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Nearshore currents and turbulent exchange processes during upwelling and downwelling events in Lake Ontario

By:
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MANAGEMENT PERSPECTIVE

The western Lake Ontario shore is rapidly becoming one continuous urban community and heavily depends on the lake for drinking water and discharge Municipal Waste Water Effluents (MWWE). Characterising the properties of the nearshore receiving waters to which MWWE is discharged is the first step to assess the non-deleterious nature of the pollutants and thus develop sustainable strategies for the protection, restoration and conservation of the western Lake Ontario coastal ecosystem. Climate induced episodic events are largely responsible for dispersing and exchanging MWWE discharged into the nearshore areas of western lake Ontario. When the lake is thermally stratified during the summer months upwelling/downwelling of coastal waters generate intense mixing of nearshore water masses with the offshore of the lake. This paper systematically parametrizes the nearshore currents and turbulent mixing processes for developing coastal outfall transport models for MWWE originating from townships in the Halton, Hamilton and Oakville regions. The results are based on sound physical limnological principles and therefore general to be applied to manage MWWE in other coastal areas of the great Lakes

Courants littoraux et processus d'échange turbulent au cours de la remontée et de la plongée des eaux dans le lac Ontario

Y.R. Rao et C.R. Murthy

PERSPECTIVES DE GESTION

La rive occidentale du lac Ontario est en train de se transformer rapidement en une vaste communauté urbaine qui dépend principalement du lac pour s'approvisionner en eau potable et pour déverser ses effluents d'eau résiduelle urbaine. La caractérisation des propriétés des eaux réceptrices du littoral dans lesquelles sont déversés ces effluents constitue la première étape permettant d'évaluer la nature non délétère de ces polluants et d'élaborer des stratégies durables pour la protection, la remise en état et la conservation de l'écosystème du littoral du lac Ontario. Les événements épisodiques générés par le climat sont en grande partie responsable de la dispersion et de l'échange des effluents d'eau résiduelle urbaine déversés dans les zones littorales de la partie occidentale du lac Ontario. Lorsque le lac est thermiquement stratifié durant les mois d'été, la remontée et la plongée des eaux littorales font que les masses d'eau du littorale sont intensément mélangées avec l'eau extracôtière du lac. Le présent document met systématiquement en paramètres les courants du littoral et les processus d'échange turbulent en vue d'élaborer des modèles de transport des exutoires côtiers destinés aux effluents d'eau résiduelle urbaine provenant des cantons situés dans les régions de Halton, de Hamilton et d'Oakville. Les résultats sont basés sur des principes limnologiques et physiques solides et, par conséquent, généraux, que l'on peut appliquer à la gestion des effluents d'eau résiduelle urbaine dans autres régions littorales des Grands Lacs.

RÉSUMÉ

La circulation littorale et les processus d'échange au cours de la stratification estivale et certains événements épisodiques, tels que la remontée et la plongée des eaux, ont été étudiés à l'aide de données chronologiques sur la vitesse horizontale et les profils de la température collectées dans le lac Ontario. Le pic primaire de l'énergie spectrale des courants et de la température enregistré au cours de la saison estivale se situe dans un interval de 10 à 12 jours correspondant à une réaction à grande échelle du lac attribuable au forçage météorologique et à la propagation des ondes internes de Kelvin. Un pic secondaire de l'énergie spectrale des courants littoraux se situe près de la bande de fréquences inertielle. Chaque épisodes de remontée et de plongée des eaux le long de la partie occidentale du lac durent environ de 4 à 6 jours sous l'influence des vents dominants. Les courants associés aux cycles de plongée sont légèrement plus forts que ceux liés aux cycles de remontée. Bien que l'énergie cinétique associée aux courants littoraux est généralement plus élevée, le débit translittoral montre une énergie plus élevée aux niveaux moyens et inférieurs au cours de ces épisodes. Les coefficients d'échange horizontal le long du littoral sont généralement plus élevés que la composante translittorale. Cependant, durant les épisodes de remontée des eaux, les coefficients d'échange horizontal sont moins élevés dans les couches superficielles et augmentent dans les couches basales. Les remontées sont caractérisées par une stabiité statique faible et un cisaillement du courant vertical réduit dans les couches superficielles. Les couches près du fond du lac sont affectées d'une turbulence intense qui est associée à un accroissement du cisaillement du courant vertical. Au cours des plongées des eaux accompagnées de la migration et de l'intersection du thermocline avec le fond du lac, les coefficients d'échange vertical sont relativement petits en raison d'une faible turbulence.

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Nearshore currents and turbulent exchange processes during upwelling and downwelling events in Lake Ontario

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Abstract. The nearshore circulation and exchange processes during summer stratification and certain episodic events like upwelling and downwelling have been examined using a time series data of horizontal velocity and temperature profiles in Lake Ontario. The primary peak of spectral energy of currents and temperature for the summer season is located at a period of 10-12 days corresponding to the large-scale response of the lake due to meteorological forcing and the propagation of internal Kelvin waves. A secondary peak of spectral energy of coastal currents is situated near the inertial frequency band. Each upwelling and downwelling episode along the western Lake Ontario has lasted for nearly 4-6 days under the influence of prevailing winds. Currents associated with downwelling cycles are slightly stronger than currents associated with upwelling events. Although the kinetic energy associated with alongshore currents is generally higher, cross-shore flow exhibited higher energy at middle and lower levels during these episodes. The alongshore horizontal exchange coefficients are generally higher than the cross-shore component. However, during upwelling episodes, horizontal exchange coefficients are reduced in the surface layers and increased in the bottom layers. Full upwelling events are characterized with weak static stability and reduced vertical current shear in surface layers. Near bottom layers are affected by intense turbulence associated with increased vertical current shear. During downwelling events with migration and intersection of the thermocline with the bottom, vertical exchange coefficients are relatively small due to weak turbulent activity.

1. Introduction

The coastal zones of large lakes and oceans are the areas of most immediate concern to the general public. Understanding the circulation and mixing in the nearshore region is very important for the loading, pathways, and fate of pollutants in lakes and for locating water intakes and waste water treatment plants. The nearshore area of lakes can be characterized from the shore to ~10 km offshore as a boundary layer within which the midlake motions adjust to the presence of the shores [*Csanady*, 1972]. Many field experiments conducted on the Great Lakes have shown a variety of circulation features associated with meteorological forcing, stratification, and topography [*Boyce et al.*, 1989]. Upwelling or downwelling of the thermocline in coastal waters affects the mixing and transport of contaminated waters in the nearshore zone and brings nutrient-rich subsurface waters to surface levels. During changeovers from upwelling to downwelling, there may be appreciable mass of inshore water exchanged with offshore water.

The theory of wind-induced upwelling in large lakes contains two basic elements. The first element concerns with the forcing of coastal upwelling by local winds, which causes the surface layer to move to the right of the wind due to the Coriolis force. The second aspect deals with the pattern of upwelling and downwelling of isotherms, once established by the wind, that propagates around the lake. The wind-induced thermocline excursions display a wave-like variation along the shore. A thermocline wave of this type is confined to a narrow strip of the coast and is known as an internal Kelvin wave. They usually propagate at the speed of gravity waves near density interfaces, but owing to the Coriolis force they are trapped near the shore. The alongshore propagation of warm and cold water after a major upwelling event has been observed many times in the Great Lakes [*Mortimer*, 1977; *Simons and Schertzer*, 1989].

The nature of the dynamics of nearshore currents during upwelling and downwelling situations is studied in the Great Lakes using both field observations and theoretical models [*Csanady and Scott*, 1974; *Blanton*, 1975; *Simons and Schertzer*, 1989; *Belestky et al.*, 1997]. However, the role of upwelling and downwelling events in the dispersion of coastal effluents is not studied in great detail mainly because of the lack of detailed measurements. There are a few studies describing the role of these events in the transport of fine-grained material, particularly in the bottom nephloid layer [*Hawley and Murthy*, 1995; *Lee and Hawley*, 1998].

