Dissipation of Turbulent Kinetic Energy in the Oscillating Bottom Boundary Layer of a Large Shallow Lake

AIDIN JABBARI^a AND LEON BOEGMAN

Environmental Fluid Dynamics Laboratory, Department of Civil Engineering, Kingston, Ontario, Canada

REZA VALIPOUR

Water Science and Technology, Canada Centre for Inland Waters, Environment and Climate Change Canada, Burlington, Ontario, Canada

DANIELLE WAIN

7 Lakes Alliance, Belgrade Lakes, and Colby College, Waterville, Maine

DAMIEN BOUFFARD

Surface Waters—Research and Management, Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Kastanienbaum, Switzerland

(Manuscript received 12 May 2019, in final form 8 January 2020)

ABSTRACT

Mixing rates and biogeochemical fluxes are commonly estimated from the rate of dissipation of turbulent kinetic energy ε as measured with a single instrument and processing method. However, differences in measurements of ε between instruments/methods often vary by one order of magnitude. In an effort to identify error in computing ε , we have applied four common methods to data from the bottom boundary layer of Lake Erie. We applied the second-order structure function method (SFM) to velocity measurements from an acoustic Doppler current profiler, using both canonical and anisotropy-adjusted Kolmogorov constants, and compared the results with those computed from the law of the wall, Batchelor fitting to temperature gradient microstructure, and inertial subrange fitting to acoustic Doppler velocimeter data. The ε from anisotropy-adjusted constants in SFM increased by a factor of 6 or more at 0.2 m above the bed and showed a better agreement with microstructure and inertial method estimations. The maximum difference between SFM ε , computed using adjusted and canonical constants, and microstructure values was 25% and 50%, respectively. This difference was 30% and 55%, respectively, for those from inertial subrange fitting at times of high-intensity turbulence (Reynolds number at 1 m above the bed of more than 2×10^4). Comparison of the SFM ε to those from law of the wall was often poor, with errors as large as one order of magnitude. From the considerable improvement in ε estimates near the bed, anisotropy-adjusted Kolmogorov constants should be applied to compute dissipation in geophysical boundary layers.

1. Introduction

Turbulence in the bottom boundary layers (BBLs) of lakes and oceans regulates basin-scale mass flux (e.g., Munk 1966; Imberger 1998), sediment resuspension (e.g., Grant

and Madsen 1986; Boegman and Ivey 2009), and sediment water interface biogeochemistry (e.g., Scalo et al. 2012; McGinnis et al. 2014; Schwefel et al. 2017). BBL turbulence is typically characterized according to the rate of dissipation of turbulent kinetic energy ε , which enables parameterization of turbulent mixing and biogeochemical fluxes (e.g., Lorke 2007; Bouffard et al. 2013). Precise calculation of ε (i.e., $\varepsilon = \nu \partial u_i / \partial x_j \partial u_j / \partial x_i$, where ν is the kinematic viscosity and u_i is the velocity component in the direction i and the overbar denotes

^a Current affiliation: Physical Ecology Laboratory, Department of Integrative Biology, University of Guelph, Guelph, Ontario, Canada.

Corresponding author: Aidin Jabbari, 0saj@queensu.ca

FIG. 1. Time series of the dissipation from TMM ($\circ$), IDM [from Nortek ($\blacktriangle$) and RDI ($\blacksquare$) measurements], LES of the oscillating flow (solid line), IDM (from LES calculations; dashed-dotted line), and log law (from LES calculations; dashed line) at a height of 1 m above the sediment for Lake Alpnach (13–14 Aug 2002). Field data are from [Lorke and Wüest \(2005\)](#). Modified from [Jabbari \(2015\)](#).

averaging with respect to the time) requires simultaneous measurement of the instantaneous velocity gradient tensor, which is observationally infeasible (e.g., [Doron et al. 2001](#)). Therefore, dissipation is usually estimated from indirect methods with the exact observed value remaining unknown due to measurement and methodological error. For example, typically applied methods to compute ε assume the flow is steady and the turbulence is isotropic and homogeneous (e.g., [Doron et al. 2001](#)), conditions that are rarely met in geophysical boundary layers.

These errors can be seen in data from Lake Alpnach ([Fig. 1](#)), where ε at 1 m above the bed from Batchelor fitting to temperature microstructure are compared to those from inertial fitting applied to data from two acoustic Doppler current profilers (ADCPs) ([Lorke and Wüest 2005](#)). Also shown are ε calculated from wall-resolved large-eddy simulations (LESs) of an oscillating flow with similar Reynolds number, as well as ε computed from both log law and inertial fitting applied to the LES data ([Jabbari 2015](#)). Order of magnitude discrepancies are evident between the different calculations (mean standard deviation of $2 \times 10^{-9} \text{ W kg}^{-1}$) resulting from methodological errors (ε from log law and inertial fits applied to LES) and methodological plus measurement errors (ε from field instruments).

To better quantify error in computation of ε , this study investigates the factors contributing to the discrepancies between ε estimated from four commonly applied field methods: the inertial fitting dissipation method (IDM), structure function method (SFM), Batchelor fitting to temperature microstructure method

(TMM), and log law. Typically, a single method is applied in isolation, and so the present objective is to reduce error in computation of ε , through inter-comparison, so the various methods will converge toward a true estimate of ε . This will allow present-day benchmarks to be set.

The SFM and IDM rely on measurement of turbulent velocity fluctuations, which may be affected by anisotropy in the boundary layer. They are based on Kolmogorov's second similarity hypothesis that relates spatial velocity correlations to the dissipation in the inertial subrange where the eddies scale with the distance from the wall (log layer; [Townsend 1976](#)). These methods have the advantage of generating long-term “instantaneous” dissipation time series (IDM) and profiles (SFM) (e.g., [Lorke 2007](#)). However, the anisotropic nature of turbulent flows within boundary layers limits their applicability ([Monin and Yaglom 1975](#)). [Jabbari et al. \(2015, 2016\)](#) showed that the Kolmogorov constants, used to fit to the theoretical energy spectrum (IDM) and to spatial correlations of velocity (SFM), both in the inertial subrange, change substantially from the canonical values within the boundary layer, where near-wall anisotropy becomes significant.

The field-based IDM data shown in [Fig. 1](#) also has error, because the ADCP data did not resolve along- and cross-stream velocity spectra, leading to an uncertainty in ε up to a factor of $(4/3)^{-3/2} \approx 0.65$, due to anisotropy ([Lorke and Wüest 2005](#)). Moreover, these data were subject to inhomogeneity, from the beam-spreading angle of 1.5° and system spatial resolution (width of the acoustic beam at a particular depth bin),

FIG. 2. (a) Map of Lake Erie and its bathymetry. The square shows the location of the mooring: Sta. 341, $41^{\circ}47'N$, $82^{\circ}16'W$. Bathymetric contours are in meters and the axis is based on Universal Transverse Mercator coordinate system (UTM) in the zone 17-North. (b) The tripod equipped with ADCPs, an ADV, and RBR TR-1060 s before deployment on the bottom at Sta. 341. Modified from Valipour et al. (2015a).

and unsteadiness in the turbulence field, which contribute to uncertainty in ε calculations. For example, Lorke (2007) found that SFM-ADCP and IDM acoustic Doppler velocimeter (ADV) computed ε was highly affected by the amount of temporal and spatial averaging in nonstationary turbulence.

