to alongshore wind forcing occurs in the low-frequency band (high coherence) at all stations. Cross-shore winds were mainly coherent with alongshore currents in the low-frequency band. In the high-frequency band significant coherence was noticed at near-inertial frequencies in both alongshore and cross-shore cases, showing the influence of winds on the rotary near-inertial motion. Further, horizontal coherence between all current meters with reference to station 2 (not shown), shows that alongshore currents were highly coherent (coherence > 0.90) and in phase for stations located from 3 to 10 km offshore in low-frequency (>3 day) and near-inertial domains. However, the currents at the inner coastal station were not significantly coherent with those at other locations along the coastal chain.

Figure 4a 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 3–4 cm s$^{-1}$ was consistent with earlier observations of mean cyclonic circulation in large lakes, attributed by Emery and Csanady (1973) to the mean cyclonic curl in the wind stress field. On the other hand, Wunsch (1970) proposed that the Lagrangian drift associated with internal Kelvin waves might account for net cyclonic drift. Csanady (1982) attributed this flow to the persistence of a 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 cm s$^{-1}$. Recent experiments using three-dimensional numerical models have shown that certain selections of surface and bottom boundary conditions and vertical mixing yield a mean cyclonic circulation in large lakes (Schwab et al. 1995; Davidson et al. 1998).

Figure 4b 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 farther 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, consistent with earlier observations (Csanyi 1972).

In order to quantify the turbulence levels in the flow, we define the relative intensity or turbulent coefficients given as $i_u = \sqrt{\langle u'^2 \rangle}$ and $i_v = \sqrt{\langle v'^2 \rangle}$. Here $u'$ and $v'$ are the fluctuating part of alongshore and cross-shore currents and $s$ is the scalar mean speed. The turbulence intensity coefficients are relatively larger as we go offshore due to increased contributions from near-inertial oscillations (Fig. 4c). Although the nearshore station at a depth of 11 m has shown slightly higher intensities due to shore and bottom frictional influences, they were not remarkably high as observed in Lake Huron (Murphy and Dunbar 1981). The magnitudes of alongshore and cross-shore turbulent intensities increase with offshore and is near-isotropic within the CBL. This is in contrast to drifter observations made on the northern California shelf, which showed approximate isotropy at 40 km from shore and nonisotropy in the inner shelf (Davis 1985).

4. Analysis of upwelling and downwelling events

The position of the 10°C or 13°C isotherm (thermocline) has generally been used to define upwelling and downwelling episodes in Lake Ontario (Blanton 1975; Simons and Schertzer 1989). During this observational program water temperature was measured along with subsurface currents at 10-m depth in the coastal chain stations, with occasional ship-based temperature profile measurement surveys. As an example the cross-sectional thermal structure obtained from several temperature transects during an upwelling event from 23 to 24 July 1990 and downwelling on 17 August 1990 are shown in Figs. 5a and 5b, respectively. During upwelling the thermocline was displaced to surface layers with the 13°C isotherm intersecting the surface in the nearshore region. The strong eastward wind stress of 1–2 dyn cm$^{-2}$ for nearly two days raised the thermocline and displaced warmer waters offshore. During the downwelling event the thermocline shifted depth to 16–20 m with a downward tilt near the shore.

Figures 5c and 5d show the hourly variations of wind stress and low-pass filtered temperature data at selected stations. The alongshore winds were primarily responsible for upwelling and downwelling of isotherms. The near-coastal stations responded more to these events than offshore stations. The eastward (westward) wind stress causes thermocline elevation (depression) indicating upwelling (downwelling) of isotherms. The upwelling events were characterized by eastward flowing subsurface currents and downwelling events by strong westward flowing currents (Fig. 3). These upwelling/ downwelling events were common during the summer regime, with each episode on average lasting for 4–6 days. Although certain upwelling and downwelling events were influenced by favorable local winds, during relatively calm (weak) wind epochs, we observe warmer currents flowing westward. In the spectral analysis of currents (Fig. 2a) a 10–12 day periodicity was observed, which may be due to the presence of internal Kelvin waves (Csanyi 1982). The westward current reversals in the CBL took on average 24–30 hours, suggesting that the wavelength of the Kelvin wave system could be of the order of 50–100 km. This was also reflected in the thermocline excursions of 10–15 m from upwelling to downwelling in 4–5 days. Surface temperatures obtained from satellite pictures during these events also show this phenomenon with upwelling (~10°C) along the north shore and downwelling (19°C–20°C) along the south shore or vice versa with similar scales. Two such upwelling and downwelling episodes along the north shore, during which both Eulerian and Lagrangian measurements were available, have been selected for detailed analysis of flow and turbulent exchange characteristics.

