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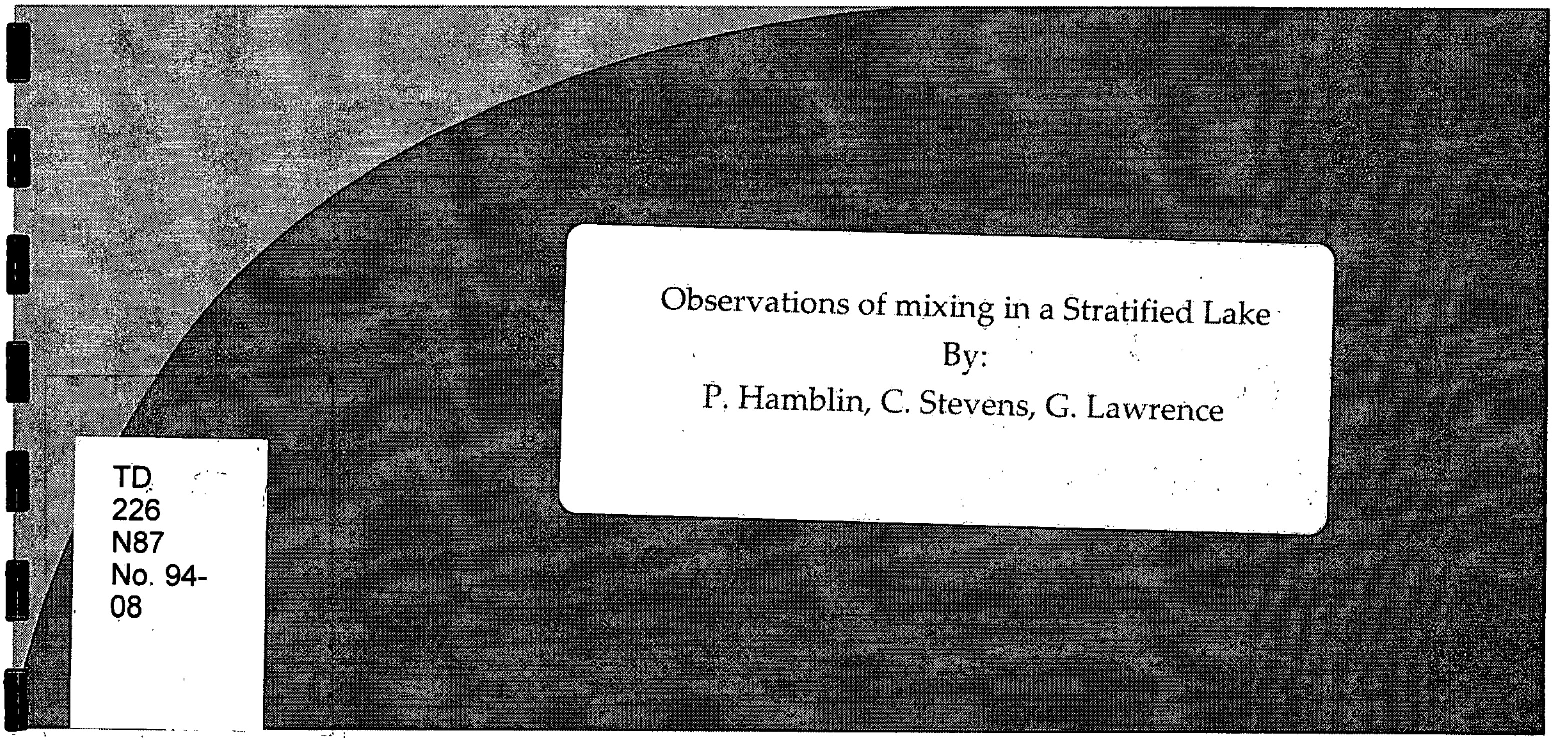

Observations of mixing in a Stratified Lake

By:

P. Hamblin, C. Stevens, G. Lawrence

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Management Perspective

Artificial fertilization of Kootenay Lake has been proposed as a means of increasing fish productivities. Because the lake is long and narrow physical experiments were necessary to determine the best site to introduce fertilizer. This contribution is part of a large coordinated study consisting of a research team of 5 scientists and engineers from NWRI and others from the Institute of Ocean Sciences, the University of British Columbia and BC Environment to investigate the problem of restoration of the Kokanee fishery by means of adding fertilzer over the productive season. The NWRI contibution focused on the question of the optimal introduction of nutients should the experiment prove successful and require fertilization on an ongoing basis. The study was funded by the Province of British Columbia and BC Hydro. We were invited to participate because of our past experience on Kootenay Lake and our expertise in physical limnology and mixing in lakes. We were able for the first time in any B.C. lake to measure profiles of current underway with an advanced ultrasonic device known as an acoustic doppler current profiler.

The present manuscript discusses the mixing near a narrows in this long lakes which accelerates the flow and promotes more intense mixing than elsewhere in the lake. This location would be a good one for unattended introduction of fertilizer. Also, we show that our new profiler is most useful in limnological research. It should have a wide application to other lakes too. Our experience points to its usefulness in such studies as the flows over zebra musel beds in Lake Erie.

Observations of Mixing in a Stratified Lake

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Abstract

Quantification of mixing in the surface layers of lakes is important for the understanding of various biological processes. Our study is a case in point where we attempted to obtain mixing rates of fertilizer added to the surface layers in order to enhance biological productivity. In this report we focus on the observations taken on June 8, 1992 in Kootenay Lake, British Columbia, during a period of strong near surface stratification and shear as well as indications of vigorous mixing at one of three moored temperature profilers. These observations were made near a constriction in the lake cross-sectional area. An acoustic doppler current profiler(ADCP), a conductivity-temperature-depth profiler(CTD), dye patch dispersion and meteorological data complemented the mooring data.

During the middle of that day strong winds (7 m/s) blew for 6 hours. Shortly before the start of the wind and after six hours of steady wind high frequency temperature fluctuations were observed at the thermistor chain located in the flow constriction. The two events appeared to be active at this location for over an hour and a half, with the region of greatest activity occurring from a depth of 10 m to around 20 m. At the beginning of the mixing period continuous temperature profiles recorded with the CTD were smooth, however, three hours later the temperature profiles had developed a step-like structure, indicating possible vertical mixing. At the same time current shear measured by the ADCP, when combined with the observed buoyancy frequency profile deduced from the temperature profiler, yielded gradient Richardson numbers in the range 0.25 to 0.6 over upper 20 m of the water column at locations several kilometres downstream in the direction of flow.

Additional evidence of vigorous vertical mixing was derived from concurrent observations of dye injected into the upper 10 m. From direct measurements of horizontal dye dispersion and dispersion theory (Fischer et al. 1979) it is possible to infer estimates of the rate of turbulent kinetic energy dissipation. Dissipation rates from the dye and scaling analysis of the high frequency temperature fluctuations are from ten to one hundred times larger in the mixing zone than those found in the ocean and in other lakes.

INTRODUCTION

The interaction between basin-scale motions in lakes and the small scale physics thought to be responsible for mixing continues to be of great interest to limnologists. In the long but narrow lakes of concern in this study Hamblin (1977) observed high frequency internal waves in the vicinity of a large river inflow and at a mid-lake location during episodes of intense basin-scale internal seiche activity, Hamblin(1978). Farmer(1978) observed high frequency internal waves and evidence of mixing following the passage of internal surges in a long narrow lake. Such observations in lakes have rarely been accompanied by measurements of the background shear necessary to interpret the suspected mixing events unlike the case in the ocean where a large number of studies have concurrently observed both the large and small scale physics, for example, Carr et al.(1992), Marmarino and Trump(1992 & 1991) and Peters et al.(1991).

The desire to better understand mixing in stratified environmental flows as exemplified by our field observations of some small-scale events which possibly indicate mixing provides the focus for the present study. The emphasis here is on the links of the small-scale physics to the large-scale physical setting as determined by the meteorological forcing, lake basin-scale internal wave-induced shear and stratification.