The western Lake Ontario shore is rapidly becoming one continuous urban community that heavily depends on the lake for drinking water and discharge of wastewater. Although substantial advances have been made in the regulation of outfall location and permissible effluent quality, the ever increasing total volumes of waste water heighten the need to understand coastal physical processes in much more detail due to the complications introduced by basin shape and bathymetry at the western end of the lake. Historical current and temperature data show periods of current stagnation, high

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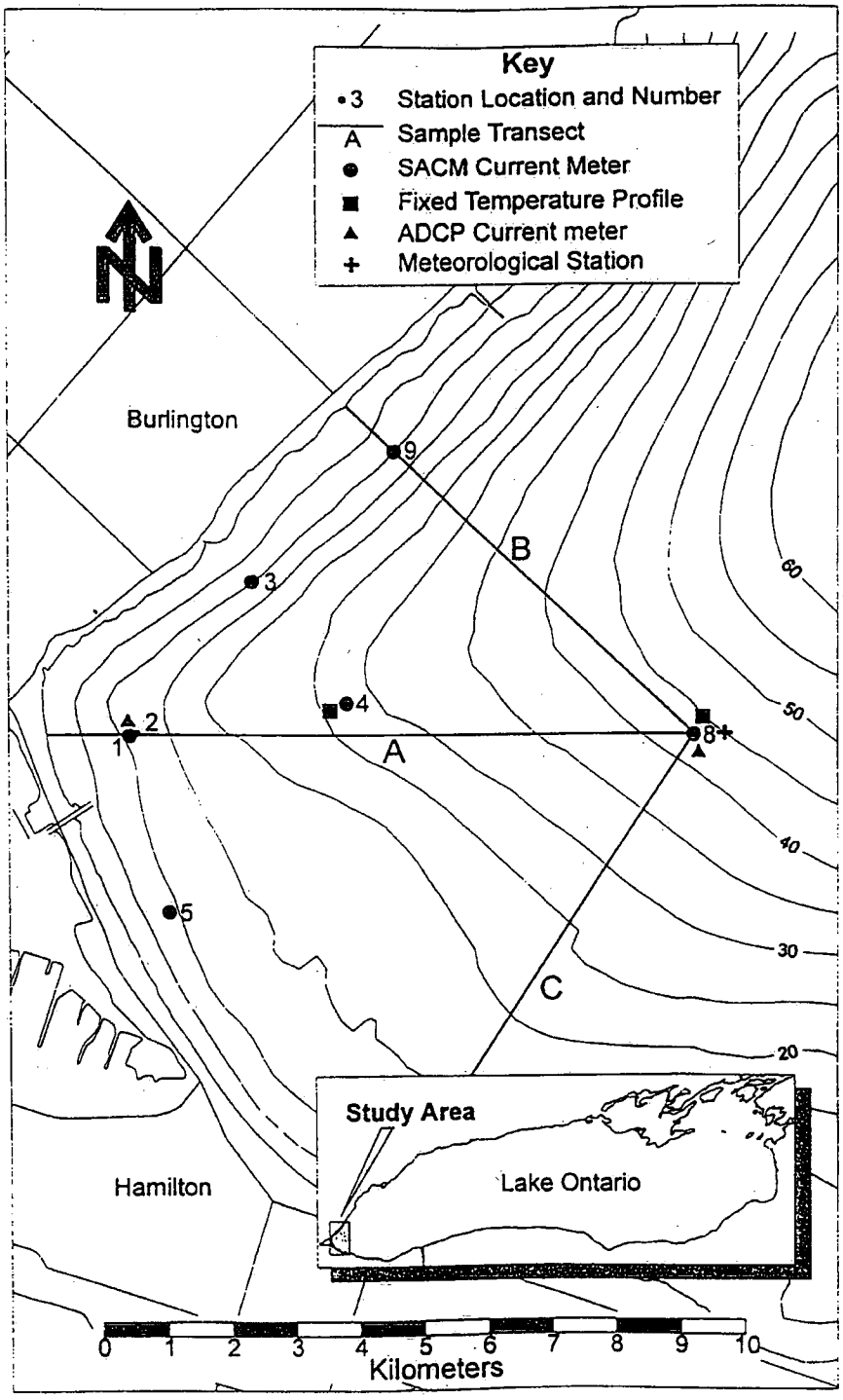

Figure 1. Map of the western Lake Ontario basin showing locations of the measurement sites.

variability of currents, and frequent episodes of upwelling and downwelling during the summer.

The main objectives of this paper are then to study the variability and dynamics of nearshore currents and to calculate horizontal and vertical mixing characteristics of western Lake Ontario during summer stratified season in particular during upwelling and downwelling events.

2. Experimental Data

During 1996 and 1997 an extensive field measurement program was undertaken by the National Water Research Institute (NWRI) in the western part of Lake Ontario in the nearshore area off Burlington and Hamilton (western Lake Ontario basin, Figure 1). As a part of this field program, two

Table 1: Mooring Deployment Periods, Types of Measurements and Water Depths at Mooring Stations From June 24 to September 2, 1997

Instrument Type	Station / Instrument Depth[a], m	Angle of Rotation From North to Shoreline, deg	Bottom Depth, m
SACM-3 current and temperature	1/ 9	0.0	15.7
	5/12	167	12.5
	4/25	0.0	28.4
	3/8	43.5	12.7
	9/9	42.5	10.2
ADCP -1200 kHz (bottom-mounted) vertical profile of horizontal currents	2/ (2-15)	0.0	16.2
	8/ (33-47)	0.0	48.1
thermistor string	4 / 20	-	28.4
	8 / 40	-	48.1
winds (+4 m)	8/ (+4)	0.0	48.1

[a]Depth ranges from ADCP measurements at 1 m interval, and winds 4 m above the surface.

1200-kHz broadband acoustic Doppler current profiler (ADCPs) by RD Instruments were deployed and continuous velocity profiles from June 24 to September 2, 1997 have been gathered. At station 2, velocity profiles were obtained at 1 m intervals from 14.3 to 2.3 m, while at station 8 the ADCP velocities were obtained from 46.4 to 33.4 m. The ADCP uses a pair of broadband encoded pulses to measure velocity throughout the water column. The data collected in each depth cell were hourly averaged for this analysis. The data screening ensures data quality and utilizes a broadband processing parameter in which the error velocity is <1 cm s^{-1} prior to temporal averaging. The long-term accuracy of velocity profiles obtained from broadband ADCP are of the order of ±0.2%. In addition to two ADCPs seven Smart Acoustic Current Meters (SACM-3) were also deployed during this period to record current velocities and water temperatures at other locations. Five of them have returned good quality data for the whole period. SACMs have been extensively used in Lake Ontario studies, whose speeds are accurate to 0.5 cm s^{-1} with a lower threshold value of 0.2 cm s^{-1}.

Temperature profiles were obtained from two thermistor strings located at stations 4 and 8. Data were recorded at 20- and 30-min intervals at stations 4 and 8, respectively. The temperature data are accurate to the order of 0.1°C. Further, we have used ship-based temperature measurements obtained from three transects during certain periods. Owing to the complicated nature of local topography, the orientation of the local shoreline differs at each current meter location. Accordingly the alongshore and cross-shore components of current velocity at SACM stations were resolved after taking local shore line into consideration. Table 1 shows the deployment locations and depths, the angle of rotation from north, and the type of measurements at the study site.

The variability of nearshore currents is determined by prevailing winds over Lake Ontario [*Csanady and Scott*, 1980]. During this experimental program a meteorological buoy was deployed near the offshore ADCP station. Therefore the wind measurements at station 8 have been taken as a representative meteorological forcing during this period. The wind stress was obtained from the quadratic law given as $\tau = \rho_a C_d \, |W| \, W$, where ρ_a = 1.2 kg m^{-3} is air density and W is wind velocity. In general, drag coefficient C_d increases with the wind speed and is estimated as $C_d = (0.8 + 0.065\, W)\times 10^{-3}$ for W>1 m s^{-1} [*Wu*, 1980]. Figure 2 shows the east-west (cross-shore) and north-south (alongshore) wind stress components (in dyn cm^{-2}) obtained from hourly wind measurements. Here the direction of wind stress points toward the reference.

