Nordic Hydrology, 32 (1), 2001, 13-28

Turbulent Exchange Characteristics in the Hypolimnion Layer of Lake Ontario

Messon B. Gbah[1], Y.R. Rao[2] and Raj C. Murthy[2]

[1] Cooperative Institute for Limnology and Ecosystems Research, University of Michigan, Ann Arbor, MI48109, USA

[2] National Water Research Institute, Burlington, Ont. L7R 4A6, Canada

Flow regime and turbulence characteristics in a hypolimnion of Lake Ontario are determined using time series current measurements from a vertical string of moored current meters and a bottom mounted Acoustic Doppler Current Profiler (ADCP). The diffusion and turbulent structures of the water column are parameterised in terms of horizontal exchange coefficients for momentum (K_x and K_y) during these deployments. The analysis suggests that the structure of the turbulent fluctuations is isotropic. The kinetic energy and horizontal exchange coefficients decrease with depth. The mean flow at all moorings appears to be strongly correlated with the zonal surface wind stress. Fifteen to twenty metres above the bottom, the flow is marked by an increase in kinetic energy, turbulence intensities, and eddy viscosity coefficients. Strong episodic wind impulse decreases horizontal exchange coefficients through the water column but probably enhances the vertical mixing due to increase in current shear. It is suggested that the associated current-induced sediment resuspension may contribute to the establishment and maintenance of a Nepheloid layer in Lake Ontario.

Introduction

Horizontal exchange of heat, energy, and momentum occur at scales generally much larger than vertical exchanges, given the large horizontal lengths of natural basins compared to their depths. This has prompted many researchers to de-couple horizontal transfers from vertical ones, considered small scale turbulent processes, even though horizontal and vertical processes interact. Numerous dye studies and tracer experiments conducted to determine the diffusion characteristics of the water column also show that the vertical exchange coefficient is much smaller than the horizontal counterparts (Greg 1980). These studies also indicate that, despite the spread in values of these exchange coefficients over several orders of magnitude, the horizontal coefficients generally decrease as one goes from the epilimnion to the hypolimnion (Okubo 1971). The circulation in lakes and oceans is composed of complex eddy motions of varying scales, superimposed on the mean flow. These differing scales of motion are responsible for the variability in measured values of exchange coefficients.

Vertical mixing in the hypolimnion is believed to be weak (Boyce *et al.* 1991; Imberger and Ivey 1991) but plays an important role in lake ecosystems. Imberger and Ivey (1991) stipulated that the energy source for sporadic vertical mixing in this layer is due to breaking of internal waves which convert wave kinetic energy into potential energy. A direct indication of mixing in the hypolimnion of deep lakes is the existence of the Nepheloid layer. Nepheloid layers are ubiquitous to many oceans and deep lakes. They are layers above the bottom where light scattering is maximum. Suspended particles in these layers originate from river plumes, continental shelf, or primary production (Sandilands and Mudroch 1983). Mixing and breaking internal waves contribute to putting and keeping these particles in suspension and thus, to sustaining the Nepheloid layer. In Lake Ontario and other Great Lakes basins, Mirex, PCBs and other hydrophobic organic contaminants have for years been known to accumulate in the biota and the foodchain (Allen *et al.* 1983; Sandilands and Mudroch 1983). For this reason, resuspension of toxic bottom sediments is an environmental concern and its mechanisms warrant attention.

Omstedt and Murthy (1994) studied the vertical mixing in Lake Ontario during summer using a string of current meters. They observed that current shear in the hypolimnion was strong and responsible for sufficient turbulence to keep particles in suspension in the whole Nepheloid layer. However, they have not attempted to study the horizontal exchange characteristics in the lake. The purpose of the present work is then to investigate the horizontal and vertical turbulent characteristics in deeper parts of Lake Ontario during summer stratification with the aid of two different profiling methods. We further discuss the effect of strong winds in the variability of mean and turbulent exchange characteristics in the hypolimnion of Lake Ontario. The vertical profiles of horizontal velocities obtained from two different profiling methods along with percent transmission measurements, and surface wind data from a meteorological buoy have been used for this purpose. The first time series consists of half-hour interval Eulerian measurements of *in situ* water temperature and currents (North and East components of velocity) recorded from a vertical string of 9 moored Niel-Brown current meters deployed from April 15 to October 15, 1992. The second data set consists of a time series of Eulerian currents recorded from a bottom mounted RD Instrument's broadband Acoustic Doppler Current Profiler (ADCP) from September 20 to October 16, 1991. The sampling rate for ADCP ob-