EXPERIMENTAL DETAILS AND DATA ANALYSIS

During a 2-week long study of the mixing characteristics of the surface waters of Kootenay Lake, British Columbia for the purposes of optimizing the dispersal of nutrients added to the lake, we observed several small-scale events at one of three moored temperature profilers on June 8, 1992. The data discussed here were observed at a meteorological station, a thermistor chain and by two motor vessels whose tracks are shown in Figure 1. Moored temperature data were also collected at the meteorological station and at a another location about 9 km to the north of the station. The meteorological station consisted of a raft supporting wind speed and direction sensors, relative humidity and temperature of the air and incoming solar radiation. A solar-powered data logger recorded all variables every ten minutes. The position of the vessels was determined electronically by Miniranger fixes. At the thermistor chain temperatures were recorded at one-minute intervals over ten unevenly spaced depths from 1 m to 50 m. Aboard one vessel a yo-yoing CTD profiler recorded temperature, conductivity and Rhodamine dye fluoresence profiles while on the other a 1.2 MHz ADCP of RDI manufacture sampled flow over 1-m depth bins down to 25 m. The ADCP data were used to estimate average shear over 2-m depth ranges from five sequential velocity profiles selected for least variability in ship's speed and heading. The error in shear is estimated to be 0.006(s^{-1}). Due to cross-bin averaging the narrow-band ADCP is known to underestimate shear. Thus, an experiment was conducted on another data set where ADCP and standard current meter measurements were observed concurrently. Based on the 70 individual comparisons of the 2-m shear between the two methods of current measurement there was no statistically significant difference in shear. At the approximately 2 m/s ship speed the shear would be averaged over a distance of 150 m. It was found that averaging over greater or smaller distances increased the variability of the shear. In order to calculate profiles of

Richardson number, Ri, associated with the shear, 30-min average profiles of stability or Brunt-Vaisala frequency, N, were formed.

$$Ri=\frac{N^2}{(\frac{du}{dz})^2+(\frac{dv}{dz})^2}; \qquad N^2=-\frac{g}{\rho}\frac{d\rho}{dz}$$

where ρ is the density, g is the acceleration of gravity and u and v are the horizontal velocity components.