3. Nearshore Currents and Thermal Structure

Mean circulation during certain episodic events such as thermal bar, current reversals and upwelling were discussed in earlier contributions [*Blanton*, 1975; *Gbah and Murthy*, 1998]. However, these studies were based on limited data with coarse vertical resolution. In this section, by using a time series of horizontal velocity and temperature profiles, we describe the variability of coastal circulation during upwelling and downwelling episodes in comparison to the summer circulation characteristics obtained from June 24 to September 2, 1997, data in the coastal zone of western Lake Ontario.

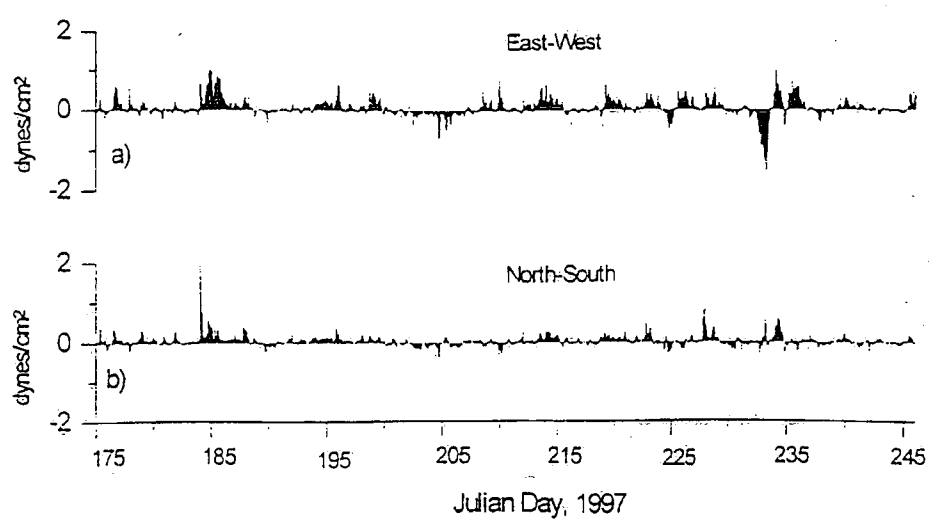

Figure 2. Time series of hourly east-west and north-south wind stress (dyn cm^{-2}) components at station 8.

Table 2: Upwelling and Downwelling Events Alongwith Predominant Wind Directions During These Episodes

Dates	Julian Days	Episode	Predominant Wind Direction (Toward)	Range of Mean Wind Speed, m s^{-1}
July 3- 8, 1997	184-189	upwelling	northeast	4-6
July 23-29, 1997	204-210	downwelling	south, southwest	3-4
July 30 to Aug 3, 1997	211-215	upwelling	northwest	3-5
Aug 4-6, 1997	216-218	downwelling	west	3-4
Aug 8-12 1997	219-224	upwelling	north-east	3-3.5
Aug 18-23 1997	230-235	downwelling	west	4-5
Aug24-28 1997	236-240	upwelling	north-east	2-3

The positions of 10-13°C isotherms were used to define upwelling and downwelling events in Lake Ontario [*Simons and Schertzer*, 1989]. By taking the position of 10°C isotherm as the depth of the thermocline we identified upwelling (downwelling) events when the thermocline sharply moved upward (downward) coinciding with favorable wind direction. Table 2 shows approximate start and end of upwelling and downwelling events, predominant wind direction, and the range of wind speeds during these episodes. Figures 3a and 3b show the daily averaged temperature (°C) obtained at stations 4 and 8 located at depths of 28.4 and 46.7 m, respectively. The mean temperature decreases as we go to deeper layers. The time series of temperature profiles show a variability at a period of 10-12 days. Comparison of temperature and wind stress time series reveals that upwelling and downwelling events correspond to north-eastward and westward winds. Except during strong upwelling and downwelling episodes the temperature profiles show a stable stratification.

The kinetic energy spectra averaged over the depth for the summer season at ADCP stations 2 and 8 exhibit oscillations at several frequencies (Figure 4). Both locations show a prominent peak corresponding to a period of 10-12 days. This was also observed in other previous studies along the north shore [*Blanton*, 1975] and in the middle of the lake [*Omstedt and Murthy*, 1994] and attributed to the large-scale

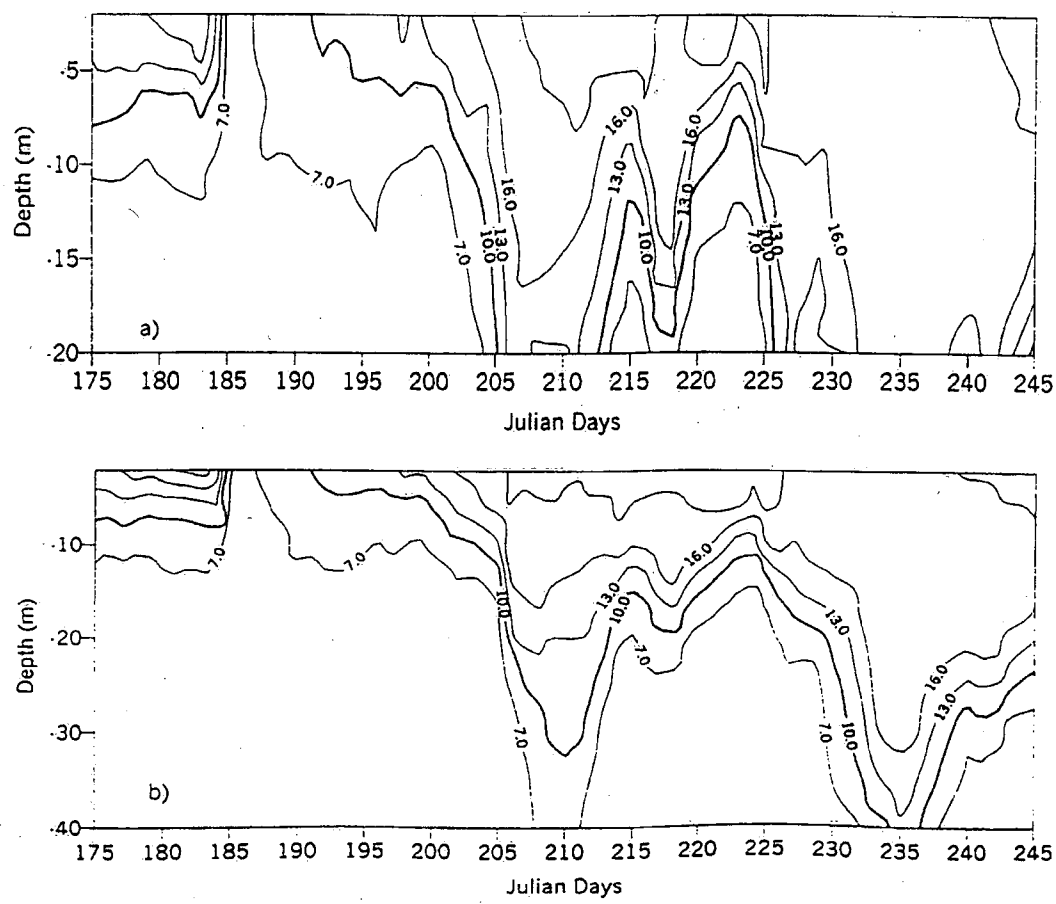

Figure 3. Daily averaged temperatures at stations (a) 4 and (b) 8 during Julian days 175-245, 1997.