It is, therefore, not surprising that the log law often gives poor results when applied to unsteady boundary layer flows (e.g., Grant and Madsen 1979; Lorke et al. 2002); although logarithmic velocity profiles are often observed (e.g., Valipour et al. 2015a; Troy et al. 2016). For example, Huntley and Hazen (1988) and Huntley (1988) found that the log law underestimates the friction velocity in combined wave and steady flow conditions, where the wave flow enhances the bottom shear stress. Conversely, in Lake Michigan Cannon and Troy (2018) found “remarkable” agreement between SFM and log-law ε , with log law becoming a much less reliable predictor at low current speeds. These field data may be contrast with numerical data (Fig. 1), showing log law to provide—at selected times other than the flow reversal—a better estimate of ε than the IDM, in comparison to the LES calculations. Given the discrepancies in ε estimates, resulting from both the measurement and methodological errors, described above, there is a need for further inter-comparison of ε estimates.

In the present study, we compared estimates of ε from four different methods (ADV-IDM, ADCP-SFM, log law, and TMM) in the bottom boundary of a large lake, in an effort to converge on the most accurate dissipation estimate and assess what a reasonable error should be in calculating ε . To account for anisotropy, the SFM was

computed using both the canonical (e.g., Wiles et al. 2006; Monin and Yaglom 1975) and anisotropy-adjusted (Jabbari et al. 2016) Kolmogorov constants. This is the first application of these numerically derived anisotropy corrections to field data. The calculated ε values were also compared to those from the log-law and Batchelor fits to temperature gradient microstructure, which were not affected by anisotropy.

2. Study site and measurements

Lake Erie (Fig. 2; 388 km long and 92 km wide) is the shallowest of the Laurentian Great Lakes and consists of distinct western, central, and eastern basins, which have maximum depths of 11, 25, and 64 m, respectively. In the summers of 2008 and 2009, extensive field measurements (Bouffard et al. 2012; Bouffard and Boegman 2013; Bouffard et al. 2013; Valipour et al. 2015a,b) were carried out in the central basin to address the hypoxia problem (e.g., Rao et al. 2008; Scavia et al. 2014). As part of the measurements, a 1.8-m tripod (Figs. 2a,b) was deployed at Sta. 341a depth of 17.5 m. The tripod was equipped with a downward-looking 2 MHz pulse coherent acoustic Doppler current profiler (HR-ADCP, Nortek with accuracy $\pm 1\%$ of measured values) at 1.84 m above the bed, that measured the velocity down to ~ 3 cm above the bed, and a Nortek Vector ADV at 1 m above the bed. At 15 min intervals, the HR-ADCP burst recorded velocity at 1 Hz over 256 s in 3 cm bins to the sediment–water interface. The ADV measured the velocity at 16 Hz for 5 min every 20 min (Fig. 2b). Here, dissipation profiles were calculated by applying the SFM

and log law to the HR-ADCP measurements and the IDM to the ADV data.

Since the adjustments in dissipation methods we applied are based on neutrally stratified flows, we minimize the contribution of density stratification on anisotropy near the bed (Sarkar 2003) by concentrating on data collected between 3 and 6 May 2009 (days of year 122.23–125). At this time, the flow was weakly stratified with the surface seiche (~ 14 h period) being the predominant process that energized the bottom boundary layer (e.g., Boegman et al. 2001; Rao et al. 2008). The significant period of surface waves was less than the theoretical threshold (~ 5 s; Valipour et al. 2017) required for orbital velocities to reach the bottom.

The dissipation from velocity measurements were compared with those from Batchelor fitting to temperature gradient microstructure measured with a self-contained autonomous microstructure profiler (SCAMP; PME Inc.; Bouffard and Boegman 2013) on 28 May and 2 July 2009 (days 147.13 and 182.64, respectively) when the flow was weakly stratified. This subsample was picked from 26 days of measurements in July and August 2008–09, when the boat was moored within 30 m of Sta. 341 (to prevent entanglement) for ~ 1 h capturing 5–12 microstructure casts on each day. The SCAMP profiled vertically through the water column at a speed of 0.1 m s^{-1} in a falling mode and sampled at 100 Hz with a time response of 7 ms, resolving water column structure with vertical scales as small as 1 mm. Batchelor fits, to estimate dissipation, were performed in 0.25 m bins through the water column up to 1 m above the bed. The sensor guard prevented profiling all the way to the sediments. These results have been published, with the methodology and data described in detail in Bouffard and Boegman (2013).

3. Methodology

a. Structure function method

We applied the second-order structure function

$$D(z, r) = \overline{[u'_b(z+r) - u'_b(z)]^2}, \quad (1)$$

which is the correlation of the in-beam fluctuation velocity u'_b , (obtained by Reynolds averaging each 256 s burst) between two points separated by a beam distance r . In Eq. (1) $D(z, r)$ represents the structure function at height z above the bed. Here, the centered difference scheme described by Wiles et al. (2006) was applied. In isotropic turbulent flows, at high Reynolds numbers, the SFM relates the rate of dissipation of turbulent kinetic energy to the spatial correlations of

velocity based on the Kolmogorov turbulent cascade theory in the inertial subrange

$$D(z, r) = C\varepsilon^{2/3}r^{2/3}, \quad (2)$$

where C is the Kolmogorov 2/3 constant (Pope 2000), which in atmospheric studies has been found to be between 2.0 and 2.2 (Sauvageot 1992). Typically, the dissipation ε_{SFC} is computed with the canonical value $C = C_C = 2.1$ (e.g., Wiles et al. 2006; Lorke 2007; Bouffard et al. 2013). These dissipation values differ from those (ε_{SFA}) calculated, as described below, using the anisotropy-adjusted Kolmogorov constants C_A [Eq. (3) and Fig. 3a; Jabbari et al. 2016], which have been adjusted for turbulence anisotropy through the boundary layer. The latter constants were computationally evaluated over $20 \leq z^+ \leq 2000$, where $z^+ = zu_\tau/\nu$ is the height above the bed normalized by the friction velocity u_τ and kinematic viscosity. The constant C_A was given by the fitting functions

$$C_A = \begin{cases} 0.048(z^+)^{0.65}, & z^+ \leq 160 \\ 0.42 + 0.45 \ln[(z^+)^{0.4}], & 160 < z^+ \leq 500 \\ 1.118 + \frac{0.44}{0.5 + 24(z^+)^{-0.61}}, & 500 < z^+ < 2000 \\ 0.699 + 0.455 \ln[(z^+)^{0.295}], & 2000 \leq z^+ \leq 16200 \\ 2, & z^+ > 16200 \end{cases}, \quad (3)$$

where C_A for $z^+ \leq 2000$ was obtained from numerical simulation of a steady turbulent open channel flow (Jabbari et al. 2016) and has been extrapolated to $z^+ \geq 2000$ using $C_A = 2$ from Saddoughi and Veeravalli's (1994) experimental results that found $C_A = 2.0 \pm 0.1$ for $z^+ = 16200$ and 62000 .