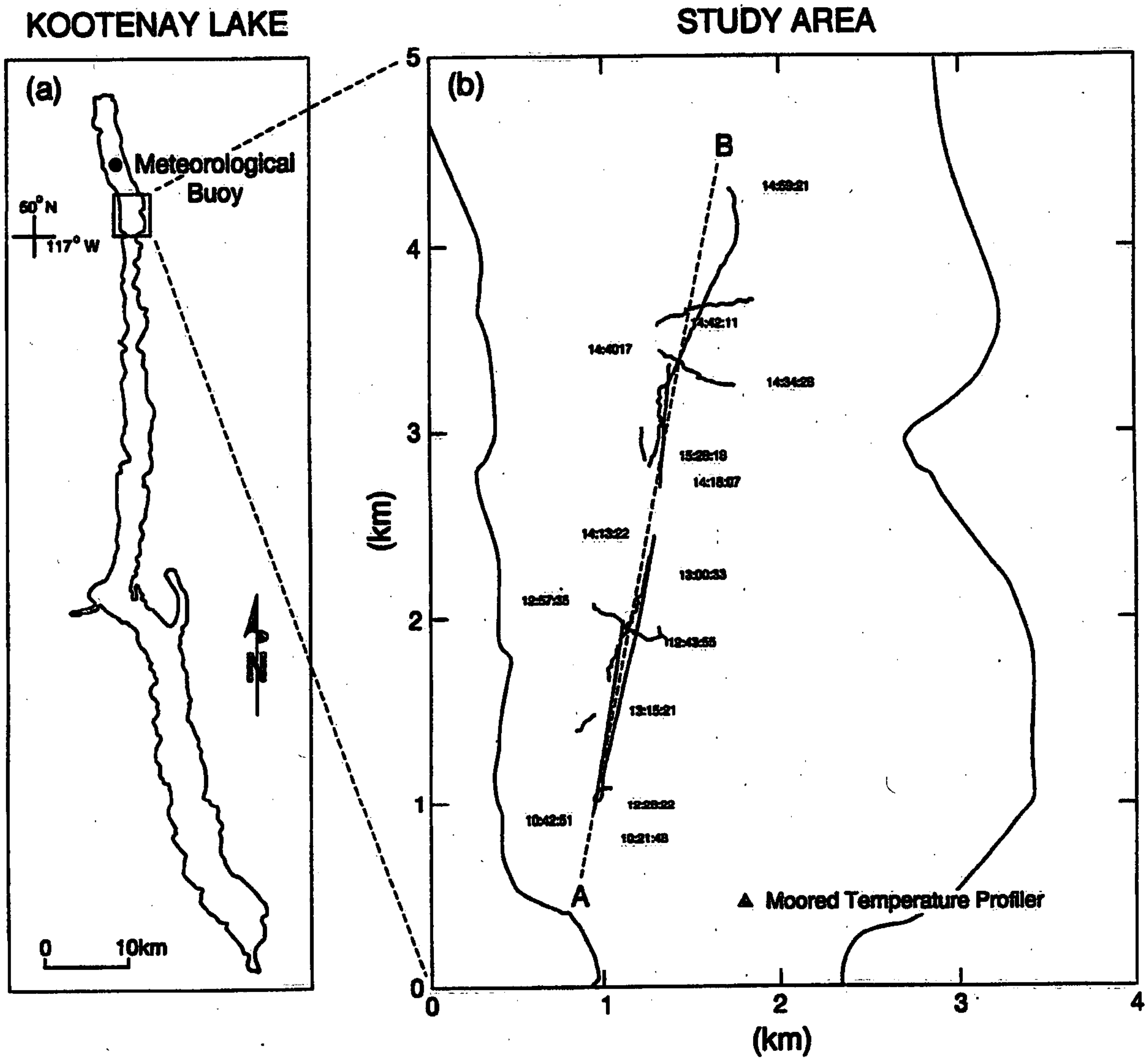

Figure 1. Study location, Kootenay Lake, and various station locations. Time is Pacific Daylight.

Air and water temperatures are displayed in the upper panel of Figure 2 for a 24-hr period covering the attended field activities. Similarly the wind speed and direction are shown below. Since the wind stress and the buoyancy flux are the major surface forcing terms for turbulent mixing, the lower two panel of Figure 2 present these quantities. Surface heat fluxes were calculated from standard bulk formulae(Fischer et al.,1979). Incoming longwave radiation was calculated from air temperature and inferred cloud cover. In the bottom panel friction velocity, u^*, is compared to a buoyancy velocity scale, w^*, assuming the