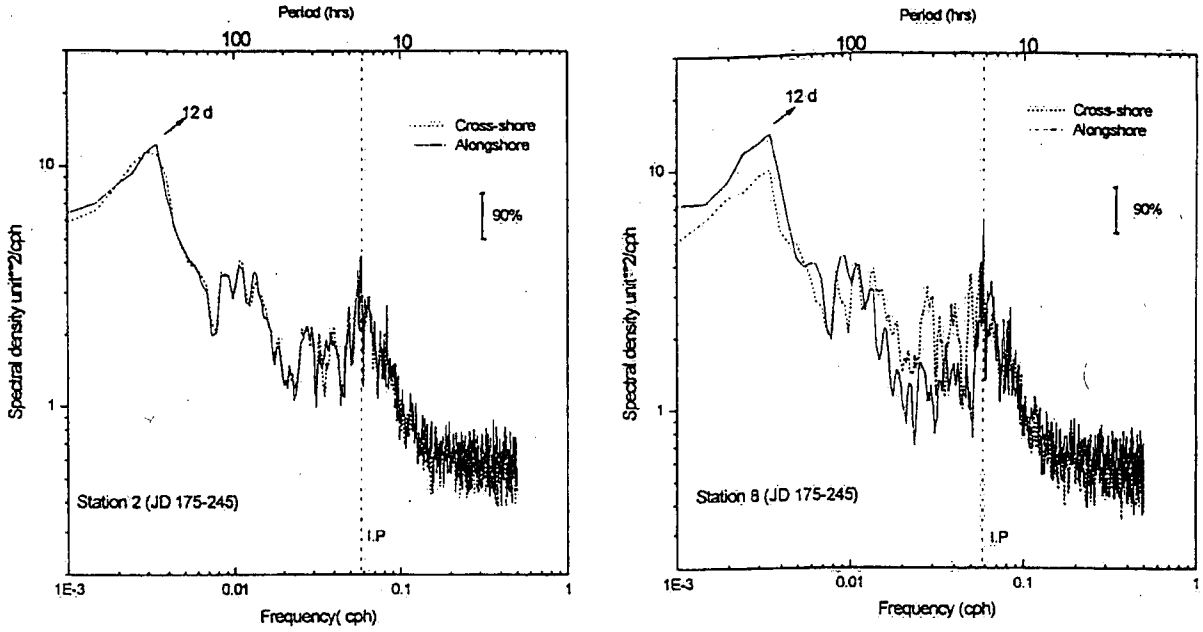

Figure 4. Depth-averaged spectra of cross-shore and alongshore current components at stations 2 and 8.

meteorological forcing. Also, it has been theoretically shown that during stratification the Great Lakes have a predominantly baroclinic response in the form of a rotating Kelvin wave with an approximate period of 10 days [*Csanady*, 1972]. The other pronounced peak was located close to the inertial period (~17 hours) and dominates the higher-frequency band (0.05 to 0.1 cph) at both stations. At this frequency band we observe weak oscillations at 14- and 11-hour periods due to internal baroclinic seiches. The energy falls quite rapidly at offshore location in the high-frequency band. The spectral minimum observed at 24-30 hours can be used as a transition between mean flow and fluctuations [*Murthy and Dunbar*, 1981]. Hence we use a low-pass filter [*Graham*, 1963] with a cut-off periodicity of 18-24 hours, which will damp out all inertial and high-frequency oscillations from the mean flow.

Time series of low-pass-filtered east-west and north-south currents show the flow reversals due to upwelling and downwelling events (Figure 5). During a full upwelling event from Julian day (JD) 184 to JD 189, the strong northeastward wind stress (1-1.5 dyn cm^{-2}) raised the thermocline to the surface. The near-surface temperatures dropped by nearly 10-11°C from 18°C within a period of 12 hours. During this period, surface currents were predominantly eastward. The net alongshore currents were relatively small coinciding with weak stratification. *Allen et al.* [1995] also noticed in their numerical experiments that in the absence of stratification, coastal jet was absent and the magnitude of alongshore currents was markedly decreased. The absence of coastal jets during the full upwelling event could also be attributed to cross-shore heat and momentum advection in the coastal zone [*Csanady and Scott*, 1980]. The mean cross-shore currents show onshore flow from just below the surface mixed layer. The onshore flow from deeper parts of the lake appears to be responsible for the drop in water temperature. In the surface Ekman layer the strong northeastward winds would have caused an offshore transport, which was compensated by an onshore adjustment drift current below the surface friction layer. Another upwelling event from JD 219 to 224 occurred under the influence of moderate north-eastward wind stress (0.5-0.8 dyn cm^{-2}). The thermocline moved up to 8-10 m below the surface. The alongshore currents were toward north with a maximum of 14 cm s^{-1} at the surface on JD 220. The cross-shore flow was weak during this episode; however, onshore flow developed in the middle and lower levels.

The downwelling of the thermocline was mainly caused by westward winds. The thermocline intersected the bottom at the offshore station on two occasions (JD 204-209 and JD 230-235) during this period (Figure 3). The surface temperatures increased considerably to 18-20°C because of the arrival of warm waters from the north. Strong southward currents were observed all through the depths. Although the cross-shore currents were toward the shore in the surface layer, they were almost in opposite direction in the middle and lower levels. The duration of the downwelling events were slightly longer (5-6 days) than upwelling events. On some occasions it was observed that although the prevailing winds were weak, the downwelling was quite strong. *Csanady and Scott* [1974] observed coastal jets with strong alongshore currents and attributed them to the propagation of internal Kelvin waves.

4. Exchange Processes

In section 3 we discussed nearshore currents and thermal structure during upwelling and downwelling episodes in western Lake Ontario. It has been illustrated that the circulation is highly variable in intensity, scale, and duration. *Blanton* [1975] noted the predominance of short-period (near-inertial) oscillations during upwelling and downwelling. However, the role of these oscillations has not been explored in detail in terms of coastal exchange processes. Although