a. Upwelling episode

Eight drifters were deployed close to the current meter moorings in the Darlington coastal chain on 17 July 1990 and were recovered on 26 July 1990. The eastward wind stress from 15 July caused an upwelling of the thermocline by rapidly dropping the temperature by 6–8°C at the near-coastal stations. The mean subsurface currents over this period changed to eastward except at the innermost station. The hourly time series of drifter positions along with mean velocity vectors obtained from current meters are plotted in Fig. 6. The drifters traveled southeastward with nearshore trajectories showing shore-parallel currents, while offshore drifters oscillated at the inertial period. The surface flow obtained from drifters shows offshore directed flow (~4.4 cm s$^{-1}$) during peak upwelling, indicating that surface winds displaced the warmer waters offshore and caused the interface to move upward within the Rossby radius of deformation. Weak onshore flow was observed at stations 3 and 5 at 10-m depth. The southeastward flow in surface layers and weak return flow at 10-m depth at a few stations suggest that the coastal divergence at the surface during upwelling period is compensated at subsurface levels. This is consistent with observations in the surface mixed layer of different coastal regions (Lentz 1992; Allen et al. 1995). The mean Eulerian currents in near-coastal stations during this episode were rather weak. As such, no coastal jet emerges from this analysis, although slightly higher velocities were observed 3–4 km from shore. The absence of a strong coastal jet during this episode could be due to the shallow nature of the thermocline and also possibly because of internal friction (Csanyi 1982).

In order to compare the Lagrangian currents at 3.5 m and Eulerian currents at 10-m depth, we have low-pass filtered the drifter currents and calculated mean currents for each drifter when they are within 20 km alongshore
and 2 km cross-shore bins centered on the respective current meters (Dever et al. 1998). Table 1 presents the statistics of mean and fluctuating currents from both experiments during upwelling. The mean alongshore and cross-shore current components obtained in the surface level (3.5 m) from drifters were higher than Eulerian values at depth 10 m, indicating the existence of shear in the upper mixed layer. The fluctuating velocities were higher than mean currents in both Lagrangian and Eulerian measurements. This may be because the Lagrangian measurements were conducted in surface levels at 3.5-m depth and, hence, were more influenced by prevailing winds. Other explanations may be equally plausible (Davis 1985, 1991). Few current meters were located in the thermocline region due to its upward movement during upwelling. Differences between drifter and current meter velocities also arise owing to wave effects. Drifters at this depth are generally affected by Stokes drift; however, estimates of wave-induced velocity differences due to Stokes drift were not attempted in this paper. Pal et al. (1999, manuscript submitted to J. Geophys. Res.) observed that the differences between drifter currents and current meter values during this period were mainly due to depth differences and, to a limited extent, to spatial variation and instrument errors. The rms values, which are mainly due to near-inertial oscillations, are higher at 3.5-m than at 10-m depth, suggesting a downward propagation of internal wave energy during this episode.

Figure 7a shows the plots of subsurface total kinetic energy, turbulent kinetic energy, and mean flow kinetic energy with distance offshore during the upwelling episode. Although total kinetic energy levels were comparatively less than summer values, the peak has shifted to 5.5 km from shore. The peak of the MKE also shifted to this distance indicating the width of the FBL. Unlike that observed in mean summer conditions, TKE during the upwelling episode increased in the first 5.5 km, and then reduced significantly in the next 2–3 km, and again increased farther offshore. The width of the CBL during this episode reduced to 9 km. Turbulent kinetic energy was comparable to mean kinetic energy in the first 3 km from shore, and in the rest of the CBL, TKE contributed more than 65% to the total kinetic energy.