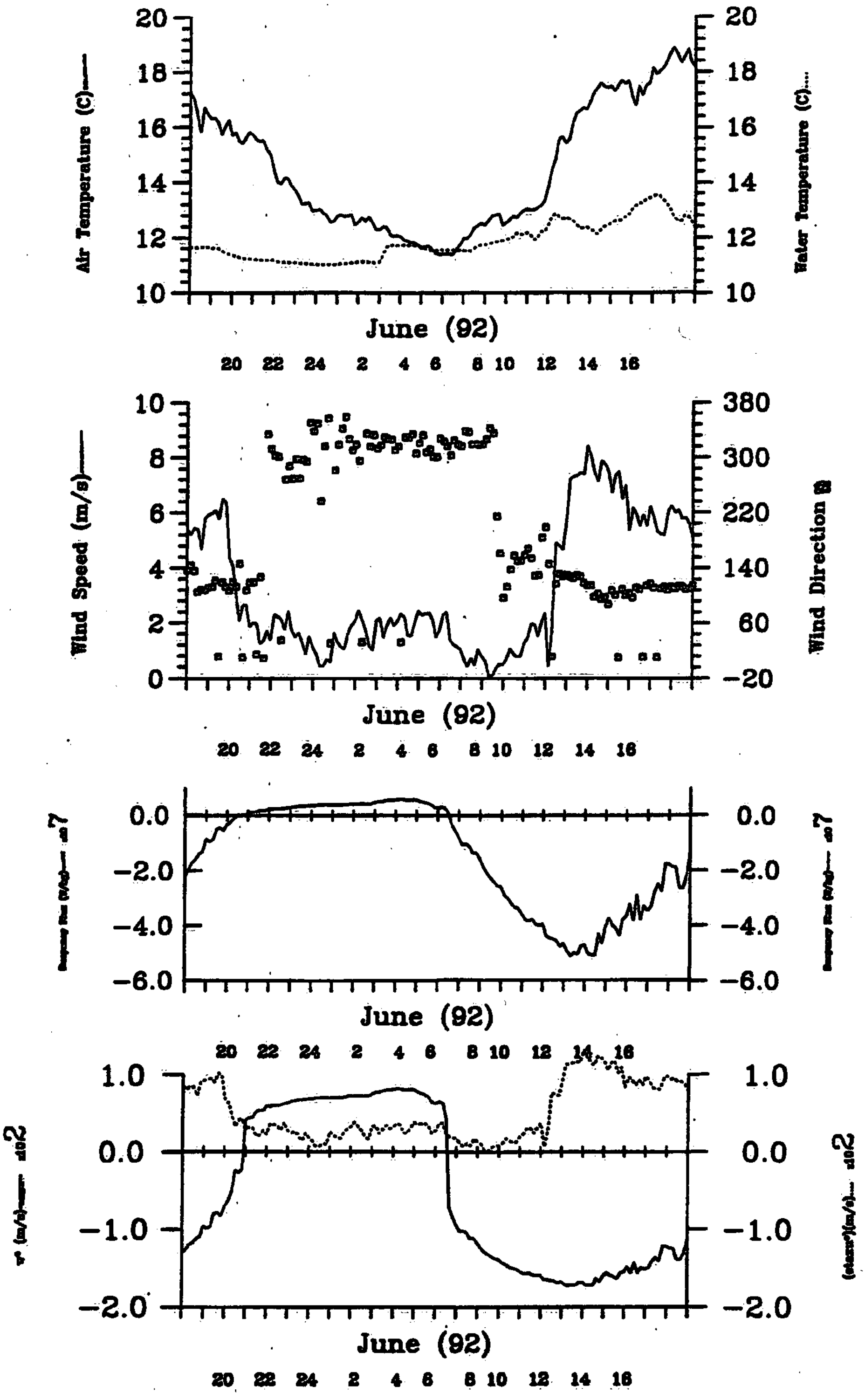

Figure 2. Selected ten-minute meteorogical forcing from 18:00 June 7 to 18:00 June 8. Time is Pacific Daylight.

mixing depth is on the order of 10 m, the depth of the dye diffusion floor. For the sake of comparison, u^* has been multiplied by the usual mixed layer efficiency factor of 1.23(Fischer et al.,1979).

Unfortunately, no direct measurements of turbulence such as the rate of turbulent kinetic energy dissipation were available. Instead, turbulent mixing was inferred in bulk from the horizontal and vertical spreading as determined by the shipboard profiler of a 8-Kg release of dye at the position marked 10:21:48 on Figure 1 over a 5-hr period. Secondly, small-scale temperature "activity" served as an indicator of turbulent mixing. This activity has been defined by Marmarino and Trump(1991) as the magnitude of the first difference of the 1-min temperatures at each thermistor normalized by the local vertical temperature difference. According to Marmarino and Trump this activity parameter serves as a qualitative measure of the likelihood that mixing has occurred.

DISCUSSION

During the present experiment stratification was developing rapidly. From an examination of the isotherm displacements at the other thermistor chains to the north it appeared that a first mode internal seiche was taking place with flow at the surface to the north until June 10. The drift of the dye as seen in Figure 1 and the ADCP data corroborate this with both indicating a northward flow of 25 to 30 cm/s at the surface decreasing to much lower flow at 25 m depth. Contours of vertical shear squared, stability frequency, and Richardson number are shown on Figure 3 as a function of depth and horizontal distance along the line A-B(Figure 1) from the dye release point. It is noteworthy that shear is strongest towards the southern end of the line which is closest to the narrows or constricted flow. A plot of the shear as a function of time(not shown) does not show a trend despite the onset of strong wind forcing at 11:30. This suggests that the northward trending flow as evidenced by the dye trajectory of Figure 1 and the ADCP data is associated partly with basin-scale internal waves and consequently should have existed before the period of data displayed in Figure 3. The likely southward intensification of the shear and continuity consideration suggest that at the thermistor chain the average shear could be up to twice as large as that measured by the ADCP in the more open portion of the lake to the north. A plot similar to Figure 3(also not shown) based on this assumption and the observed temperature data at the thermistor chain indicates Richardson numbers less than the critical value of 0.25 over the upper 6 m of the water column for the entire 3-hr period in contrast to a much more limited area of the plot shown in Figure 3. Either plot demonstrates that the stability frequency is relatively constant in the area of the dye release but that low Richardson numbers are due to intensified vertical shear as the surface is approached.