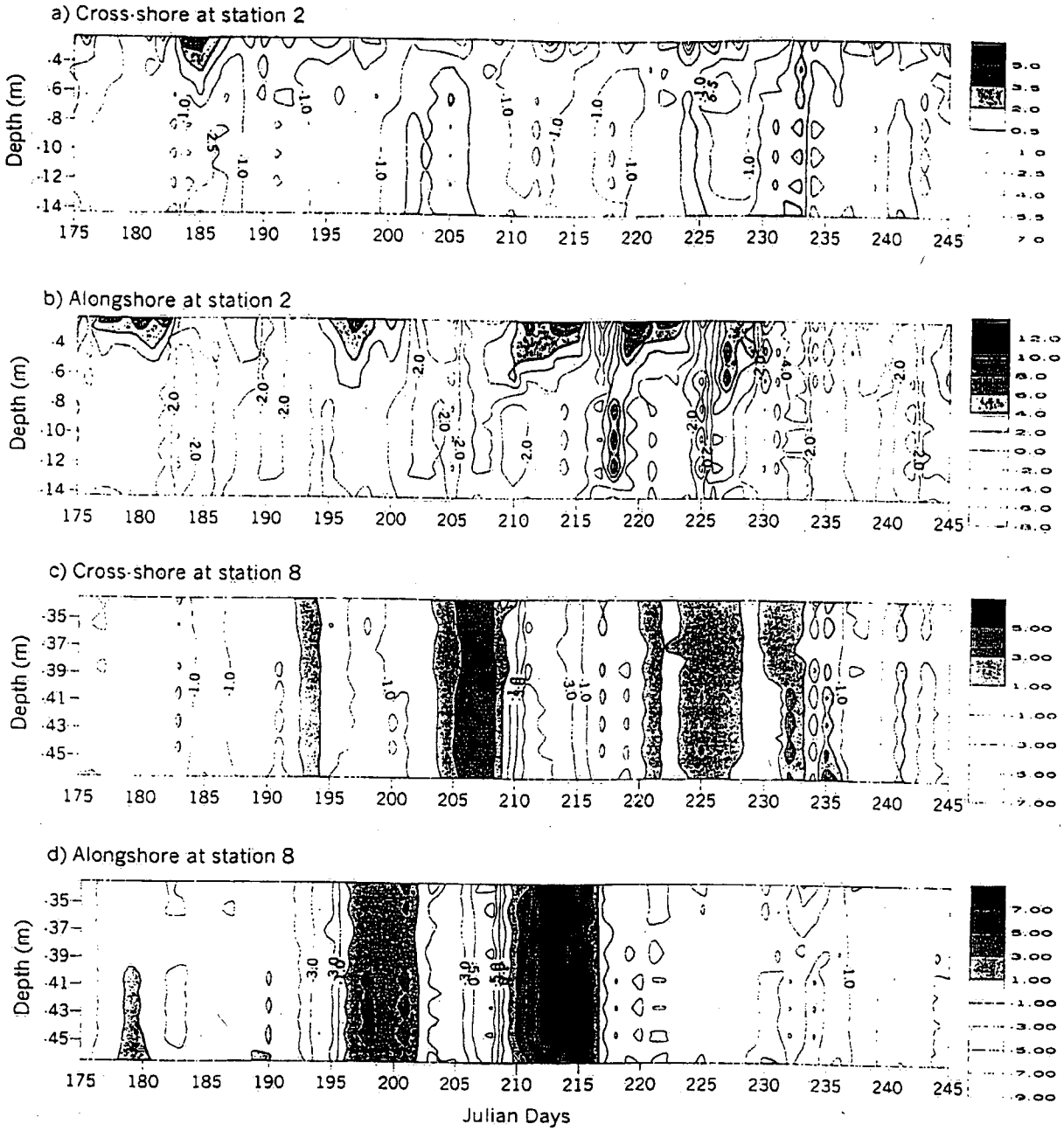

Figure 5. Daily averaged low pass filtered cross-shore and alongshore current components (cm s^{-1}) at ADCP stations 2 and 8. Eastward and northward components are shaded.

inertial oscillations are organized flow, characteristic of summer conditions, because of their oscillatory nature they can be viewed as large-scale fluctuations and as such contribute to dispersal processes. In addition to near-inertial oscillations being generated during upwelling, the effect of offshore Ekman transport and turbulent entrainment in the surface mixed layer, and the offshore transport of the upwelling front will also lead to increased mixing [*Shaffer*, 1984]. These processes would mix heat downward and enhance flow in the thermocline. In this section, the time series description as well as means and statistics of turbulent exchanges of momentum are considered as an approach for studying mixing characteristics during upwelling and downwelling events and their variability in comparison to mean summer conditions.

4.1 Horizontal Mixing

In small- and medium-sized lakes, horizontal mixing is fast compared to vertical mixing so that major concentration gradients develop along the vertical axis. However, in large lakes and oceans, horizontal mixing is a consequence of both

fluctuations of the velocity field and the shear in the advective fields. In order to estimate horizontal exchange coefficients in western Lake Ontario we use current velocity data obtained from both ADCP and SACM stations. The time series of low-frequency (filtered, >24 hours) flow values in section 3 $\bar{u}(t)$ and $\bar{v}(t)$ are subtracted from the observed hourly values $u(t)$ and $v(t)$ to obtain the fluctuations $u'(t)$ and $v'(t)$. The variance ($\langle u'^2 \rangle$ and $\langle v'^2 \rangle$) is used as a measure of the magnitude of velocity fluctuations. Here $\langle . \rangle$ indicates the time averaging from JD 175 to JD 245 for mean summer conditions, JD 184-189 for upwelling and JD 230-235 for downwelling. Turbulence intensity levels in coastal waters can be characterized by root-mean-square (rms) values as $\sqrt{\langle u'^2 \rangle}$ and $\sqrt{\langle v'^2 \rangle}$. The mean flow kinetic energy (MKE) and the fluctuating currents kinetic energy (FKE) are then simply given as

$$\{\mathrm{MKE}, \mathrm{FKE}\} = \{ \frac{1}{2}\left(\overline{u}^2 + \overline{v}^2\right), \frac{1}{2}\left(\langle u'^2 \rangle + \langle v'^2 \rangle\right) \}.$$

By following *Taylor*'s [1921] analysis a relationship has been developed between the horizontal exchange coefficient and the Eulerian current fluctuations in Lake Ontario [*Gbah and Murthy*, 1998]. In their study the horizontal exchange coefficient in terms of Eulerian statistics was written as

$$K = \beta \overline{u'^2} \tau \text{ , where}$$

$$\tau = \int_0^\infty R(\tau) d\tau$$

is the Eulerian integral timescale and $R(\tau)$ is the Eulerian auto-correlation coefficient. *Schott and Quadfasel* [1979] have determined values of β to the order of 1.4 ± 0.4 based on simultaneous Lagrangian and Eulerian measurements in the Baltic Sea. We have chosen $\beta = 1.4$ as a mean value for the present study to estimate the horizontal exchange coefficient. Nevertheless, 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 parameters. Also, from a practical point of view, a seasonal climatological characteristic of horizontal exchange coefficients during summer and its variability during upwelling and downwelling episodes can be established from a long time series of current profiles under actual meteorological conditions. Hence, in this paper the cross-shore (K_x) and alongshore (K_y) exchange coefficients are described along with other parameters.

The rms values that are plotted against depth at ADCP stations 2 and 8 in Figure 6 show near-isotropic conditions in the middle and lower levels and nonisotropic nature of horizontal turbulence with alongshore variance dominating in surface layer. The full upwelling episode shows less horizontal turbulence intensity, with substantial decrease in alongshore variance. The maximum turbulence intensity was located at a slightly shallower depth (4 m) indicating the shift of the thermocline and turbulence activity toward the surface levels. The cross-shore variance increased below the mixed layer indicating the onshore flow during upwelling. During the downwelling, both alongshore and cross-shore variances increased compared to mean summer values. At the offshore station the turbulence intensity has increased at 3-5 m above the bottom.