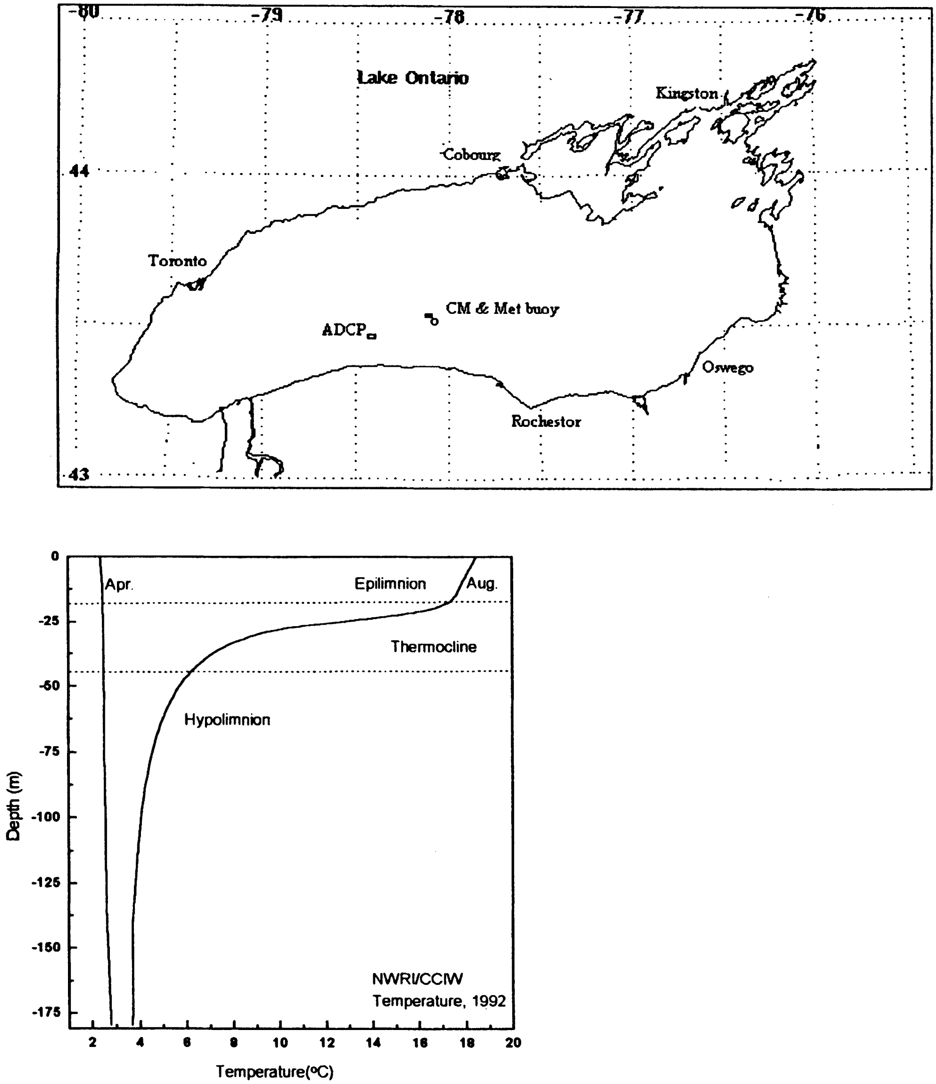

Fig. 1. a) Map of Lake Ontario showing the location of the vertical chain and met buoy and ADCP and b) mean vertical temperature profiles in spring and summer

servations is 10 minutes at every 1 m bin. Water transparency measurements were made using SeaTech transmissometers (10 cm path length). The half-hourly interval time series of transmission in percentage was obtained at depths of 166 and 161 metres. In addition, a moored meteorological buoy provided 30-minute interval time series of wind speed and direction for the duration of the experiment. Fig. 1a shows a map of Lake Ontario with locations of measurements. The mean temperature profiles during early spring (April) and summer (August) are shown in Fig. 1b. Spring temperatures indicate well mixed nature of the lake. During the summer stratification a well-mixed surface layer extends below 12 m. Below the surface mixed layer, the stable thermocline region decreases the temperatures from 18°C to 4.5°C in about 25 m. In the hypolimnion layer of Lake Ontario the mean temperatures show little variations during summer stratification.

Theoretical Considerations

Generally, the diffusion of chemical and biological substances is modelled as if it is similar to molecular diffusion *i.e.*, the diffusion rate is assumed to be the gradient of concentration multiplied by a factor referred to as eddy diffusivity or turbulent exchange coefficient. Although this approach may yield model-dependent eddy diffusivity coefficients (Pollard 1975), it has the advantage of being generally simpler than self-contained turbulence models reviewed by Rodi (1987). In order to develop a relation between the horizontal turbulent exchange coefficient and current fluctuations, we follow Taylor's (1921) analysis. The dispersal tendencies of the flow are parameterised by relating Lagrangian current fluctuations to horizontal Eulerian (current meter) turbulence exchange parameters (Gbah and Murthy 1998). The East-West components of velocity u, and the North-South current v at time $t$are hourly averaged then split into low frequency or means ($\bar{u}$ and $\bar{v}$ and high frequency fluctuations (u' and v'). We used an 18 to 24-hour low-pass filter Graham (1963) to separate mean flow and fluctuating currents.

In a stationary and homogeneous turbulence, the Lagrangian variance can be assumed to be equivalent to Eulerian variance $\langle u'^2_e \rangle$ (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 rather change quickly, as turbulent eddies are advected past the instrument. They have shown that the Lagrangian correlation function $R_{ii}{}^L(\tau)$ and the Eulerian counterpart $R_e(\tau)$ have similar shape and differ only by a factor β, where β is an empirical constant greater than unity. $R_e(\tau) = R_{ii}{}^L(\beta\tau)$. Introducing these assumptions, the horizontal exchange coefficient in terms of Eulerian statistics can be written as

$$K_e = \beta \langle u_e'^2 \rangle T_e \tag{1}$$

where T_e is the Eulerian integral time scale given as $\int_0^\infty R_e(\tau) d\tau$. For oceanic cases, Schott and Quadfasel (1979) have determined values of β, a factor somewhat similar to 1.4±0.4, based on simultaneous Lagrangian and Eulerian measurements in Baltic. We have set β =1 as an average value in our calculations based on previous computations in Lake Ontario. The east-west and north-south components of horizontal exchange coefficients are calculated as K_x and K_y, respectively. The integration is carried out only up to t_e because the turbulent eddies are assumed to have lost their origins beyond these times. As stated earlier, the above theoretical framework for calculating horizontal exchange coefficients is strictly valid in a field of stationary and homogeneous turbulence, which rarely exists in actual lake conditions. However, from a practical point of view, a climatology of horizontal exchange coefficients can be established from a long time series of current meter data in actual lake conditions. The analysis presented in this paper is aimed towards this goal.