Mixing in the study area may be inferred indirectly by comparison of the CTD temperatures with those upstream at the mooring allowing for varying advection of fluid parcels at the appropriate depths. Stability frequencies at the mooring are, in general, twice as large as those downstream. As well, despite the surface heating due to penetrative shortwave radiation and buoyancy flux surface temperatures are 1.5 ^{0}C less in downstream zone, presumably due to vigorous mixing. Finally,the

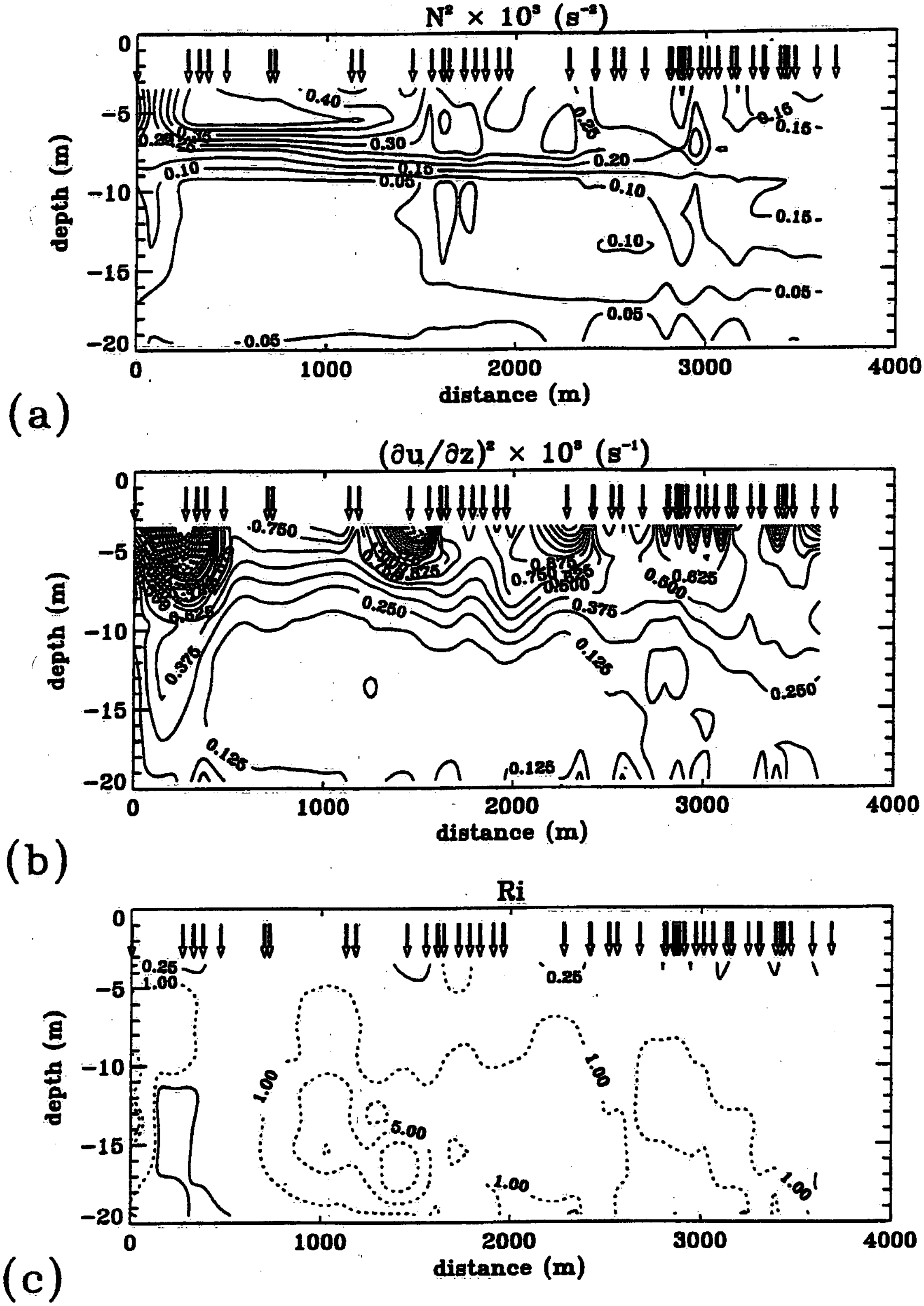

Figure 3. (a) average vertical shear squared (s^{-2}); (b) N^2 (s^{-2}); (c) Richardson number: note uneven contour intervals, Observation points are indicated by arrows. Distance from dye release. CTD profiles taken in the area of the dye tracking develop a step-like structure which may be an indicator of mixing.

While a surrogate for direct measurements of turbulent mixing, the temperature activity is a more direct indicator of turbulent mixing than the above considerations. The activity plot of Figure 4 suggests that turbulent events over depths from 10 to 20 m occur just before the wind increases at the meteorological buoy and also after the wind has been blowing strongly for 4 to 5 hours. It is evident from Figure 2 that during the wind event the wind stirring is about the same magnitude as the counteracting buoyancy flux. Thus, turbulent energy input from the wind and associated wave breaking may not be dampened and so diffuses downward. The question arises of why the first mixing event occurs apparently before the wind strength increases. This may be due to the direction of the wind disturbance travelling in the same direction as the wind. Since the wind was observed about 9 km north of the thermistor chain it may have taken an hour for the wind disturbance to reach the meteorological raft.