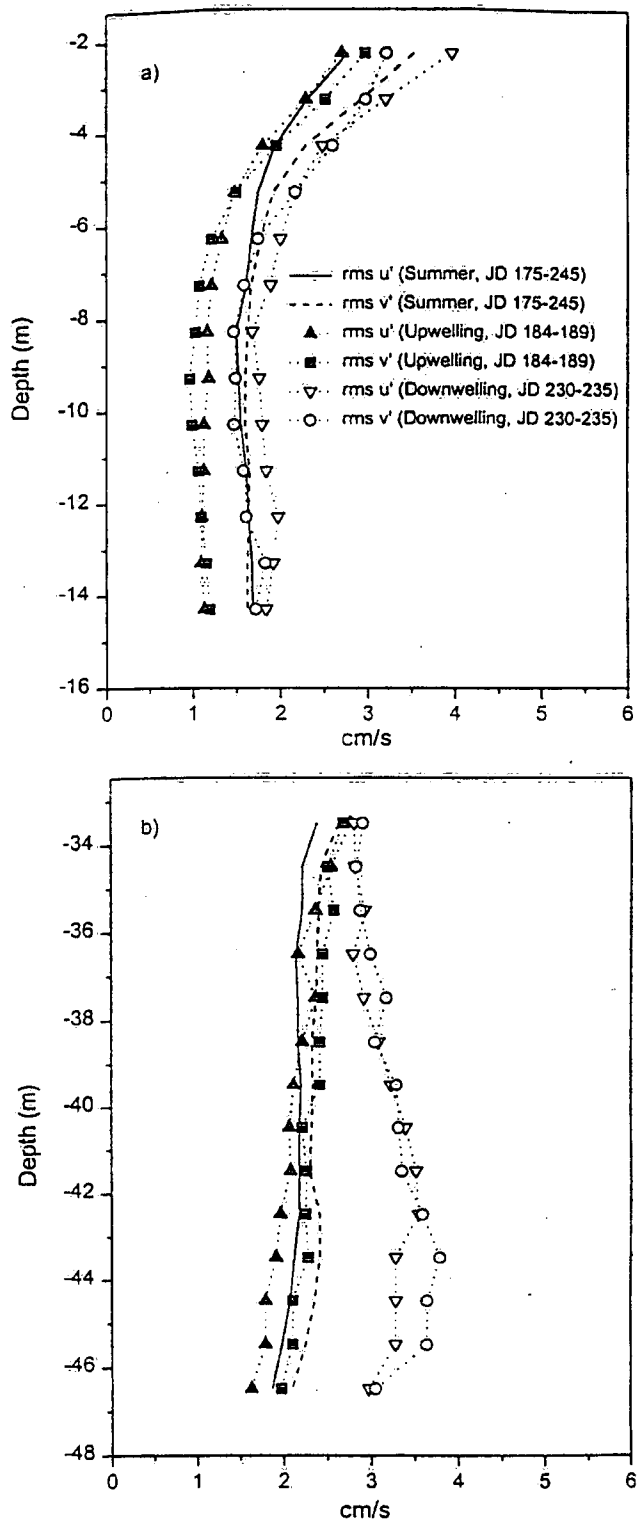

Figure 6. Root-mean-square (rms) values of u' and v' at stations (a) 2 and (b) 8.

Figure 7 shows that mean flow kinetic energy was generally higher than fluctuating flow kinetic energy during

Table 3: Horizontal Turbulent Exchange Statistics Obtained From SACM Current Meters in the Western Lake Ontario

Current Meter/ Depth, m	rms u'	rms v'	MKE, $cm^2 s^{-2}$	FKE, $cm^2 s^{-2}$	K_x, 10^4 $cm^2 s^{-1}$	K_y, 10^4 $cm^2 s^{-1}$
1 / 9	1.90	2.29	17.40	4.68	2.21	3.70
5 / 12	1.39	1.49	4.12	2.14	1.08	1.45
4 / 25	1.69	1.50	6.05	2.66	1.77	1.41
3 / 8	2.11	1.79	10.48	4.04	3.16	2.68
9 / 9	1.55	1.60	6.43	2.62	1.34	1.62

the summer. The alongshore exchange coefficients were higher in surface layer (9 x 10^4 cm^2 s^{-1}) in comparison to cross-shore exchange coefficients (3.5 x 10^4 cm^2 s^{-1}). However, at the offshore station the magnitudes of both the components are comparable. During upwelling, the FKE was comparable to the MKE in surface mixed layer because of the decrease of mean flow currents due to near homogeneous conditions. This is consistent with the numerical experiments of *Allen et al.* [1995]. In the bottom layers at the offshore station the FKE dominated over the MKE mainly because of the increase in near-inertial oscillations. The alongshore exchange coefficient, though still dominant in surface layers, was somewhat reduced to 5.4 x 10^4 cm^2 s^{-1} and increased at the offshore station. The other important feature during this episode was the slight increase in cross-shore exchange coefficient just below the mixed layer, indicating onshore momentum exchange at those depths. During the downwelling episode the magnitude of the FKE slightly increased in surface levels under the influence of westward winds. Although the MKE was less in surface layers compared to mean summer conditions, it has increased considerably in the rest of the water column. At the offshore station the FKE was comparatively higher than the MKE at 5 m above the bottom. This is because of the increase of near-inertial oscillations in the thermocline. The downwelling events were characterized with 16-hour oscillations in the surface layer and 14-hour oscillations in the hyplomnion. These short-period oscillations are because of the presence of baroclinic seiches due to the thermocline movements. The cross-shore exchanges dominated over the alongshore coefficients below the mixed layer, indicating that the offshore transport was mainly due to turbulent currents.

Table 3 presents properties of velocity fluctuations recorded from five SACM current meters during the whole summer period. These turbulence statistics will supplement the ADCP data in western Lake Ontario. The magnitudes of the turbulence parameters obtained here were comparable to the values obtained from ADCP station 2 at respective depths. The alongshore turbulent variances and exchange coefficients were generally higher than cross-shore components, except at station 4 which was at 25 m depth. This probably indicates some cross-shore exchanges taking place in the deeper layers in the corner of the lake.

4.2 Vertical Mixing

Several mechanisms such as current shear, breaking of internal waves, or convective overturns contribute to the generation of vertical turbulence in lakes and coastal oceans. The strong influence that the vertical shear and stability have on turbulence can be estimated from the gradient Richardson number, $Ri = N^2/Sh^2$. Here N is the Brunt-Vaisala frequency given as $N^2=-g/\rho_o(\partial\rho/\partial z)$ and the vertical current shear $Sh^2=(\partial u/\partial z)^2+(\partial v/\partial z)^2$, where z is the vertical coordinate positive upward, u and v are hourly cross-shore and alongshore currents, respectively, g is the acceleration due to gravity, and ρ_o is reference density. Some implications of Richardson number can be studied from the conservation equation of turbulence kinetic energy (q), which under the assumption of horizontal homogeneity and neglecting horizontal advection can be written in a simple form as [*Omstedt and Murthy*, 1994]

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z}\left(\frac{K_z}{\sigma_k}\frac{\partial q}{\partial z}\right) + p_s\left(1 - \frac{1}{\sigma_t}Ri\right) - \varepsilon \quad . \tag{1}$$

Here σ_k and σ_t are Schmidt and Prandtl numbers, ε is the dissipation rate, P_s is turbulence production due mean current shear, and K_z is vertical eddy viscosity. It can be readily noticed from (1) that by assuming the vertical diffusion term as negligible, the Prandtl and Schmidt numbers equal to one, and ε constant, the turbulence is damped if gradient Richardson number becomes greater than zero. On the other hand, when $Ri < 0$, turbulence production due to mean current shear increases the turbulence kinetic energy.

The turbulent mixing can be calculated on the basis of different models. However, in this study, instead of applying a more advanced turbulence closure model we employ a simple empirical formula. *Pacanowski and Philander* [1981] related the eddy viscosity to the Richardson number and studied the modeling of temperature structure in the tropical ocean which is given as

$$K_z = \frac{K_o}{(1+5Ri)^2} + K_b \, , \tag{2}$$

where $K_o = 10^{-2}$ m^2 s^{-1} is an adjustable parameter and K_b is the background eddy viscosity which is equal to 10^{-6} m^2 s^{-1}. In this study, K_b is reduced by a factor of 100 corresponding to molecular values to account for low eddy viscosity values observed in Lake Ontario [*Omstedt and Murthy*, 1994]. The density of the lake water was estimated from the temperature data from the fixed thermistor string moorings and SACM current meters and calculated according to *Chen and Millero* [1986]. The temperature data at different levels were smoothly interpolated using a cubic spline technique to match with ADCP current measurement levels. Since our main interest was not studying diurnal variations of different parameters, we calculated daily averages of Brunt-Vaisala frequency (N), vertical shear (Sh^2), Richardson number (Ri),