The dissipation was estimated by fitting the measured structure function from the HR-ADCP [D ; Eq. (1)] to Eq. (2) within the inertial subrange and beam averaging. Individual fits, at each height, were over $0.03 < r/2 < 0.18$ m, where the maximum separation distance was six bins (Lorke 2007) and the minimum range of r was given by the distance between two adjacent bins (i.e., 2 times the bin size of 0.03 m). The bottom flow velocity and the friction velocity were < 0.1 and $< 0.01 \text{ m s}^{-1}$, respectively.

b. Inertial dissipation method

Similar to the structure function method, the inertial dissipation method is based on fitting the energy spectrum E to the theoretical form within the inertial subrange. From Kolmogorov's universal equilibrium hypothesis, at sufficiently high Reynolds number, the

FIG. 3. (a) The vertical velocity component Kolmogorov 2/3 constant adjusted for anisotropy obtained from numerical simulation C_A . Circles are from numerical analysis and the solid line is from the fitting function [Eq. (3)]. The data in $z^+ = 16\,000$ are from [Saddoughi and Veeravalli \(1994\)](#). The dashed line shows the canonical constant $C_C = 2.1$. (b) An example of the burst-averaged along-beam structure function [Eq. (1)] from the three HR-ADCP beams at $z^+ = 2113$ ($z = 1.32$ m) on day 123.98. The dashed line shows a 2/3 slope.

turbulence is isotropic and the one-dimension longitudinal and transverse spectra are

$$E_{11}(k_1) = \alpha_{11} \varepsilon_{\text{IDM}}^{2/3} k_1^{-5/3} \quad (4)$$

and

$$E_{22}(k_1) = E_{33}(k_1) = \frac{4}{3} \alpha_{11} \varepsilon_{\text{IDM}}^{2/3} k_1^{-5/3}, \quad (5)$$

where $\beta\beta = 1, 2, 3$ represents the streamwise, spanwise, and vertical (or x, y, z) directions, respectively, k_1 is the longitudinal wavenumber, and $\alpha_{11} = 0.5$ is the canonical Kolmogorov $-5/3$ constant ([Monin and Yaglom 1975](#)). To be consistent with the in-beam SFM calculations and minimize noise, we used only the vertical velocity components from the ADV for calculation of spectra. The inertial subrange was considered the wavenumber range with 20% error from the plateau of $E_{33}(k_1)k_1^{5/3}$, that is, the region where $E_{33}(k_1)k_1^{5/3}$ is independent of the wavenumber and equal to $4/3\alpha_{11}\varepsilon_{\text{IDM}}^{2/3}$ [Eq. (5); [Saddoughi and Veeravalli 1994](#)]. For $z^+ < 160$ the vertical constant adjusts with anisotropy ([Jabbari et al. 2015](#)); however, this condition was not observed at 1 m above the bed; indicating the flow at 1 m was isotropic. The local mean velocity was used to relate the wavenumber and frequency spectra.

c. Logarithmic law of the wall

The observed velocity profiles (u) were compared with those from logarithmic law of the wall (log law; u_L) for a steady turbulent wall flow

$$u_L = u_\tau \left(\frac{1}{\kappa} \ln \frac{z}{z_0} \right), \quad (6)$$

where $\kappa \approx 0.41$ is the von Kármán constant and z_0 the roughness length, calculated by fitting the velocity profiles to Eq. (6). The log-law dissipation is

$$\varepsilon_L = \frac{u_\tau^3}{\kappa z}, \quad (7)$$

which is based on a local equilibrium between the dissipation and production P of turbulent kinetic energy in stationary flows ([Lorke and MacIntyre 2009](#)).

d. Friction velocity

The friction velocity was calculated from log law, which is common in field studies. Following [Valipour et al. \(2015a\)](#), we first located the logarithmic constant-stress layer, by finding the depth range over which

$$\frac{du_\tau}{dz} = \frac{d}{dz} \left(\kappa z \frac{du}{dz} \right) = 0 \pm 0.1 \text{ s}^{-1}. \quad (8)$$

Then u_τ and z_0 were evaluated by least squares fitting Eq. (6) to the profiles of u over the constant-stress layer (e.g., [Kundu and Cohen 2002](#)).

Deviation from log-law behavior will lead to error in C_A [i.e., Eq. (3)], through the usage of u_τ in computation of z^+ . To examine the accuracy of the log-law-based friction velocity, we also computed u_τ by three other methods, applied to the ADV data. In these methods,

FIG. 4. (a) Predicted relationship ($\epsilon_{p,1m}$; solid line) between the dissipation and the flow velocity at 1 m above the bed with 95% error (dashed lines). (b) Ratio of the calculated dissipation from SFM ($\epsilon_{SFA,1m}$) to the predictions from (a) ($\epsilon_{p,1m}$) vs velocity direction at 1 m above the bed (u_{1m}).

the bed shear stress τ was calculated from (i) the quadratic law

$$\tau = \rho C_d U^2 \quad (9)$$

using a drag coefficient $C_d = 4.5 \times 10^{-3}$, as determined by Valipour et al. (2015a) for this site in Lake Erie through log-law fits to an extended HR-ADCP dataset; (ii) the turbulent kinetic energy (TKE)

$$\tau = \rho C_t \overline{w'w'}, \quad (10)$$

where $C_t = 0.9$ (Bluteau et al. 2016), and (iii) the Reynolds stress (e.g., Zurberti et al. 2018)

$$\tau = \rho \overline{u'w'}. \quad (11)$$

The shear velocity was then computed from bed stress $u_\tau = \sqrt{\tau/\rho}$.

e. Numerical simulations

The numerical data in this study are from LES of turbulent flows on a smooth wall using a well-validated numerical code (Keating et al. 2004a,b). The top and the bottom boundaries were free-slip symmetry and no-slip boundary conditions, respectively, and periodic conditions were applied in the streamwise and spanwise directions. The data here are from LES of a fully developed turbulent and steady open channel flow with $Re_\tau = L_z u_\tau / \nu = 2000$, where $L_z = 1$ is the height of the channel (Jabbari et al. 2015, 2016) and an oscillating flow with zero-mean freestream current with $Re_\delta = \delta U / \nu = 3600$, where U was the maximum free freestream velocity, $\delta = \sqrt{2\nu/\omega}$ was the Stokes layer thickness, and $\omega = 2\pi/T$ was the angular frequency of the oscillation

with period T (Jabbari 2015). The numerical model has been widely used for the simulation of similar geophysical flows (e.g., Scalo et al. 2012; Yuan and Piomelli 2014).