To complete the characterisation of the flow regime, we also calculate the mean currents during the summer (U,V), the mean temperature Θ, the total kinetic energy E, the mean flow kinetic energy e, and the turbulent kinetic energy, q given by

$$[E, e, q] = \frac{1}{2}\left[u^2+v^2, (\bar{u})^2+(\bar{v})^2, (\overline{u'})^2+(\overline{v'})^2\right] \tag{2}$$

The intensity of horizontal turbulence is calculated as the ratios

$$[i_u, i_v] = \left[\frac{\sqrt{(u')^2}}{\sqrt{(\bar{u})^2+(\bar{v})^2}}, \frac{\sqrt{(v')^2}}{\sqrt{(\bar{u})^2+(\bar{v})^2}}\right] \tag{3}$$

which measure the magnitude of turbulent pulsations relative to the mean flow velocity.

Wind and Current Climatology

The zonal currents are higher than the meridional components, in accord with observations in Lake Ontario (Murthy *et al.* 1986). The time variability of wind stresses and currents at various depths is shown in Fig. 2 by their 12-hour zonal averages. East-West wind and current variations tend to be strongly correlated at all mooring depths. This strong correlation indicates that currents at all depths respond directly to, and are affected by large scale variations of the zonal surface winds. Episodes of strong easterly wind generate a return flow and induce large bottom currents even near the bottom.

Figs. 3 and 4 show typical kinetic energy spectral density plots of surface winds and currents at selected mooring depths. The spectral maximum of winds (Fig. 3) is around 12.5 days and corresponds to lake wide meteorological forcing. Low frequency winds (time scales longer than one day) in the direction parallel to the main axis of the lake (East-West) account for most of the kinetic energy in the spectra. The energy spectra of currents (Figs. 4a to 4d) show several peaks and valleys among which, there is a maximum at about 10-12 days, associated with lake wide wind forcing, a smaller dominant peak near 16-18 hours, corresponding to the local theoretical inertial period of 17.3 hours, a minimum around 30 hours, and several smaller high frequency peaks associated with lake breeze. The inertial peak, around 17 hours, is inherent to all mooring depths and its peak is progressively damped ap-

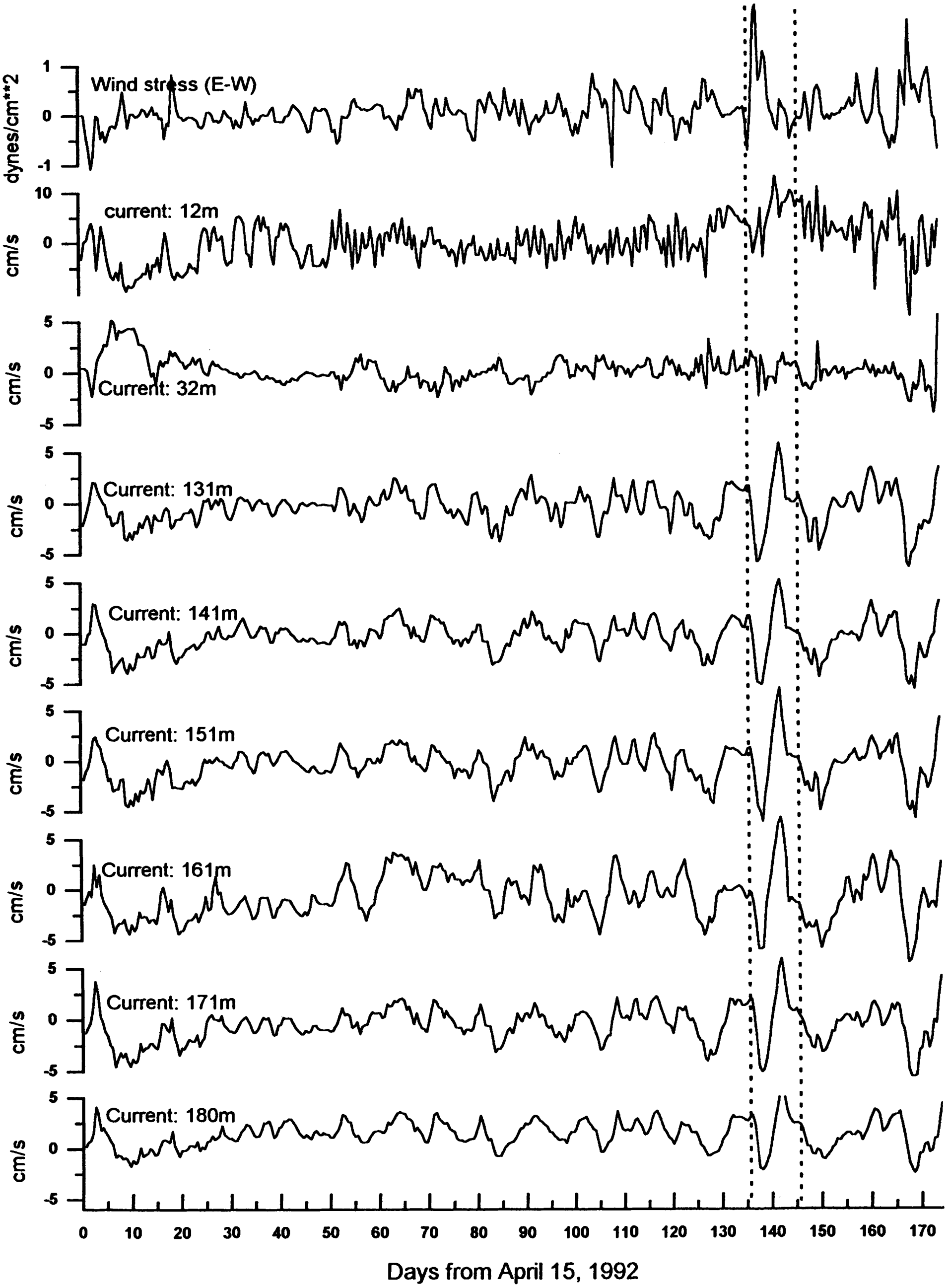

Fig. 2. 12-hour average zonal wind stress and currents from the vertical chain. The vertical dashed lines delineate the time period of easterly wind episode.