Figure 7b shows significant increase in turbulence intensity and near-isotropic conditions of turbulence within the CBL. Outside the coastal boundary layer the turbulent intensities sharply dropped to small values. The high values of turbulent intensity in the CBL, which was also reflected in high TKE values, was primarily due to increased near-inertial oscillations and reduced mean scalar current speed during this cycle. The peak of turbulent intensity slightly shifted inshore compared to the summer regime. It may be noted that during an upwelling cycle the cross-shore turbulent intensity was slightly higher at the near-coastal station and again outside the frictional boundary layer.

Near-inertial oscillations

Upwelling and downwelling of the thermocline represents a deviation from equilibrium due to the influence of wind stress. Once the winds subside, internal waves of clockwise motion will develop and contribute to the decay of kinetic energy. Ivey (1987) observed that mixing at ocean boundaries may be due to the reflection of internal waves or to the interaction of mean flow with the bottom. Recently, Bogucki et al. (1997) also observed sediment resuspension by breaking internal solitary waves during upwelling on the California shelf. Further, Lee and Hawley (1998) noted that mean upwelling currents by themselves did not resuspend bottom material in Lake Michigan and speculated that near-inertial internal waves could be a possible mechanism for resuspension. Although short period oscillations in the near-inertial band (11–18 h) were analyzed by a few earlier studies in large lakes (Mortimer 1977) their structure was not fully explored during these events. Since it was observed that standard spectral analysis fails to detect different frequencies in the inertial band, earlier studies used a best-fit method for Poincaré modes. We used both power spectrum analysis with high resolution and a frequency search method. In the frequency search method a fast orthogonal search algorithm (Adeney and Korenberg 1994) was used for a set of candidate frequencies ranging from 11 to 17.5 h for two different upwelling and downwelling episodes. In this method a modified Gram–Schmidt procedure is used to create an orthogonal basis for arranging the time series. The most significant frequencies were obtained by reducing the mean square error between observations and model fit. The periods for candidate frequencies for the internal waves were based on the theoretical values for Lake Ontario (Schwab 1977). For this study the inertial period was taken as 17.4 h and the transverse baroclinic seiches (Poincaré type oscillations) with 1 to 5 modes were taken to be 16.9, 15.7, 14.2, 12.7, and 11.2 h periods.

During the upwelling the kinetic energy of the fluctuations slightly increased due to the increase in near-inertial oscillations. Federuik and Allen (1996) observed a similar increase in their model study over the Oregon continental shelf. Upwelling events were mainly characterized by a 16-h (4–5 cm s\(^{-1}\)) wave in the CBL. Less significant, 16.9-h (≈2.5 cm s\(^{-1}\)) and 14.2-h (≈2 cm s\(^{-1}\)) waves were also observed at many stations. The amplitudes and phases of these waves varied all along the coastal chain of stations. The station outside the CBL was mainly influenced by inertial waves with 17.3-h periodicity, whereas the near-coastal station was dominated by relatively shorter period waves (11 h). The 14.2-h wave was observed at the station 3.4 km from shore in most of the upwelling events. Temperature data also showed main oscillations at 16- and 17-h periodicity. During the initial phase of upwelling events, the short bursts of eastward winds generated waves of period 11.2 and 14.2 h, which were later replaced by more
regular 16.0-h and 17-h waves. This probably suggests that the short wind bursts generate higher mode baroclinic waves in the initial phase, which will be replaced by more regular waves. These observations also show the absence of pure inertial motion within the CBL.

b. Downwelling episode

During the downwelling episode eight drifters were deployed near the same stations as in the upwelling case on 16 August 1990 and recovered on 23 August 1990. The initial eastward winds from 14 to 15 August caused a strong upwelling of isotherms along the north shore of Lake Ontario. The cool temperatures prevailed for two more days even though the winds subsided. This was followed by strong westward winds from 17 August, which caused an increase in water temperatures of 10°–12°C in two days. This downwelling event was associated with strong westward currents of the order of 30–40 cm s⁻¹ at some stations (see Fig. 3). The hourly time series of drifter positions and mean velocity vectors obtained from current meters are shown in Fig. 8. The nearshore drifters traveled westward under the influence of predominantly shore par-
allel currents, and the offshore drifters oscillated at near-inertial frequency.