4. Results

a. Flow interference

The field data were first evaluated to identify when spurious dissipation measurements resulted from frame interference at 1 m above the bed, where the ADV battery canister was located (Fig. 2; see also Valipour et al. 2015a). As expected from theory (Pope 2000; Lorke and MacIntyre 2009) the observed dissipation correlated with the flow velocity. We followed McGinnis et al. (2014) and related ϵ_{SFA} to the mean flow at 1 m above the bed (Fig. 4a). Dividing ϵ_{SFA} by the predicted dissipation from the correlation allowed identification of the flow directions associated with outlier data (Fig. 4b). The largest deviations occurred when flow was from 275° to 360°, resulting in discrepancy of the dissipation by a factor of up to 23. The same results were achieved from correlation of dissipation with the third power of velocity [e.g., Eq. (7); not shown here]. Therefore, HR-ADCP and ADV data from these directions were neglected in the analysis.

b. Time variations of friction velocity and Kolmogorov constant

In general, u_τ from all methods, were within one standard deviation ($2 \times 10^{-4} \text{ m s}^{-1}$) of the mean (Fig. 5a). The value of u_τ from log-fits was within 6%, 16%, and 21% of that from the quadratic law, TKE,

FIG. 5. (a) Flow velocity (m s^{-1}) at 1 m above the bed (dashed black line) and 10 times the friction velocity calculated by log law [Eq. (8); solid black], the quadratic law [Eq. (9); blue], the TKE [Eq. (10); green], and the Reynolds stress method [Eq. (11); red]. (b) Time series of dissipation of turbulent kinetic energy at 1 m above the bed from the structure function method using the anisotropy-adjusted constants (ϵ_{SFA} ; filled circles) and canonical constants (ϵ_{SFC} ; hollow circles), log law [ϵ_L ; Eq. (7); solid line], and inertial dissipation method (ϵ_{IDM} ; red dashed-dotted line). (c) Variation of the Reynolds number at 1 m above the bed ($\text{Re}_{1\text{m}} = u_{1\text{m}} \times 1/\nu$) and the ratio of shear length scale to the Kolmogorov length scale $B = L_s/\eta$. The data with flow direction 275° – 360° were removed because of the frame interference (see Fig. 3b).

and Reynolds stress methods, respectively, giving $<17\%$ error in ϵ_{SFA} due to uncertainties in u_τ [based on a maximum discrepancy of 22% in z^+ ; Eqs. (2) and (3)]. These errors were similar to the 4%–11% error found by Zulberti et al. (2018) in applying the same methods to estimate bottom stress at more energetic ocean site. These uncertainties do not affect ϵ_{SFC} , which uses the canonical constant that is independent of u_τ .

The friction velocity was oscillatory, following the barotropic mode-one seiche with a period of 14 h (Fig. 5a), leading to periodicity in u_τ as is typically observed (e.g., Valipour et al. 2015a) and here $u_\tau \sim 0.07u_{1\text{m}}$ (e.g., Lorke and MacIntyre 2009). The barotropic flow caused time variations of z^+ , and consequently C_A that varied with both time and height above the bed due to changes in z^+ . For instance,

at 0.2 m above the bed, $z^+ = 50$ and $z^+ = 320$ on low (day 123.98, $u_\tau = 0.00025 \text{ m s}^{-1}$, Figs. 6a,c) and high (day 123.07, $u_\tau = 0.0016 \text{ m s}^{-1}$, Figs. 6d,f) turbulence intensity days, with corresponding Kolmogorov constants (Fig. 3a) of $C_A = 0.61$ and 1.46, respectively. The Kolmogorov constant at 1 m above the bed changed from 1.41 on day 123.98 ($z^+ = 253$, Figs. 6a,c) to 1.69 on day 123.07 ($z^+ = 1600$, Figs. 6d,f).

c. Dissipation of turbulent kinetic energy

Time series of velocity and flow direction measured by the HR-ADCP are shown (Figs. 7a,b, respectively), along with the computed ϵ_{SFA} (Fig. 7c), ϵ_{SFC} (Fig. 7d), and ϵ_L (Fig. 7e). The velocity and dissipation time series exhibited an oscillatory pattern with a period of ~ 14 h consistent with the surface seiche (Boegman et al. 2001; Valipour et al. 2015a). From these figures,

FIG. 6. (a),(d),(g),(j) Velocity profiles from HR-ADCP (circles) compared with log law [u_L ; Eq. (6); solid line]. (b),(e),(h),(k) Reynolds stress: $\rho u'w'$ (filled circles) and $\rho v'w'$ (hollowed circles). Note the change in x-axis limits in these panels. (c),(f),(i),(l) Dissipation of turbulent kinetic energy from structure function method using the anisotropy-adjusted constants (ϵ_{SFA} ; filled circles) compared with those from canonical constants (ϵ_{SFC} ; hollow circles), inertial dissipation method (ϵ_{IDM} ; filled red circles), and log law [ϵ_L ; Eq. (7); solid line]. Also included in (i) and (l) is the dissipation from temperature microstructure method (ϵ_{TMM} ; dashed-dotted line). Rows are from (a)–(c) day 123.98 ($u_\tau = 0.00025 \text{ m s}^{-1}$ and $z_0 = 0.003 \text{ m}$), (d)–(f) day 123.07 ($u_\tau = 0.0016 \text{ m s}^{-1}$ and $z_0 = 0.002 \text{ m}$), (g)–(i) day 182.64 ($u_\tau = 0.0032 \text{ m s}^{-1}$ and $z_0 = 0.0016 \text{ m}$), and (j)–(l) day 147.13 ($u_\tau = 0.005 \text{ m s}^{-1}$ and $z_0 = 0.0019 \text{ m}$). In (c), (f), (i), and (l) the width of the shaded area shows the difference between maximum and minimum dissipation predictions from the three beams using canonical constants.

it is striking how $\epsilon_L \gg \epsilon_{SFA} > \epsilon_{SFC}$, particularly during periods of strong mean flow, when log-law behavior was expected, suggesting ϵ_L fundamentally overestimates dissipation at this site. That $\epsilon_{SFA} > \epsilon_{SFC}$, during strong flow, shows how anisotropy near the bed enhanced dissipation.