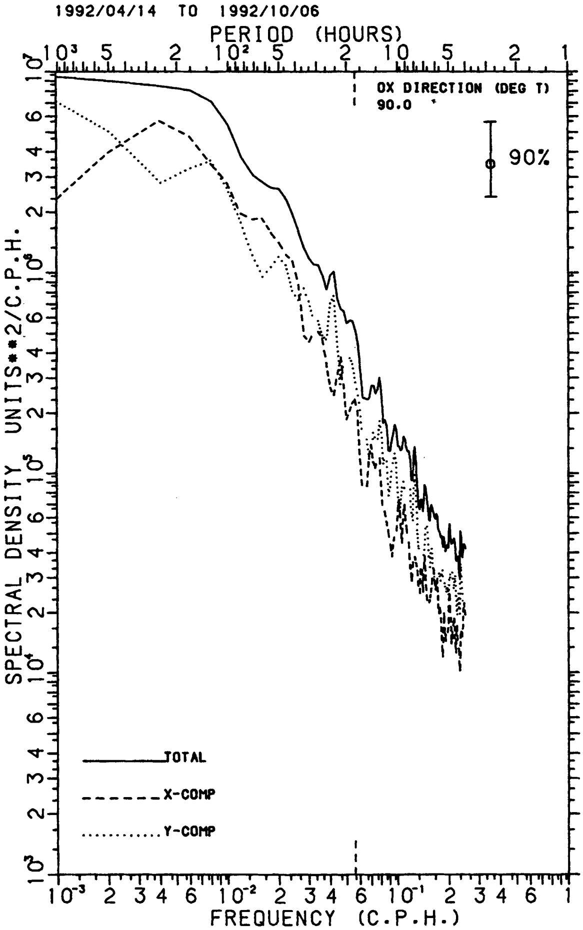

Fig. 3. Kinetic energy spectra of wind stress

proaching the bottom. The 12-day spectral maximum becomes dominant below the mixed layer where it is responsible for the predominant currents. The mixed layer is predominantly driven by wind and inertial forces while the hypolimnion derives its energy from large scale wind forcing.

Horizontal Turbulent Characteristics

The circulation in lakes is composed of complex eddy motions, of varying scales, superimposed on the mean flow. An analysis of the entire temperature and current time series will reveal an average flow regime for the duration of the whole record, in response to the associated synoptic wind forcing. The characteristics of the mean flow and fluctuations are presented in Table 1 and Table 2 as a function of depth.

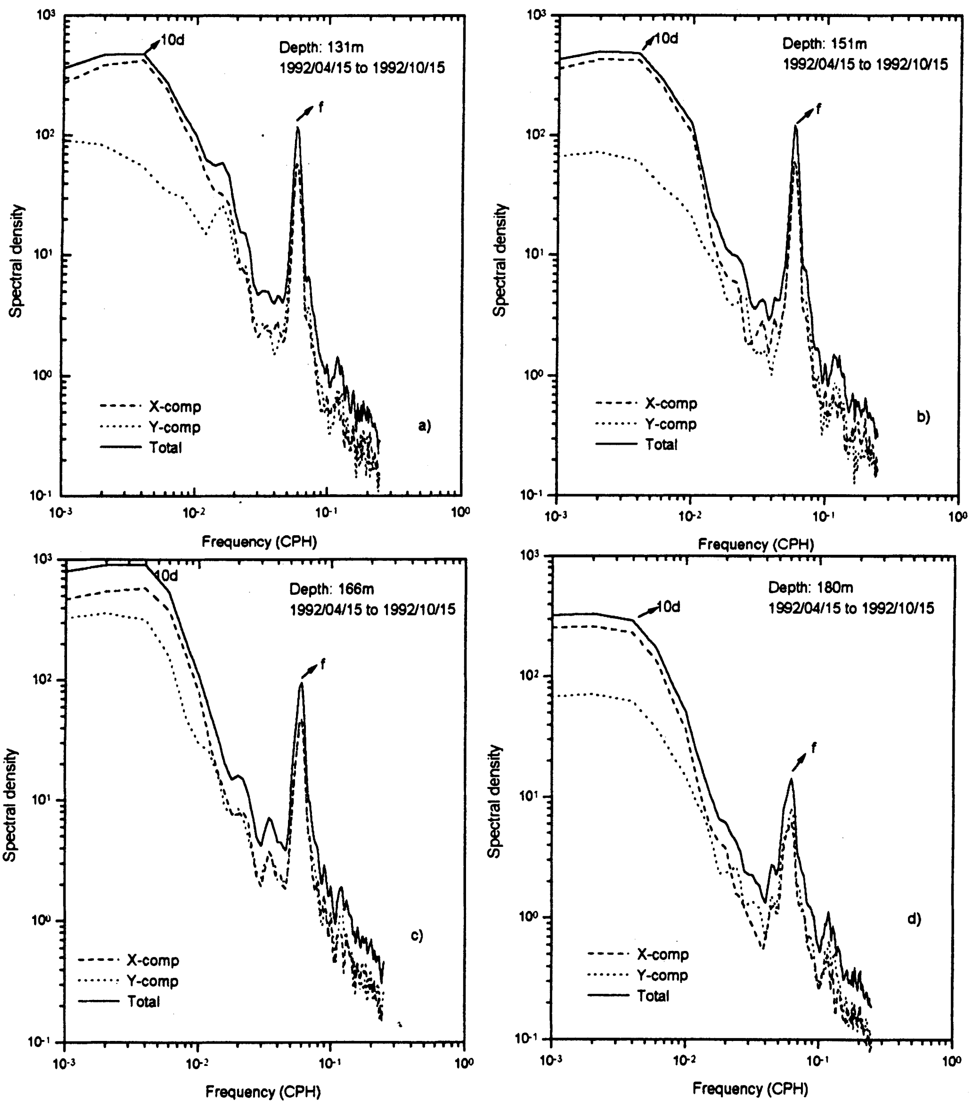

Fig. 4. Kinetic energy spectra currents at selected depths. Here, f denotes the inertial frequency.