Figure 9a shows the components of kinetic energy obtained from Eulerian measurements as a function of offshore distance. During downwelling mean kinetic energy sharply increased to a peak at 3 km from shore, thus dividing FBL and IBL regimes. The width of the CBL extended over 14 km during this episode. The turbulent kinetic energy was smaller than summer regime in the FBL, but comparable in the IBL. The contribution from the TKE was less than 5% within the FBL during these events. Outside the CBL TKE and mean kinetic energy were more or less of equal magnitude. Figure 9b shows decreased turbulent intensities all through the CBL. This is mainly due to decreased fluctuating velocities and increased mean currents.

Table 2 shows that the mean Eulerian alongshore currents were toward west with a coastal jet concentrated near 3 km from the shore. This episode shows that the CBL characteristics are similar to the summer regime with increased current speeds. It may be observed from Lagrangian and Eulerian currents that the mean currents at 10-m depth were much stronger than surface currents supporting the fact that downwelling currents extend over the deeper levels (Allen and Newberger 1996). The mean surface currents flowed onshore, whereas the currents at 10-m depth outside the FBL showed offshore flow. Eulerian currents show nonisotropic nature of turbulence, with the alongshore component dominating over the cross-shore component in the CBL. Eulerian currents also showed that rms values of fluctuating velocities, although comparable to summer regime were much less than mean currents, thereby decreasing the turbulence intensities within the CBL.

**NEAR-INERTIAL OSCILLATIONS**

The short period near-inertial oscillations were studied during downwelling events as done in upwelling episodes. As observed in other downwelling regions the spectral energy of fluctuations decreased for the downwelling case compared to upwelling episodes (Federauk
and Allen 1996). Frequency search analysis carried out for two downwelling events showed that main oscillations were located at 15.7 h (1.5–2.2 cm s\(^{-1}\)) and 16.9 h in the CBL and 17.3 h outside the CBL. Temperature data showed oscillations at 14.2 h and 17.3 h periodicity in the CBL; however, it was noticed that the amplitudes of these near-inertial oscillations were much smaller than during upwelling events.

c. Alongshore momentum and cross-shore fluxes

This analysis as well as past studies in Lake Ontario indicate that low-frequency alongshore currents are primarily driven by alongshore winds (Csanady and Scott 1980). The wind and current records during the upwelling and downwelling episodes were a valuable source for understanding the dynamics of alongshore flow. Neglecting alongshore momentum advection, the vertically integrated momentum balance for the alongshore current component can be given as

\[
f
\overline{\nabla} \overline{\psi} = - \left[ g \frac{\partial \eta}{\partial x} + \frac{g}{h \rho_o} \int_{-h}^{0} \frac{\partial \eta}{\partial z} dz \right] + \frac{\tau_x}{\rho_o h} - \frac{\tau_y}{\rho_o h},
\]

where \(\overline{\psi}\) is vertically integrated cross-shore velocity, \(f\)

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**TABLE 1.** Mean and rms velocities of Eulerian and Lagrangian measurements during upwelling cycle (subscript \(L\) indicates Lagrangian and \(E\) indicates Eulerian measurements).

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<th>Station</th>
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<th>(V_E) (cm s(^{-1}))</th>
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</tbody>
</table>
2 cm s$^{-1}$, the error in the Coriolis term will be $0.2 \times 10^{-3}$ and uncertainty in calculating density could be as high as $0.1$ kg m$^{-3}$. The alongshore slope was not measured in this study, but was obtained from the balance of other terms in the momentum equation.

The average values of alongshore momentum balance during upwelling show that the cross-shore current term ($0.7 \times 10^{-5}$) was balanced by a combined barotropic and baroclinic pressure gradient ($0.5 \times 10^{-3}$) and the wind stress ($0.15 \times 10^{-5}$). The bottom stress was significantly small. The alongshore slope obtained in this study is consistent with earlier studies during summer stratification (Csanady and Scott 1980; Simons and Schertzer 1989) where the observed mean alongshore thermocline gradient was of the order of $5 \times 10^{-3}$, which gave a surface-level gradient of roughly $10^{-7}$ in the eastward direction. This suggests that during upwelling the Coriolis force associated offshore flow and the pressure gradient term are roughly in balance, indicating that the flow seeks geostrophic equilibrium. However, during the downwelling episodes the alongshore momentum balance is more complicated. During this episode the cross-shore geostrophic current ($0.96 \times 10^{-3}$) was in balance with combined contributions from pressure gradient ($0.4 \times 10^{-5}$), wind stress ($0.36 \times 10^{-5}$), and bottom stress ($0.19 \times 10^{-5}$). The bottom stress was higher due to the increased mean currents in the downwelling.