Close to boundary, the difference between ϵ_{SFC} and ϵ_{SFA} was >6 (e.g., $\epsilon_{SFA}/\epsilon_{SFC} = 6.8$ at $z^+ = 50$ or $z = 0.2 \text{ m}$, Fig. 6c), but the values converged away from the bed where C_A approached C_C (Fig. 3a) (e.g., $\epsilon_{SFA}/\epsilon_{SFC} = 1.82$ at $z^+ = 253$ or $z = 1 \text{ m}$, Fig. 6c; $\epsilon_{SFA}/\epsilon_{SFC} = 1.16$ at $z^+ = 8000$ or $z = 1.62 \text{ m}$, Fig. 6l). As a result, the average value of the lognormal distribution of the dissipation within 0.5 m above the bed was 1.9 times greater for

ϵ_{SFA} ($9.55 \times 10^{-8} \text{ W kg}^{-1}$) compared to ϵ_{SFC} ($3.02 \times 10^{-8} \text{ W kg}^{-1}$; Fig. 8a).

During these measurements, at 1 m above the bed ($z^+ > 160$, Fig. 6c) where the canonical value of the vertical $-5/3$ Kolmogorov constant is valid, ϵ_{IDM} was within $\sim 30\%$ and $\sim 55\%$ of ϵ_{SFA} and ϵ_{SFC} , respectively, at times of high-intensity turbulence when the Reynolds number was $> 2 \times 10^4$ ($Re_{1m} = u_{1m} \times 1/\nu$) (Figs. 5b,c). The difference between SFM and IDM increased during flow reversal (Fig. 7a), when turbulence intensity was low and both methods were inaccurate (e.g., $\epsilon_{IDM}/\epsilon_{SFA} = 3$ and $\epsilon_{IDM}/\epsilon_{SFC} = 5.5$ at 1 m above the bed on day 123.98, Fig. 6c). Comparison of the dissipation calculated from SFM with those from Batchelor fits to

FIG. 7. Time series of the flow on days 122.23–125: (a) flow direction, (b) flow velocity, and log of the dissipation of turbulent kinetic energy calculated from structure function based on (c) anisotropy-adjusted Kolmogorov constants [C_A ; Eq. (3)] and (d) canonical constant ($C_C = 2.1$) as well as (e) that calculated from log law [Eq. (7)]. Note that the data with flow direction from 275° to 360° have been removed from (b)–(e) (Fig. 3). The dissipation is in W kg^{-1} .

SCAMP data (ε_{TMM} ; Figs. 6i,l and Table 1) shows that ε_{SFA} had better agreement with ε_{TMM} than ε_{SFC} (ε_{SFA} was within 25% of ε_{TMM} , while ε_{SFC} had differences up to 50%; ε_{IDM} was within 25% of ε_{TMM} at 1 m above the bed).

Velocity profiles showed better logarithmic characteristics during high-intensity turbulence (Figs. 9b–d) compared to those during low turbulence flow reversal (Fig. 9a). The dissipation from the log law showed discrepancies relative to that calculated from the other methods (e.g., $\varepsilon_L/\varepsilon_{\text{SFA}} = 4.4$ at $z^+ = 2592$ or $z = 1.62$ m, Fig. 6f). The log law underestimated the dissipation during the flow reversal (Fig. 6c), due to laminar flow during these phases of oscillation. However,

the log law overestimated the dissipation close to the boundary ($z < 0.5$ m) on most days (Figs. 6f,i,l and 7e). This difference can be as high as a factor of 4 or more (Fig. 6f) and may be due to the lack of equilibrium between production and dissipation of turbulent kinetic energy, which is not always satisfied in boundary layers of oscillatory seiche-induced lake flows (Lorke 2007; Lorke and MacIntyre 2009; Jabbari 2015). Consequently, the mean value of the lognormal dissipation $\varepsilon_L \sim 2 \times 10^{-7} \text{ W kg}^{-1}$ from the entire measurement region ($0.18 < z < 1.65$ m) was an order of magnitude greater than those from $\varepsilon_{\text{SFA}} = 4.8 \times 10^{-8} \text{ W kg}^{-1}$ and $\varepsilon_{\text{SFC}} = 3.02 \times 10^{-8} \text{ W kg}^{-1}$ (Fig. 8b). This difference was magnified near the bed ($z < 0.5$ m;

FIG. 8. Frequency distributions of dissipation rate (normalized by the total number of observations) from the structure function based on anisotropy-adjusted Kolmogorov constants [red circles; Eq. (3)], based on canonical constants (blue circles), and calculated from log law (black circles) (a) within 0.5 m from the bed, (b) in the whole region ($0.18 < z < 1.65$ m), and (c) at 1 m above the bed. The frequency distributions are calculated for $\log_{10}(\epsilon)$ based on the entire dataset of 260 bursts at 15 min intervals (days of year 122.23–125 in 2009). Solid lines show a fit to a lognormal distribution.

$z^+ < 2685$), where the boundary leads to anisotropy (Fig. 8a) and decreased where the flow became isotropic ($z = 1.0$ m; $z^+ < 5188$), and the three methods predicted very similar dissipation (Fig. 8c).

5. Discussion and conclusions

This study computed dissipation of turbulent kinetic energy within an unsteady boundary layer of a large lake by applying four common methods: log law, inertial subrange fitting, structure function, and Batchelor fitting.

The log law overestimated dissipation near the wall (e.g., at $z < 0.5$ m in Figs. 6f,i,l). This can be explained from analysis of turbulent open channel flows. For example, in Figs. 10a and 10b the log law is only valid for $z^+ > 30$, where the flow is in equilibrium (production $\sim$ dissipation), but it overestimates dissipation for $z^+ < 30$, where the shear from the bed affects the flow (Pope 2000). To evaluate the deviation of near-bed dissipation from log-law predictions, we calculated the ratio of dissipation from log law to that from the structure function ($\epsilon_L/\epsilon_{SFA}$) versus a local shear-flow Reynolds number $Re_s(z) = u(z)z/\nu$, which captures the large-eddy

scale of bed-induced mean-flow shear that drives near-bed turbulence. Here, $u(z)$ is the burst-averaged mean flow velocity at height z (Fig. 11). For $Re_s < 2 \times 10^4$ ($z < 0.5$ m) the log law overestimated the dissipation by more than two orders of magnitude; however, farther from the bed $\epsilon_L \rightarrow \epsilon_{SFA}$ ($0.5 < z < 1.8$ m; $Re_s > 2 \times 10^4$). This highlights the poor performance of log law near the wall, in this complex geophysical flow. The log regression on $\epsilon_L/\epsilon_{SFA}$ versus Re_s in Fig. 11 ($R^2 = 0.64$) provides a measure for accuracy of log-law calculations. Usage of a Stokes's Reynolds number (Jabbari 2015; Cannon and Troy 2018) did not collapse the data.

In Lake Erie it has been shown that the log layer can extend 0.5–3 m above the bed during the measurements in this study and the velocity profiles < 1 m above the bed follow the log law with 20% error (Valipour et al. 2015a). Here, we showed that error in friction velocity, from fitting velocity profiles to the log law over the constant-stress layer, can result in $\leq 17\%$ uncertainty in dissipation from anisotropy-adjusted constants using the structure function.