The synoptic mean flow direction is towards the south-west except in the near bottom where there is a large velocity shear. Csanady (1982) predicts coastal flows parallel to the wind and a return flow in the central basin. The velocity variances and turbulence intensities are direction insensitive and suggests near-isotropy of horizontal turbulence in both type of measurements. The root mean square (rms) values

Table 1 – Summary of flow characteristics measured from the vertical current meter chain.

Depth m	U cm/s	V cm/s	rms u' cm/s	rms v' cm/s	θ (°C)
12	-0.11	0.18	5.05	4.84	10.53
32	-0.06	0.18	0.95	1.10	4.14
131	-0.10	-0.44	0.76	0.76	3.60
141	-0.14	-0.45	0.75	0.73	3.55
151	-0.10	-0.48	0.77	0.76	3.59
161	-0.08	-0.76	0.76	0.75	3.58
166	0.01	-0.40	0.75	0.83	3.58
171	-0.23	-0.56	0.68	0.67	3.89
180	-0.32	1.38	0.39	0.35	3.69

Table 2 – Summary of flow characteristics measured from the ADCP.

Depth m	U cm/s	V cm/s	rms u' cm/s	rms v' cm/s
128	-0.32	-0.14	0.95	0.97
129	-0.33	-0.13	0.94	0.94
130	-0.32	-0.14	0.93	0.92
131	-0.32	-0.15	0.90	0.90
132	-0.32	-0.18	0.88	0.89
133	-0.31	-0.18	0.86	0.87
134	-0.31	-0.19	0.84	0.84
135	-0.30	-0.19	0.82	0.83
136	-0.29	-0.20	0.80	0.81
137	-0.28	-0.19	0.79	0.79
138	-0.27	-0.20	0.77	0.77
139	-0.27	-0.19	0.74	0.76
140	-0.27	-0.18	0.71	0.73
141	-0.33	-0.18	0.68	0.71
141.3	-0.35	-0.29	0.67	0.70

of velocity fluctuations are highest near the surface due to wind and inertial motions, and decrease with depth.

Graphs of the components of kinetic energy for the current meter data as a function of depth are shown in Fig. 5a. The kinetic energy is maximum in the upper mixed layer, owing to the direct effect of surface wind forcing, then decreases with depth and reaches a local maximum at 15 to 20 metres above the bottom. As a result, 32% of the total kinetic Energy, E is in the upper layers whereas, only 2-3% in the bottom layer. The existence of this local maximum could be due to large horizontal velocities associated with a return flow in the central part of the basin (Csanady

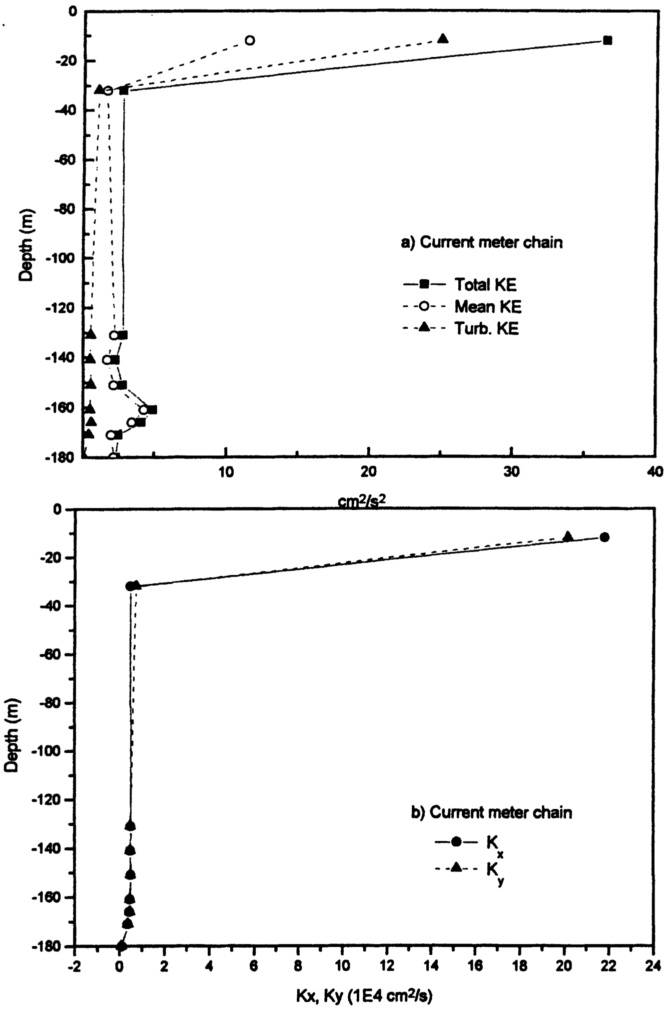

Fig. 5. Various components of a) kinetic energy and b) horizontal exchange coefficients of the current meter chain.