Mean values of the products $\langle u' v' \rangle$ and $\langle v' T' \rangle$ represent the cross-shore transport of momentum and heat, respectively. During both upwelling and downwelling events the mean values of horizontal momentum and heat fluxes at 10-m depth were not statistically significant and were noisy. Near-inertial oscillations were probably responsible for this large scatter. By removing near-inertial oscillations between 18 and 14 h using a bandpass filter, we have observed weak offshore transport in the FBL during upwelling episodes. Heat flux is negative in the IBL at this depth. During downwelling events significant negative fluxes were observed between 4 and 6 km in the coastal zone.

5. Turbulent exchange coefficients

a. Lagrangian statistics

The methods of computing Lagrangian timescale and eddy diffusion coefficients have been discussed by many authors (Poulain and Niiler 1989; Dever et al. 1998). The Lagrangian integral timescale ($T_i^l$) and length scale ($L_i^l$) are the time and distance over which the drifter motion remains correlated are given by

$$ T_i^l = \int_0^T R_i^l(\tau) \, d\tau \quad \text{and} \quad L_i^l = \sqrt{\langle u_i^2 \rangle} \int_0^T R_i^l(\tau) \, d\tau. $$

Here $R_i^l$ is the autocorrelation function defined as
Fig. 8. Trajectories of drifters deployed during 16–23 Aug 1990. The arrows indicate the mean current vectors obtained from current meters.

When diffusion time elapses beyond some lag time $t_l$ (Lagrangian correlation time scale), $R_L^2(\tau)$ will drop to zero. Physically $t_l$ is the decay timescale of those eddies that contribute to diffusion. Therefore, for large timescales $t > t_l$ the horizontal eddy exchange coefficient is given by

$$K^2 = \langle u'^2 \rangle T^2,$$

b. Eulerian statistics

In stationary and homogeneous turbulence, the Lagrangian variance $\langle u'^2 \rangle$ can be assumed to be equivalent to Eulerian variance $\langle u'^2 \rangle$ (Lumley and Panofsky 1964). Hay and Pasquill (1959) also pointed out that the essential difference between Eulerian and Lagrangian velocities is that, at a fixed point, velocity fluctuations appear to move rather quickly as turbulent eddies are advected past the instrument. They have shown that the Lagrangian correlation function $R_L^2(\tau)$ and the Eulerian counterpart $R_L^2(\tau)$ have similar shape but differ only by a factor $\beta$, which is greater than unity: $R_L^2(\tau) = R_L^2(\beta \tau)$. Introducing these assumptions, the horizontal exchange coefficient in terms of Eulerian statistics can be written as

$$K^2 = \beta \langle u'^2 \rangle T^2.$$
where $T_e$ is the Eulerian integral timescale.

The autocorrelations for Lagrangian and Eulerian currents show a number of interesting features. An example of autocorrelations for a drifter (5385) and current meter (station 3) during an upwelling cycle is presented in Figs. 10a and 10b. Similar patterns were observed for other locations. Autocorrelations of filtered Lagrangian velocities have fallen to near-zero values for all drifters within 8–12 hours and have shown peaks at 14-h periodicity. The filtered Eulerian values show a steady drop of alongshore autocorrelations, whereas cross-shore autocorrelations show that a peak at a period of 24 h. Lagrangian timescales ($\tau_L$) estimated from autocorrelations were less than Eulerian timescales ($\tau_e$). Similar characteristics were observed on the northern California shelf and in Santa Barbara Channel (Davis 1985; Dever et al. 1998). This was attributed to the effect of the total acceleration in Lagrangian measurements, which includes advection, whereas Eulerian timescales were only a function of local acceleration. This indicates the nonlinearity of the evolution of time-varying currents.