Farther away from the wall, however, in highly unsteady flows such as Lake Erie with oscillatory forcing

TABLE 1. Rate of dissipation of turbulent kinetic energy ($W\ kg^{-1}$) from Batchelor fitting (ϵ_{TMM}), SFM based on anisotropy-adjusted (ϵ_{SFA}) and canonical (ϵ_{SFC}) constants, log law (ϵ_L), and the inertial dissipation method (ϵ_{IDM}).

Day of year (2009)	z (m)	z^+	ϵ_{TMM}	ϵ_{SFA}	ϵ_{SFC}	ϵ_L	ϵ_{IDM}
182.64	1	3240	7.65×10^{-9}	5.09×10^{-9}	3.99×10^{-9}	8.74×10^{-9}	6.13×10^{-9}
182.64	1.25	4050	1.23×10^{-8}	8.87×10^{-9}	7.12×10^{-9}	7.03×10^{-9}	
182.64	1.5	4860	8.14×10^{-9}	6.02×10^{-9}	4.93×10^{-9}	5.88×10^{-9}	
147.13	1	4980	1.02×10^{-6}	6.76×10^{-7}	5.78×10^{-7}	3.08×10^{-7}	8.98×10^{-7}
147.13	1.25	6225	2.37×10^{-6}	1.65×10^{-6}	1.39×10^{-6}	2.42×10^{-7}	
147.13	1.5	7470	2.42×10^{-6}	2.33×10^{-6}	2.00×10^{-6}	2.03×10^{-7}

FIG. 9. Velocity profiles from the HR-ADCP normalized by u_τ compared with log law [u_L ; Eq. (6); solid line] at (a) day 123.98, (b) day 182.64, (c) day 123.07, and (d) day 147.13, which correspond with Figs. 6a, 6e, 6c, and 6g, respectively.

from the basin-scale seiches (Valipour et al. 2015b), nonboundary layer processes [e.g., baroclinic shear (Bouffard et al. 2012), entrainment (Ivey and Boyce 1982)] may be generating/damping turbulence, and therefore, the velocity and dissipation profiles can deviate from the logarithmic behavior due to these energetic events (e.g., Lorke et al. 2002; Cannon and Troy 2018). This can be seen in increased Reynolds stress ($\rho u'w'$ and $\rho v'w'$; Figs. 6b,e,h,k), where the dissipation increases significantly above log-law behavior, which can only be attributed to locally generated turbulence. For example, at $z > 1.25$ m, $\varepsilon_L < 4\varepsilon_{\text{SFA}}$ (Fig. 6l) as the Reynolds stress increases by $> 0.1 \text{ N m}^{-2}$ (Fig. 6k). Evaluation of the impacts of these events on boundary layer dynamics requires further study that includes consideration of the basin-scale processes in the water column.

Time series of ε_{IDM} were in reasonable agreement with the ε_{SFA} at 1 m above the bed (Fig. 5b); however, the predictions between these two methods had $\sim 30\%$ difference at times when the Reynolds number was $> 2 \times 10^4$ (Fig. 5c). That difference increased during flow reversal (Fig. 5b). The difference may result from several factors, including (i) the HR-ADCP beam angle, (ii) point versus spatial acoustic observations, (iii) spatial differences in dissipation along HR-ADCP beams, and

(iv) the averaging time scale in the IDM. These are discussed in detail below:

- (i) ADCP beam angle: We applied vertical velocity component Kolmogorov constants to in-beam HR-ADCP velocities measured at 25° to the vertical. The horizontal velocity component coefficients differ from the vertical, leading to a potential overestimation of dissipation by a factor of 1.33 (Cannon and Troy 2018). This error is within the range of that from other methods (Lorke and Wüest 2005).
- (ii) Inhomogeneity between instruments: The IDM fits velocity fluctuations at a single point to the inertial subrange, where the data are converted to wave-number space using the mean velocity. Conversely, the SFM relies on spatial correlations of velocity fluctuations in the inertial subrange with height (e.g., $0.03 < r/2 < 0.18$ m in this study). In unsteady boundary layer flows, where turbulence can be generated from nonboundary layer processes (e.g., baroclinic seiches, wave-wave interactions, and shear instability) inhomogeneous turbulence may cause variability in the estimation of dissipation between these methods.
- (iii) Inhomogeneity between ADCP beams: Beam averaging the dissipation in the SFM relies on the

FIG. 10. (a) Velocity profile from LES of a steady turbulent open channel flow (solid line) vs log law [$u_L^+ = (1/\kappa) \ln z^+ + 5.1$; dashed line] and laminar sublayer flow ($u^+ = z^+$; dashed-dotted line). (b) Production (dotted line) and dissipation (solid line) of turbulent kinetic energy from LES of $Re_\tau = 2000$ vs ϵ_L [dashed line; Eq. (7)]. Nondimensional production P^+ and dissipation ϵ^+ are normalized by u_τ^4/ν and the velocity u^+ is normalized by u_τ .

assumption of homogeneous turbulence, the difference between the dissipation calculated from the beams (Fig. 3b) shows that this condition was not fulfilled. Wiles et al. (2006) showed that upstream facing beams can give greater dissipation in tidal flows and attributed that to inhomogeneity and anisotropy in the shear and Reynolds stresses. Here, D [Eq. (2)] in each of the three beams was—at times—different, which gave differing realizations of dissipation (e.g., 4.65×10^{-9} , 3.12×10^{-9} , and $1.61 \times 10^{-9} \text{ W kg}^{-1}$ for the top, middle, and the bottom lines, respectively, in Fig. 3b). The difference between the dissipation from beams typically increases with the distance from the bed according to the divergence of the ADCP beams (Figs. 6c,f,i,l). The difference between the maximum ($\epsilon_{\max}$) and minimum ($\epsilon_{\min}$) dissipation between the three beams can overshadow the improvement in dissipation from using anisotropy-adjusted constants; for example, at $z^+ = 4050$ ($z = 1.25 \text{ m}$) in Fig. 6i, $\epsilon_{\max}/\epsilon_{\min} = 2.26$, whereas $\epsilon_{\text{SFA}}/\epsilon_{\text{SFC}} = 1.24$ and $\epsilon_{\text{TMM}}/\epsilon_{\text{SFA}} = 1.40$, which shows that inhomogeneity errors can be greater than the errors due to

anisotropy. Differences in dissipation from each beam are common when the SFM is applied to ADCP data, and the results are typically beam averaged (Wiles et al. 2006; Lorke 2007), contributing to measurement error.