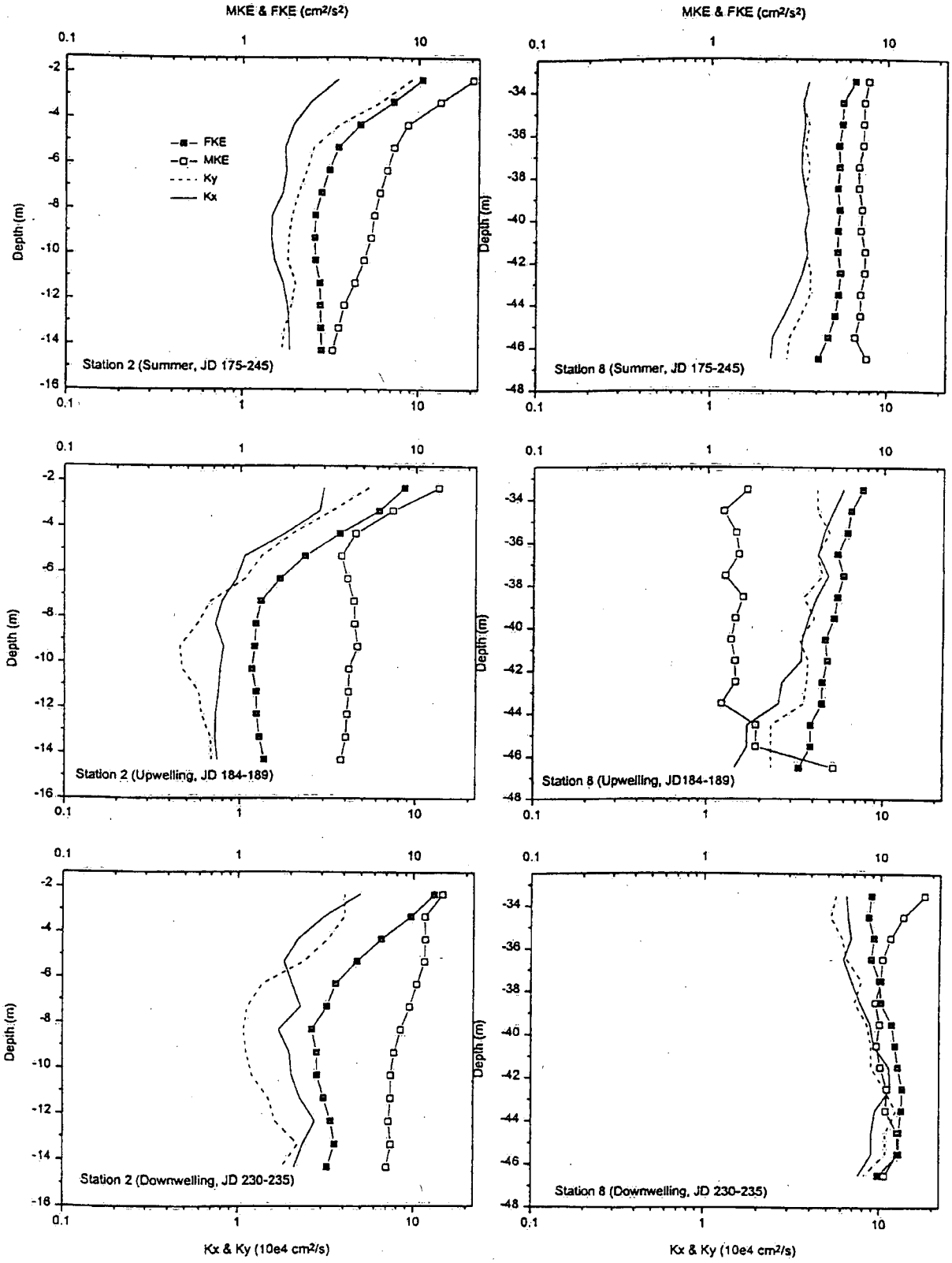

Figure 7. Horizontal exchange coefficients, mean flow energy (MKE) and fluctuations kinetic energy (FKE) as a function of depth at ADCP stations. Solid curve is cross-shore, dashed curve is alongshore exchange coefficients in 10^4 cm^2 s^{-1}, solid squares are FKE, and open squares are MKE in cm^2 s^{-2}.

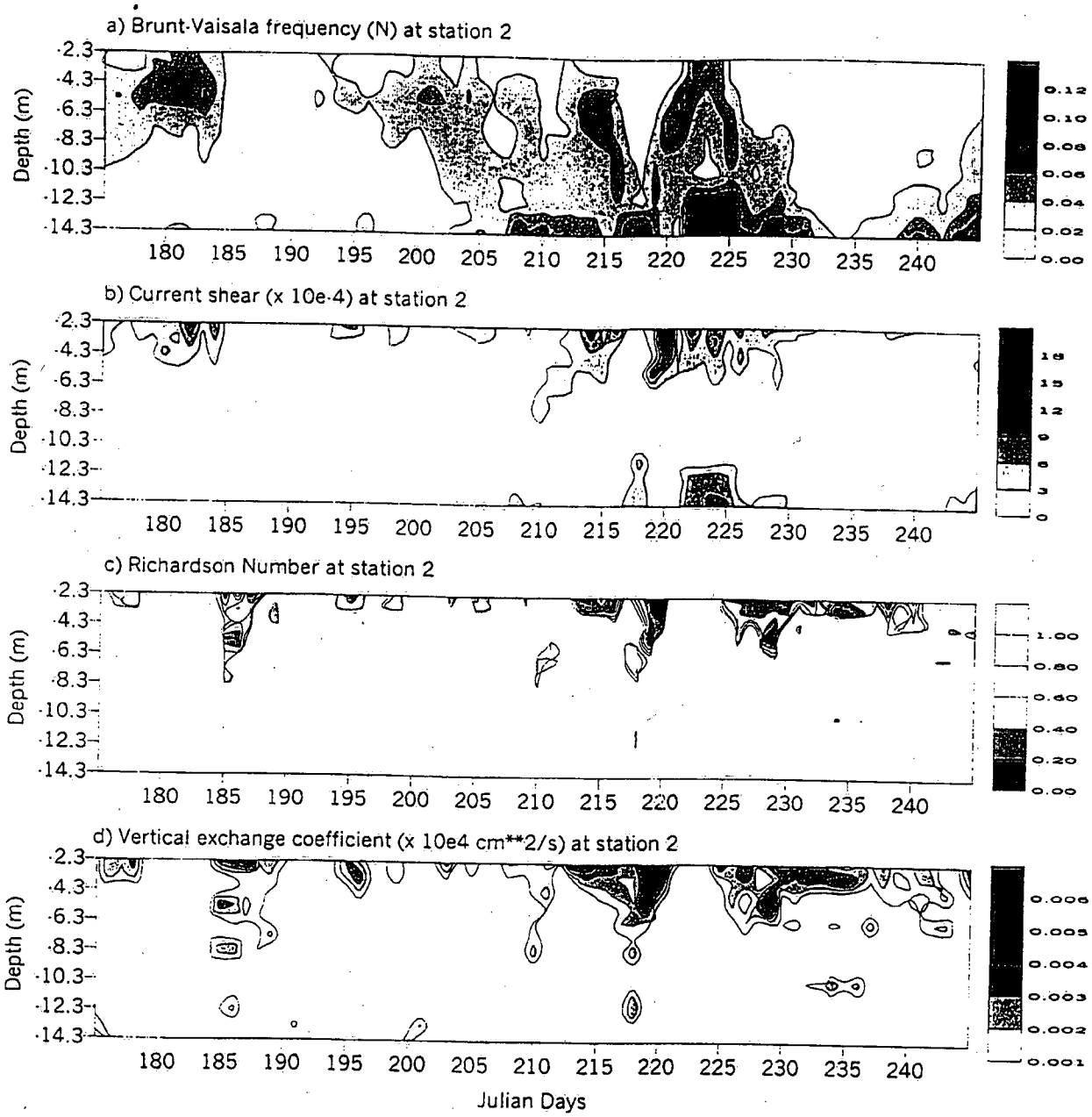

Figure 8. Daily averaged Brunt-Vaisala frequency (N), Richardson Number (Ri), Shear (x 1.0^{-4}) and vertical eddy viscosity (K_z) at station 2.

and eddy viscosity (K_z) obtained by (2). These are presented in Figures 8 and 9 for ADCP stations 2 and 8, respectively.