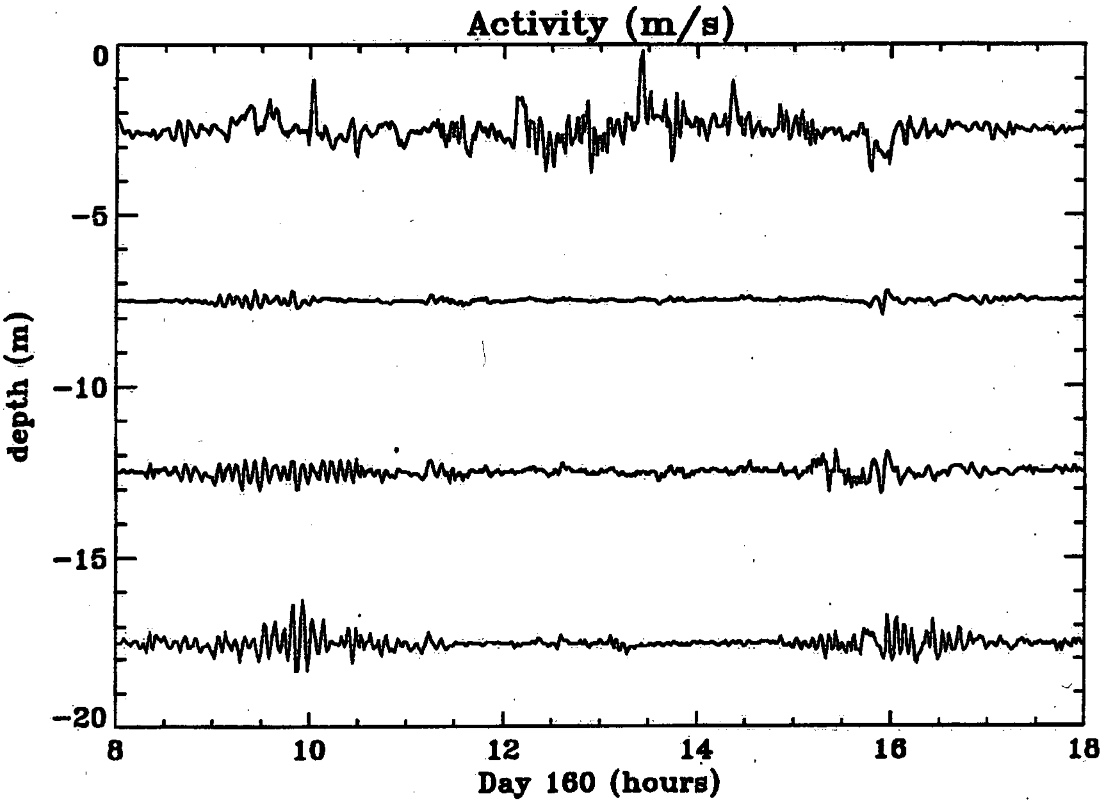

Figure 4 Four levels of temperature activity at the thermistor chain.

The temperature activity seen in Figure 4 is associated with vertical isotherm displacements of amplitudes of about 1 to 2 m and periods of 6 minutes. Since temperature activity was not observed during the period of nocturnal convective cooling, it is hypothesized that the activity is evidence of shear instabilities. If these displacements are associated with Kelvin-Helmholtz instabilities then the scale of the most energetic overturns, l_0, may be estimated as O(0.1 times the billow height or 10-20 cm)(Marmarino and Trump, 1991). A 10-cm overturning scale corresponds to an rate of turbulent kinetic energy dissipation of $(l_0/1.25)^2 N^3$ or $5.x10^{-4}$ cm^2/s^3. The dissipation downstream may be inferred from the dispersion of a patch of dye according to the standard scaling arguments(Fischer et al., 1979). Measured horizontal dispersion coefficients of).095, 0.7 and 0.12 m^2/s and patch sizes of 95, 400 and 300 m respectively are consistent with a dissipation rate of 1 to $6x10^{-5}$ cm^2/s^3. These rates are from 10 to 60 times larger than oceanic values(Fischer et al.,1979) and those observed in other lakes(Lawrence et al., 1994). As well as enhanced vertical mixing horizontal mixing may be accelerated by turbulent eddies shed by flow separation downstream of the flow constriction. We have mapped eddies during the ADCP surveys near promontories in Kootenay Lake. It is noteworthy that dissipation is possibly even larger in the restricted channel at the thermistor chain.

CONCLUSIONS