1982). These large current speeds in the bottom layers generates shear induced vertical mixing in the hypolminion layer. Epilimnion mixing due to the influence of surface winds and breaking internal waves may also contribute to this maximum through vertical turbulent mixing processes. Plots of the horizontal exchange coefficients, K_x and K_y, as a function of depth are shown in Fig. 5b. It is clear from this figure that the horizontal exchange coefficients are direction insensitive, $K_x \approx K_y = K_H$ because of turbulence isotropy. The current meter data shows the horizontal exchange coefficients are one order of magnitude larger near the surface and decrease rapidly with depth. In the hypolimnion, they continue to decrease slowly with depth,

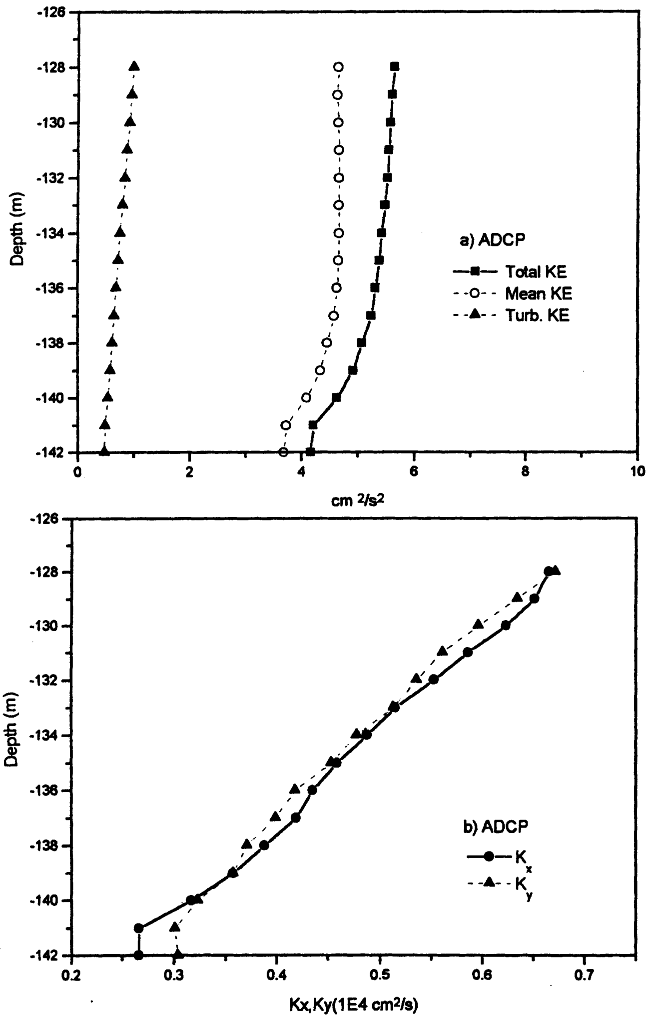

Fig. 6. Various components of a) kinetic energy and b) horizontal exchange coefficients for ADCP data.

except in the last 10 metres above the bottom where they drop rapidly.

A finer spacing between depths, as given by an Acoustic Doppler Current Profiler data would considerably improve these estimates. Figs. 6a and 6b shows the components of kinetic energy and horizontal exchange coefficients as a function of depth for ADCP data. Although energy levels obtained from ADCP data are similar to current meter data, the local maximum above 20 m from bottom is not observed in 1991 data. The magnitude of the components of kinetic energy and exchange coefficients are approximately in the same range of current meter measurements.

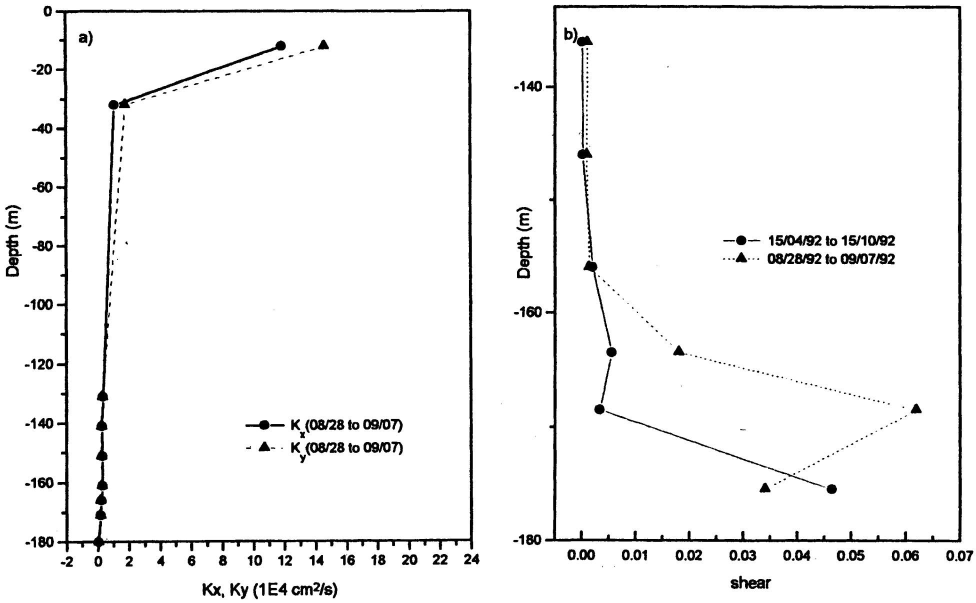

Fig. 7. a) Exchange coefficients Kx, and Ky during the strong easterly wind episode and b) vertical current shear (1/ s) in the bottom layer for synoptic conditions and easterly wind episode

Vertical Mixing Induced by the Nepheloid Layer

Light intensity $I(z)$ over a path length z is given by

$$I(z) = I(0)e^{-\alpha z} \tag{4}$$

where α is the attenuation coefficient in m^{-1} and $I(0)$ is the light intensity at the source. From Eq.(4), the attenuation coefficient is given as

$$\alpha = \frac{1}{z}\ln T \tag{5}$$

where T is the percentage of $I(0)$ transmitted over the path length z. The attenuation coefficient α is directly proportional to the sediment concentration (Bartz *et al.* 1978; Zaneveld *et al.* 1980; Spinrad 1986). An increase of mixing in the water column should translate into an increase in α. We will use α as an indication of sediment flux and mixing effects in the water column.