Following Schott and Quadfasel (1979) we have chosen $\beta = 1.4$ in Eq. (4), which may sometimes underestimate the horizontal exchange coefficients. However, this is a reasonable estimate as our primary goal is not the precise quantification of the exchange coefficient but the general analysis of various turbulence exchange characteristics. Since during the summer regime only Eulerian measurements were available, these values serve as an indicator of dispersal tendencies in the flow as well as a comparison of the influence of upwelling and downwelling episodes. The horizontal exchange coefficient values increased from 0.5 to 48 m$^2$ s$^{-1}$ in the offshore direction.

Table 3 presents the horizontal exchange coefficients obtained by Eulerian and Lagrangian measurements during upwelling and downwelling episodes. 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, that is, 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. Although the magnitude of alongshore Lagrangian eddy coefficients were higher than Eulerian values, they show a peak nearly at the same distance. The cross-shore exchange coefficients in the surface levels were less than subsurface values in the IBL. During downwelling 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

![Figure 9](image-url)  
*Fig. 9.* (a) Components of kinetic energy (total, mean flow, and turbulent) with distance offshore and (b) turbulence intensity coefficients with distance offshore during downwelling event.
Table 3. Alongshore ($K_x$) and cross-shore ($K_y$) eddy diffusivities from Eulerian and Lagrangian measurements during upwelling and downwelling cycles (subscript $L$ indicates Lagrangian and $E$ indicates Eulerian measurements).

<table>
<thead>
<tr>
<th>Station/distance from shore (km)</th>
<th>$K_{xL}$ ($\times 10^4$ cm$^2$ s$^{-1}$)</th>
<th>$K_{yL}$ ($\times 10^4$ cm$^2$ s$^{-1}$)</th>
<th>$K_{xE}$ ($\times 10^4$ cm$^2$ s$^{-1}$)</th>
<th>$K_{yE}$ ($\times 10^4$ cm$^2$ s$^{-1}$)</th>
<th>Drifter bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upwelling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/0.68</td>
<td>0.277</td>
<td>0.864</td>
<td>1</td>
<td>7.13</td>
<td></td>
</tr>
<tr>
<td>2/3.24</td>
<td>10.36</td>
<td>6.173</td>
<td>2</td>
<td>68.8</td>
<td>10.2</td>
</tr>
<tr>
<td>3/5.42</td>
<td>26.98</td>
<td>16.78</td>
<td>3</td>
<td>15.5</td>
<td>2.02</td>
</tr>
<tr>
<td>4/7.30</td>
<td>16.62</td>
<td>20.38</td>
<td>4</td>
<td>13.4</td>
<td>2.28</td>
</tr>
<tr>
<td>5/9.28</td>
<td>19.26</td>
<td>20.42</td>
<td>5</td>
<td>17.5</td>
<td>6.43</td>
</tr>
<tr>
<td>6/14.2</td>
<td>24.30</td>
<td>20.33</td>
<td>6</td>
<td>27.8</td>
<td>2.75</td>
</tr>
<tr>
<td>Downwelling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/0.68</td>
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<td>0.652</td>
<td>1</td>
<td>6.51</td>
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<td>2/3.24</td>
<td>7.161</td>
<td>4.197</td>
<td>2</td>
<td>23.1</td>
<td>3.43</td>
</tr>
<tr>
<td>3/5.42</td>
<td>30.97</td>
<td>21.55</td>
<td>3</td>
<td>14.7</td>
<td>4.10</td>
</tr>
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<td>28.42</td>
<td>4</td>
<td>83.2</td>
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<td>41.57</td>
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<td>201.2</td>
<td>31.9</td>
</tr>
<tr>
<td>6/14.2</td>
<td>60.09</td>
<td>72.37</td>
<td>6</td>
<td>214.3</td>
<td>48.8</td>
</tr>
</tbody>
</table>

FBL, but significantly increased in the IBL. The exchange coefficients at 3.5-m depth from drifters have also shown higher alongshore values within the CBL. Both alongshore and cross-shore values increased rapidly to high values outside the CBL with increasing Lagrangian timescales. As observed in the upwelling case, the cross-shore exchange coefficients from Lagrangian measurements were smaller compared to Eulerian coefficients.