The ADCP measurements are a useful complement to the underway CTD profiles and permit Richardson numbers to be calculated and consequently zones of likely mixing to be identified. We conclude that vigorous mixing can occur even during periods of active development of stratification under certain conditions. Vertical shear associated with lake basin-scale internal waves which has been enhanced by coincident wind forcing of even short-term duration and focussed by basin geometry may increase to critical levels leading to mixing. Under these circumstances, despite the stabilizing effect of buoyancy flux, mixing rates as inferred from dye dispersion and fine-scale temperature activity are seen to be more intense than typical mixing rates found in the ocean and other lakes. Direct measurement of such turbulent quantities as the rate of dissipation would have been required in order to parameterize the mixing rates in terms of readily observable large-scale variables such as wind, shear and stability.

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REFERENCE

Farmer,D.M. 1978. Observations of long nonlinear waves in a lake. J.Phys. Oceanogr. Vol.8, 63-78

Hamblin,P.F., 1977. Short-period internal waves in the vicinity of a river-induced shear zone in a fjord lake. J. Geophys. Res. 82(21): 3167-3174

Hamblin,P.F., 1978. Internal waves in a fjord lake. J. Geophys. Res. 85(C5):2409-2418

Lawrence, G.A, K.I.Ashley, N.Yonemitsu and J.R.Ellis, 1994 Natural dispersion and the fertilization of a small lake. Manuscript submitted for publication

Marmorino,G.O. and C.L.Trump, 1992 High-wavenumber shear and temperature structure during the patches experiment.J. Geophys. Res. 97(C2): 2309-2318

Marmorino,G.O. and C.L.Trump, 1991 "Turbulent mixing" induced by upgoing near inertial waves in the seasonal thermocline of the Norwegian Sea. J. Geophys. Res. 96(C4): 7137-7143

Peters, H.,M.C.Gregg and T.B.Sanford,1991. Equatorial and off-equatorial fine-scale and large-scale shear variability at 140W J. Geophys. Res. 96(C9):16,913-16,928

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