As observed in Fig. 2, the hypolimnion layer clearly responds to the strong and persistent zonal wind impulse from August 27 to September 7, 1992. But in the synoptic analysis, effects due to such short time scale events are smoothed out and only large scale flow features are inferred. To assess the diffusion characteristics of the water column and the flow regime during such persistent short term meteorological events, an episodic analysis was deemed necessary. This analysis stands to give an indication of the effects of the associated wind forcing.

Fig. 7a shows the exchange coefficients as a function of depth during this easterly wind episode. The horizontal exchange coefficients are reduced in comparison to the synoptic wind conditions (Fig. 5b). The strong wind impulse seems to inhibit horizontal exchanges as fluctuating currents decreased. Omstedt and Murthy (1994) observed that under weak stratification in the hypolimnion the current shear can enhance the vertical turbulence. During this episode although fluctuating currents decreased, we observe an increase in zonal currents in the hypolimnion. Fig. 7b shows the profiles of vertical current shear in the bottom layers during synoptic conditions and the easterly wind episode. Close to the bottom the shear is significantly higher and decreased sharply within 10 m from the bottom during the whole period. This indicates bottom induced turbulence is confined to near bottom layers. However, during the easterly wind episode the current shear increased considerably till 20 m above the bottom, thus enhancing the vertical mixing. The transmissometer data for this period also indicates a steady increase in the light attenuation coefficients as seen in Fig. 8. As mentioned above, since the attenuation coefficient is linearly correlated with sediment concentration, it is reasonable to expect an increase in sediment concentration. The vertical current shear in horizontal velocities could be a possible mechanism for sediment resuspension, and will contribute to the formation and maintenance of a Nepheloid layer under such persistent easterly wind.

Summary

The analysis of Eulerian time series of temperature and currents from a vertical string of nine moored current meters and a bottom mounted ADCP in the centre of Lake Ontario provided the structure of the flow and horizontal turbulent exchanges. It has been observed that zonal currents are higher than meridional components supporting the earlier observations (Csanady 1982; Murthy *et al.* 1986). Further, this study shows that the currents in the hypolimnion are directly influenced by large scale wind forcing over the lake.

The horizontal exchange characteristics of the water column are parameterised with two horizontal exchange coefficients for momentum (K_x and K_y). Owing to the direct effect of surface wind forcing, the kinetic energy is one order of magnitude higher in the epilimnion and decrease with depth supporting the earlier studies (Omstedt and Murthy 1994). This study further confirms that the horizontal exchange coefficients also decrease with depth, however, they are slightly increased to a maximum at 20-30 metres above the bottom where internal vertical mixing becomes dominant. The horizontal velocity fluctuations and turbulence intensity coefficients

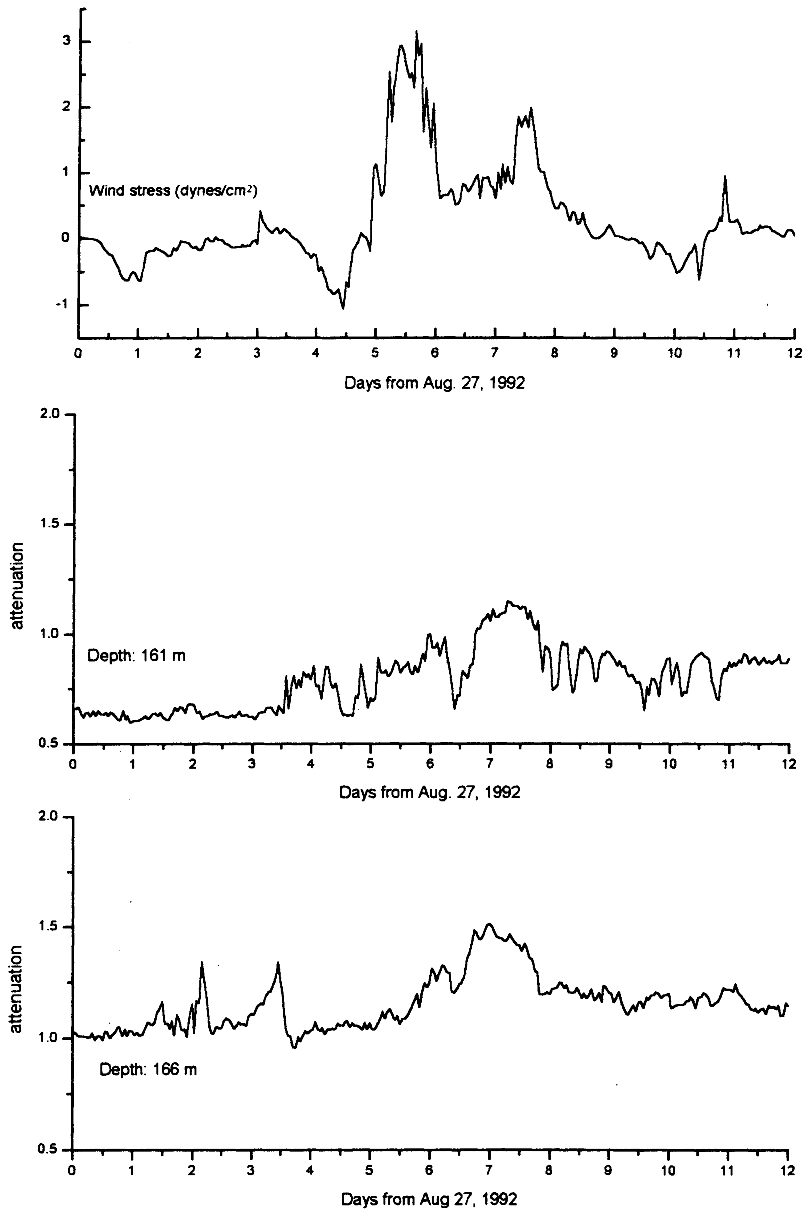

Fig. 8. Zonal wind stress and light attenuation coefficients associated with the easterly wind episode.