- (iv) Frozen time assumption: The IDM ideally fits over one to two decades of wavenumber space (Bluteau et al. 2011), with the mean velocity typically applied as a convection velocity to convert frequency spectra into wavenumber space. Since the IDM is strictly valid in steady-state turbulence, by applying the IDM to oscillating flows, the Reynolds-averaging time scale should be short enough to allow unsteadiness in the mean velocity to be neglected, but long enough to capture the inertial subrange. In this study the 5-min Reynolds averaging (burst length) was relatively short compared to the $\sim 14 \text{ h}$ surface seiche or $\sim 17 \text{ h}$ Poincaré wave, giving about one decade of inertial subrange during strong turbulence ($Re_{1m} > 2 \times 10^4$), for example, day 122.51 (Figs. 5c and 12). However, during flow reversal, with a decrease in velocity and turbulence intensity, the shear reduced the extent of the inertial subrange

FIG. 11. The log of the ratio of the dissipation from log law [Eq. (7)] to those from the structure function based on anisotropy-adjusted Kolmogorov constants C_A [Eq. (3)] vs log of parameter $Re_s = u(z)z/\nu$. The plot is colored by the height above bottom. The solid black line is a fit $\{\log Re_s = 0.047[\log(\epsilon_L/\epsilon_{SFA})]^2 - 0.77[\log(\epsilon_L/\epsilon_{SFA})] + 2.74, R^2 = 0.64\}$ and the dotted black lines show 95% prediction interval.

(Bluteau et al. 2011; Jabbari et al. 2015), for example, day 123.39 (Figs. 5c and 11). Figure 5c shows the ratio of shear length scale $L_s = (\epsilon_{IDM}/S^3)^{1/2}$, where $S = (2\overline{S_{ij}}\overline{S_{ij}})^{1/2}$ is the mean velocity shear, to the Kolmogorov length scale ($\eta = \nu^3/\epsilon_{IDM})^{1/4}$) as $B = L_s/\eta$ at 1 m above the bed. In general, $B < 100$ during the deployment, which is significantly less than $B > 3000$, as required to observe more than decades of inertial subrange (at much higher Reynolds numbers and farther from the boundary, Bluteau et al. 2011; Jabbari et al. 2015). However, at 1 m above the bed about one-half decade of inertial subrange was observed during weak turbulence in this study.

Density stratification may also be causing anisotropy through the Ozmidov scale. The anisotropy-adjusted constants were calculated from LES of the boundary layer in a neutrally stratified flow, where the anisotropy was due to bed shear (Jabbari et al. 2016). In this study the measurements were during weak spring stratification, $N^2 < 10^{-4} s^{-2}$ (average $N^2 \sim 10^{-6} s^{-2}$), where N is the buoyancy frequency (Valipour et al. 2015a). Considering the average dissipation $\epsilon_{SFA} \sim 10^{-8} W kg^{-1}$ (Fig. 7c) and average friction velocity $\sim 0.003 ms^{-1}$ (Fig. 5a), the ratio of the Ozmidov length scale [$L_0 = (\epsilon/N^3)^{1/2}$] to Kolmogorov length scale [$\eta = (\nu^3/\epsilon)^{1/4}$] [$I = L_0/\eta = (\epsilon/\nu N^2)^{3/4}$] was ~ 1000 , which is much less than 3000, as required for stratification to influence anisotropy (Bluteau et al. 2011).

A combination of measurements and methodological errors can result in scatter in the dissipation estimates.

FIG. 12. Spectral density of ADV velocity measurements at 1 m above the bed on days 123.39 (dashed-dotted line) and 122.51 (solid line). The dashed line shows the inertial subrange $-5/3$ slope.

In case of an oscillating flow (Fig. 1), IDM and log law have error of 40% and 66%, respectively, in comparison to the LES, with RMSE $\sim 10^{-10} W kg^{-1}$ (Table 2). When measurement error is included, the percentage ranges between 72% and 436% for the TMM and IDM, with RMSE $\sim 10^{-9} W kg^{-1}$. The errors are larger in the laminar phases ($0^\circ < \phi < 90^\circ$ and $180^\circ < \phi < 270^\circ$, where ϕ is phase) before the turbulent bursts during the deceleration phases ($90^\circ < \phi < 180^\circ$ and $270^\circ < \phi < 360^\circ$; Akhavan et al. 1991). These benchmarks against numerical simulations may be applied to better interpret the accuracy of the results from the present study. Here, we compare against the mean of the observational realizations $(\epsilon_{IDM} + \epsilon_{TMM} + \epsilon_{SFA})/3$, which appear convergent (Fig. 6 and Table 2). Error ranges from 4% to 51%, with RMSE from $\sim 10^{-8}$ to $\sim 10^{-7} W kg^{-1}$ while log law remains least accurate. From these comparisons we may ascertain that method errors can be as low as $\sim 10^{-10} W kg^{-1}$ (Table 2). This is a negligible level, as it is close to the noise floor for the TMM applied to SCAMP data (J. Imberger 2004, personal communication). Adding measurement error results in an order of magnitude increase in RMSE.

Comparison with DNS and LES has shown that methodological errors can be reduced by anisotropy

TABLE 2. Dissipation error analysis. The top section shows an evaluation of method and measurement error between dissipation computed from the large-eddy simulations (ε^{LES}) and other methods shown in Fig. 1. The bottom section shows an evaluation of relative error from dissipation estimates in the present study.

Dissipation estimate (Fig. 1)	RMSE (W kg^{-1})	Error (%)	Error in laminar phases (%)	Error in turbulent phases (%)
$\varepsilon_{\text{IDM}}^{\text{LES}}$ vs ε^{LES} (Method error)	5.2×10^{-10}	40	61	15
$\varepsilon_L^{\text{LES}}$ vs ε^{LES} (Method error)	7.8×10^{-10}	66	83	47
$\varepsilon_{\text{IDM}}^{\text{RDI}}$ vs ε^{LES} (Measurement and method error)	2.8×10^{-9}	436	640	54
$\varepsilon_{\text{IDM}}^{\text{Nortek}}$ vs ε^{LES} (Measurement and method error)	2.1×10^{-9}	74	80	62
$\varepsilon_{\text{TMM}}^{\text{SeaBird}}$ vs ε^{LES} (Measurement and method error)	1.9×10^{-9}	72	75	55
Dissipation estimate (this study)	RMSE (W kg^{-1})	Error (%)		
ε_{SFA} vs. $[(\varepsilon_{\text{IDM}} + \varepsilon_{\text{TMM}} + \varepsilon_{\text{SFA}})/3]$ (Measurement and method error)	1.5×10^{-7}	22		
ε_{IDM} vs. $[(\varepsilon_{\text{IDM}} + \varepsilon_{\text{TMM}} + \varepsilon_{\text{SFA}})/3]$ (Measurement and method error)	3.2×10^{-8}	4		
ε_{TMM} vs. $[(\varepsilon_{\text{IDM}} + \varepsilon_{\text{TMM}} + \varepsilon_{\text{SFA}})/3]$ (Measurement and method error)	1.2×10^{-7}	21		
ε_L vs. $[(\varepsilon_{\text{IDM}} + \varepsilon_{\text{TMM}} + \varepsilon_{\text{SFA}})/3]$ (Measurement and method error)	3.9×10^{-7}	51		