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 entering into lake waters. Since the mean currents and lateral shears decreased considerably during upwelling episodes, it is likely that short period fluctuations play an important role in the nearshore and cross-shore exchange processes. During downwelling episodes mean alongshore currents often...
exceeded 20 cm s\(^{-1}\), which could result in alongshore water displacements of more than 100 km during an episode. Although turbulent exchange coefficients were small in the FBL, increased lateral shear may play a role in dispersing the material within the FBL.

6. Summary and conclusions

This study presents an analysis of simultaneously observed time series data from six Eulerian current meters and from satellite-tracked drifters for two experiments during the summer season in the coastal region of Lake Ontario. Flow and structure of the coastal boundary layer along the north shore of Lake Ontario presents a complex scenario during upwelling and downwelling episodes under summer stratified conditions. The theoretical framework that has been created to explain these events comprises two kinds of models. The first model deals with the initial response of the lake to uniform wind stress, and the second type of model deals with the closed nature of the basins wherein the transient response is described in terms of internal wave propagation. From the observations we have delineated elements of both theoretical models. The flow is divided into a mean (large-scale) circulation and turbulent (near-inertial and other small-scale fluctuations) oscillations on the basis of the spectral minimum observed at 24 to 30 hours. Following earlier studies (Csanady 1972; Murthy and Dunbar 1981) in the Great Lakes we have delineated the CBL into a FBL with a width of ~3 km and an IBL of 5–6 km width during summer stratification. These flow regimes varied significantly in upwelling and downwelling episodes.

The observed circulation within the FBL was predominantly shore parallel, while farther offshore the flow was dominated by near-inertial oscillations. The summer regime was characterized by an increase in turbulence intensity with increased distance from shore. Alongshore winds were mainly responsible for low-frequency motion in the CBL; however, some instances were identified where cross-shore component of the winds influenced the near-inertial oscillations of the coastal circulation. The net flow (3–4 cm s\(^{-1}\)) and thermal gradients between coastal stations and offshore stations confirm the earlier studies that the flow seeks geostrophic equilibrium (Csanady 1982).

During this experimental period temperature variations were dominated by the influence of a few short wind events. The eastward (westward) wind stress caused thermocline elevation (depression). The upwelling events were characterized by relatively weaker eastward flow (~5 cm s\(^{-1}\)), and downwelling events with strong westward currents (20–30 cm s\(^{-1}\)), with each episode lasting for about 4 to 6 days. The results show inferences to the propagation of internal Kelvin waves due to the thermocline oscillations within the CBL.

Southeastward transport in surface levels of the FBL and weak onshore flow just below the surface mixed layer in the IBL were observed during upwelling episodes. Alongshore vertically integrated momentum balance shows quasigeostrophic equilibrium. These results are consistent with earlier observations in Lake Ontario (Csanady and Scott 1980) and other coastal upwelling regions (Davis 1985; Lentz 1992; Allen et al. 1995). No coastal jet was observed during this upwelling episode. The subsurface currents showed considerable increase in turbulence intensity due to increased near-inertial and decreased mean scalar current speeds. During the upwelling the peak turbulence intensity as well as total kinetic energy were slightly shifted inshore. The width of the FBL increased to 5.5 km and the IBL width decreased to 3.5 km. Upwelling events were also characterized by dominance of TKE in the CBL. During these episodes momentum transfer occurred in the alongshore direction in the FBL, but cross-shore momentum transfer dominated in the IBL. In contrast to the earlier observations (Blanton 1975) this study shows that a wave of 16-h periodicity is more dominant than 17-h and 14-h waves during upwelling.

During downwelling episodes a coastal jet was observed in deeper levels with peak speeds of 20–30 cm s\(^{-1}\) at 3 km from the shore. This is consistent with earlier observations in Lake Ontario (Simons and Schertzer 1989) as well as on the Oregon continental shelf (Allen and Newberger 1996). The turbulent intensities decreased significantly in comparison to the summer regime. During the downwelling the width of the CBL increased to 14–15 km with the IBL extending over 10 km. The alongshore exchange coefficients were slightly higher in the FBL, but cross-shore exchanges became important in the IBL. Downwelling episodes are also characterized by less contribution from the TKE. Relatively weaker short period oscillations at 15.7 and 16.9 h due to baroclinic seiches in the FBL, and 17.3 h due to inertial motion, were observed in the outer boundary layer.

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