indicate near-isotropy of horizontal turbulence in the hypolimnion. A persistent easterly wind impulse is shown to inhibit horizontal mixing and enhance the vertical mixing in the hypolimnion layer of Lake Ontario. These observations suggest that current-induced vertical mixing associated with significant wind events could be responsible for the resuspension of toxic bottom sediments and may contribute to the formation and maintenance of a Nepheloid layer.

Acknowledgements

We are grateful to the staff of CCIW for discussions of this work and thank in particular Jim Bull for providing light transmission data and Ken Miners and Fausto Chiocchio for organising the data. The authors wish to thank the anonymous reviewers for providing many constructive comments and suggestions.

References

Allen, R. J., Mudroch, A., and Sudar, A. (1983)An introduction to the Niagara River/Lake Ontario pollution problem, *J. Great Lakes Res., Vol. 9*, pp. 117.

Bartz, R., Zaneveld, J. R., and Pak, H. (1978) A transmissometer for profiling and moored observations in water, *SPIE, Ocean Optics, V,* pp. 102-108.

Boyce, F. M., Schertzer, W. M., Hamblin, P. F., and Murthy, C .R. (1991) Physical behaviour of Lake Ontario with reference to contaminant pathways and climate change, *Can. J. Fisheries and Aquatic Sci., Vol. 48(8)*, pp. 1517-1528.

Csanady G. T. (1982) Circulation in the coastal ocean, *Environmental Fluid Mechanics*, D. Reidel Publishing Company, Boston, pp. 279.

Gbah, M. B., and Murthy, R. C. (1998) Characteristics of turbulent cross and along shore momentum exchanges during a thermal bar episode in Lake Ontario, *Nordic Hydrol., Vol. 29*, pp. 57-72.

Graham R. J. (1963) *Determination and analysis of a numerical smoothing weights,* NASA TR R-179, Marshall Space Flight Centre, pp. 28.

Gregg, M. C. (1980) Microstructure patches in the thermocline, *J. Phys. Oceanogr., Vol. 10,* pp. 915-943.

Hay, J. S., and Pasquill, F. (1959) Diffusion from a continuous source in relation to the spectrum and scale turbulence, *Adv. in Geophys., Vol. 6*, pp. 345-365.

Imberger, J., and Ivey G. N. (1991) On the nature of turbulence in a stratified fluid. Part II: Application to lakes, *J. Phys. Oceanogr., Vol. 21*, pp. 659-680.

Lumley, L., and Panofsky, H. A. (1964) *The structure of atmospheric turbulence*, Interscience Publ., New York.

Murthy, C. R., Simons, T. S., and Lam, D. C. L. (1986) Simulation of pollutant transport in homogeneous coastal zones with application to Lake Ontario, *J. Geophys. Res., Vol. 91(C8)*, pp. 9771-9779.

Okubo, A. (1971) Horizontal and vertical mixing in the sea, *Impingement of man on the oceans*, D. W. Hood (eds.), pp. 89-168, Wiley Interscience.

Omstedt, A., and Murthy, C. R. (1994) On currents and vertical mixing in Lake Ontario during summer stratification, *Nordic Hydrol., Vol. 25*, pp. 213-232.

Pollard, R. T. (1975) Observations and Models of the Structure of the Upper Ocean, *Modelling and Prediction of the Upper Layers of the Ocean,* E. B. Kraus (ed), Pergamon Press, Oxford, New York, pp. 102-117.

Rodi, W. (1987) Examples of Calculation Methods for Flow and Mixing in Stratified Fluids, *J. of Geophys. Res., Vol. 92(C5)*, pp. 5305-5328.

Sandilands, R. G., and Mudroch, A. (1983) Nepheloid layer in Lake Ontario, *J. Great Lake Res., Vol. 9(2)*, pp. 90-200.

Schott, F., and Quadfasel, D. (1979) Lagrangian and Eulerian measurements of horizontal mixing in the Baltic, *Tellus, Vol. 31*, pp. 138-144.

Spinrad, R. W. (1986) A calibration diagram of specific beam attenuation, *J. of Geophys. Res.*, pp. 7761-7764.

Taylor, G. I. (1921) Diffusion by continuous movements, Proc. London Math Soc., 20, pp. 196-21.

Zaneveld, J. R. V., Richard, W. S., and Bartz, R. (1980) Optical properties of turbidity standards, *SPIE, Ocean Optics*, *Vol. VI*, pp. 159-167.

Received: 12 January, 1999
Revised: 13 April, 2000
Accepted: 20 June, 2000

Addresses:
Messon B. Gbah,
Cooperative Institute for Limnology and Ecosystems Research,
University of Michigan,
2200 Bonisteel Boulevard,
Ann Arbor, MI 148109,
U.S.A.

Y. R. Rao,
National Water Research Institute,
867 Lakeshore Road,
P.O.Box 5050,
Burlington, Ont. L7R 4A6,
Canada.
Email: Ram.Y.rao@cciw.ca

Raj C. Murthy,
Same address
Email: Raj.Murthy@cciw.ca