Comparison of the time series of wind stress (Figure 2) and vertical current shear (Figures 8 and 9) shows that current shear in the upper mixed layer was closely related to the east-west component of wind stress. During the full upwelling episode from JD 185 to JD 189 when the thermocline surfaced, N dropped to small values ($<2 \times 10^{-2}$) and the vertical shear was weak all through the water column because of nearly homogeneous conditions. Because of low values of N this weak current shear was sufficient to reduce Richardson numbers to near critical values (<0.25) in the upper mixed layer thus enhancing the turbulence. Part of this enhanced turbulence has resulted in increasing the vertical eddy viscosity coefficients (30-40 $cm^2\ s^{-1}$) during this episode. In the bottom layers at station 8, Richardson numbers were near critical values resulting in high vertical eddy coefficients. During the other upwelling events when the thermocline has not surfaced, the vertical current shear was considerably high in the surface mixed layer, increasing eddy coefficients to 60 $cm^2\ s^{-1}$.

The downwelling episodes from JD 204-210 and JD 230-235 produced low N in the upper mixed layer and higher values in the bottom layers. This was due to a deepening of

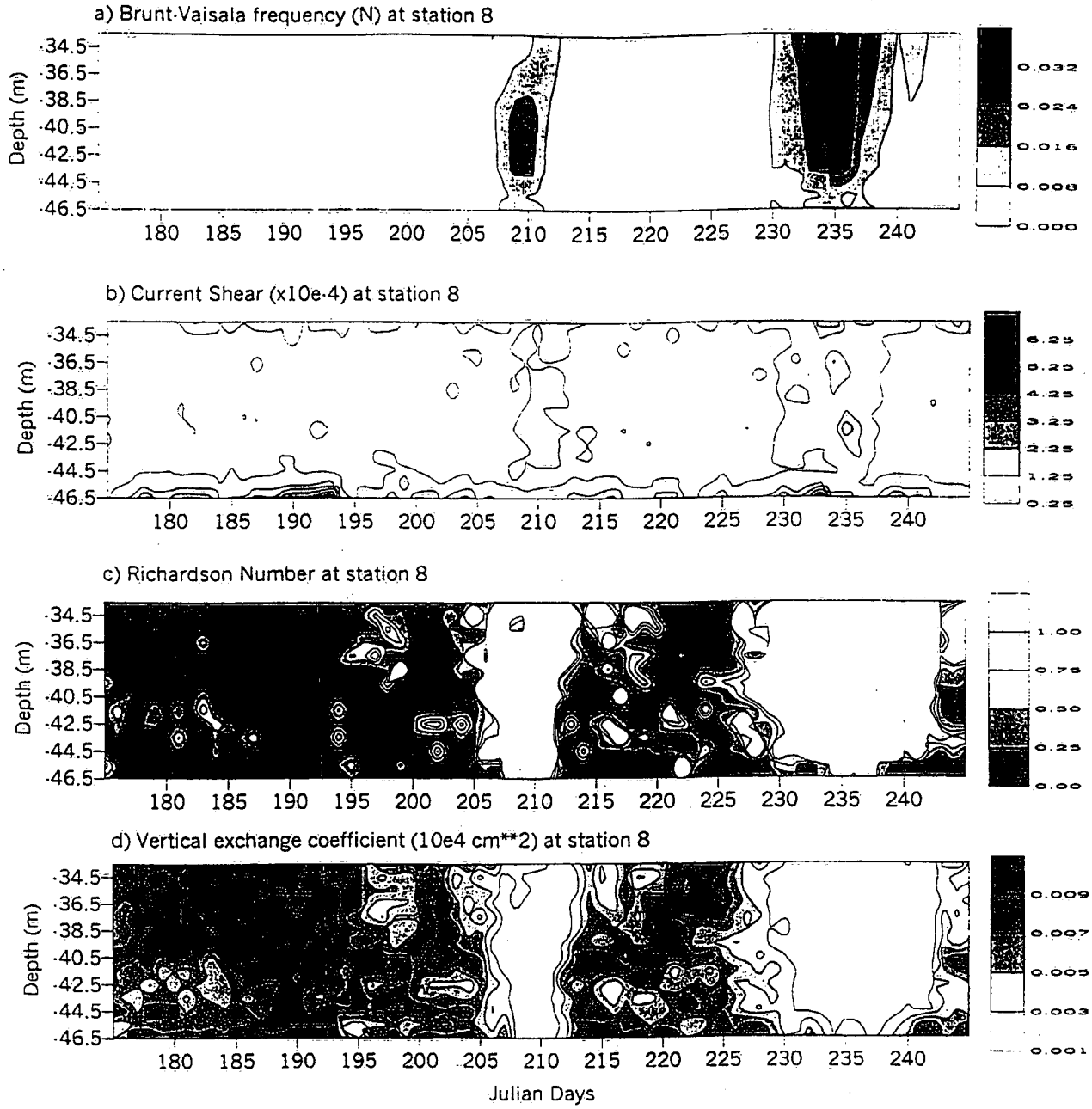

Figure 9. Same as Figure 8 except for station 8.

the mixed layer and the migration and intersection of thermocline with the bottom. Vertical current shears slightly increased at a depth of 8-9 m at the base of the mixed layer on JD 210. This slightly reduced the Richardson number and enhanced mixing at that level. Although the vertical current shear was strong due to near-inertial internal waves at station 8 in deep layers, it was not sufficient to overcome the stable stratification. Richardson numbers were large during these episodes in deeper layers indicating low turbulence activity, which was reflected in low eddy viscosity coefficients. The K_z values were reduced in the thermocline region of the bottom layers during downwelling due to stable stratification.

5. Summary

The Eulerian data during the summer of 1997 in the western Lake Ontario show upwelling and downwelling of the thermocline associated with northward and southward flowing currents under the influence of prevailing winds. The mean currents are generally directed offshore in the surface mixed layer, and onshore flow developed below the mixed layer during upwelling. Downwelling events are characterized with stronger alongshore currents and weak offshore flow in deeper depths. Each episode on average lasted for nearly 4-6 days, indicating the typical period of upwelling and

downwelling in the lake. The current and temperature spectra showed a prominent peak at around 10-12 days indicating the presence of rotating Kelvin waves. Although the peak energy at the high-frequency end was located mainly at the near-inertial frequency band, significant energy was observed at much smaller scales, indicating the presence of different baroclinic seiches due to the thermocline movements.

The horizontal turbulent exchange parameters for the summer stratification show nonisotropic conditions in the surface layers and isotropic conditions in the middle and bottom layers. The alongshore horizontal exchange coefficients were higher than cross-shore exchange coefficients. During an upwelling event when the thermocline surfaced, mean flow kinetic energy decreased, and kinetic energy of fluctuations played an important role in coastal exchange characteristics. However, in the other upwelling events when the thermocline was below 8-10 m, the MKE was higher than the FKE in the surface mixed layer. Upwelling events show an increase in cross-shore exchange coefficients below the mixed layer because of onshore turbulent exchanges. Downwelling events are characterized by a significant increase in the MKE in the upper mixed layer. However, in the thermocline region at the offshore station the FKE is high due to the presence of near-inertial internal waves.

Vertical exchange coefficients closely relate to the dynamic stability of the water column. The general range of K_z varied from 0.1 to 60 $cm^2 s^{-1}$. The high values are usually noticed in the surface layers during upwelling events associated with enhanced vertical shear and reduced Brunt-Vaisala frequencies. Downwelling events did not show much variation in vertical eddy viscosities though they are slightly larger in upper layers. The eddy viscosity coefficient calculated by (2) is not quite complete, as K_z becomes constant under homogeneous conditions. Also, (2) indicates turbulence even when Richardson number values are > 1. Given the uncertainties, K_z values obtained here are only an order of magnitude estimates. The range of K_z values of 1-5 $cm^2 s^{-1}$ during the average summer conditions were comparable to the typical values obtained in Lake Ontario and Lake Baikal [*Kullenberg et al.*, 1974; *Killworth et al.*, 1996]. While the observations presented here give a description of turbulent exchanges of momentum during upwelling and downwelling under varying meteorological conditions, the role of surface heat fluxes and the advection of heat into the coastal zone are omitted. Future studies to characterize the vertical and horizontal exchanges of both heat and momentum are needed.

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