adjustment with regard to the flow conditions (Jabbari et al. 2015, 2016). Using field measurements, this study showed that application of anisotropy-adjusted constants in the SFM can result in higher dissipation values, which are closer to those from IDM and TMM, and consequently reduce the discrepancy between different methods (Table 1). For example, the mean standard deviation at 1m above the bed decreases from $\sim 6.41 \times 10^{-6}$ and $3.87 \times 10^{-9} \text{ W kg}^{-1}$ in Figs. 5c and 8, respectively, using canonical constants to $\sim 4.13 \times 10^{-6}$ and $1.01 \times 10^{-9} \text{ W kg}^{-1}$, respectively, using anisotropy-adjusted constants. In general, it is recommended that anisotropy-adjusted coefficients be applied when $z^+ < \sim 10000$ (Jabbari et al. 2016), leading to significant changes (improvements) in near-bed estimation of dissipation.

In conclusion, because the observed dissipation cannot be obtained directly from the dissipation tensor (e.g., as in DNS) and there is no “true” observational value to which various methods, each with inherent assumptions and limitations, may be compared. As a consequence, we must rely on assessing accuracy through intercomparing our results in the context of the underlying physics. Our results show that the log law overestimates the dissipation close to the boundary with unreliable differences as large as one order of magnitude in comparison to the other methods. The dissipation from the structure function, using isotropy adjusted constants, increased by a factor of 6 or more close to the bed and showed improved agreement in comparison to dissipation from microstructure and inertial fitting. We can conclude that, when carefully applied, the isotropy-adjusts structure function, microstructure

and inertial fits provide estimates of dissipation that converge to within $\sim 20\%$ of each other.

Acknowledgments. The authors thank Ram Yerubandi at Environment and Climate Change Canada and the captain and crews the Limnos for deploying the instruments in Lake Erie. This research was funded by an NSERC Discovery Grant to LB.

REFERENCES

- Akhavan, R., R. D. Kamm, and A. H. Shapiro, 1991: An investigation of transition to turbulence in bounded oscillatory Stokes flows. Part 2. Numerical simulations. *J. Fluid Mech.*, **225**, 423–444, <https://doi.org/10.1017/S0022112091002112>.
- Bluteau, C. E., N. L. Jones, and G. N. Ivey, 2011: Estimating turbulent kinetic energy dissipation using the inertial subrange method in environmental flows. *Limnol. Oceanogr. Methods*, **9**, 302–321, <https://doi.org/10.4319/lom.2011.9.302>.
- , S.-L. Smith, G. N. Ivey, T. L. Schlosser, and N. L. Jones, 2016: Assessing the relationship between bed shear stress estimates and observations of sediment resuspension in the ocean. *20th Australasian Fluid Mechanics Conf.*, Perth, Australia, Australasian Fluid Mechanics Society.
- Boegman, L., and G. N. Ivey, 2009: Flow separation and resuspension beneath shoaling nonlinear internal waves. *J. Geophys. Res.*, **114**, C02018, <https://doi.org/10.1029/2007JC004411>.
- , M. R. Loewen, P. F. Hamblin, and D. A. Culver, 2001: Application of a two-dimensional hydrodynamic reservoir model to Lake Erie. *Can. J. Fish. Aquat. Sci.*, **58**, 858–869, <https://doi.org/10.1139/f01-035>.
- Bouffard, D., and L. Boegman, 2013: A diapycnal diffusivity model for stratified environmental flows. *Dyn. Atmos. Oceans*, **61–62**, 14–34, <https://doi.org/10.1016/j.dynatmoce.2013.02.002>.
- , —, and Y. R. Rao, 2012: Poincaré wave induced mixing in a large lake. *Limnol. Oceanogr.*, **57**, 1201–1216, <https://doi.org/10.4319/lo.2012.57.4.1201>.

- , J. D. Ackerman, and L. Boegman, 2013: Factors affecting the development and dynamics of hypoxia in a large shallow stratified lake: Hourly to seasonal patterns. *Water Resour. Res.*, **49**, 2380–2394, <https://doi.org/10.1002/wrcr.20241>.
- Cannon, D. J., and C. D. Troy, 2018: Observations of turbulence and mean flow in the low-energy hypolimnetic boundary layer of a large lake. *Limnol. Oceanogr.*, **63**, 2762–2776, <https://doi.org/10.1002/lno.11007>.
- Doron, P., L. Bertuccioli, J. Katz, and T. R. Osborn, 2001: Turbulence characteristics and dissipation estimates in the coastal ocean bottom boundary layer from PIV data. *J. Phys. Oceanogr.*, **31**, 2108–2134, [https://doi.org/10.1175/1520-0485\(2001\)031<2108:TCADEI>2.0.CO;2](https://doi.org/10.1175/1520-0485(2001)031<2108:TCADEI>2.0.CO;2).
- Grant, W. D., and O. S. Madsen, 1979: Combined wave and current interaction with a rough bottom. *J. Geophys. Res.*, **84**, 1797–1808, <https://doi.org/10.1029/JC084iC04p01797>.
- , and —, 1986: The continental-shelf bottom boundary layer. *Annu. Rev. Fluid Mech.*, **18**, 265–305, <https://doi.org/10.1146/annurev.fl.18.010186.001405>.
- Huntley, D. A., 1988: A modified inertial dissipation method for estimating seabed stresses at low Reynolds numbers, with application to wave/current boundary layer measurements. *J. Phys. Oceanogr.*, **18**, 339–346, [https://doi.org/10.1175/1520-0485\(1988\)018<0339:AMIDMF>2.0.CO;2](https://doi.org/10.1175/1520-0485(1988)018<0339:AMIDMF>2.0.CO;2).
- , and D. G. Hazen, 1988: Seabed stresses in combined wave and steady flow conditions on the Nova Scotia continental shelf: Field measurements and predictions. *J. Phys. Oceanogr.*, **18**, 347–362, [https://doi.org/10.1175/1520-0485\(1988\)018<0347:SSICWA>2.0.CO;2](https://doi.org/10.1175/1520-0485(1988)018<0347:SSICWA>2.0.CO;2).
- Imberger, J., 1998: Flux paths in a stratified lake: A review. *Physical Processes in Lakes and Oceans*, J. Imberger, Ed., Coastal and Estuarine Studies, Vol. 54, Amer. Geophys. Union, 1–18.
- Ivey, G. N., and F. M. Boyce, 1982: Entrainment by bottom currents in Lake Erie. *Limnol. Oceanogr.*, **27**, 1029–1038, <https://doi.org/10.4319/lno.1982.27.6.1029>.
- Jabbari, A., 2015: Analysis of idealized numerical simulations to calibrate and validate boundary layer models. Ph.D. thesis, Queen's University, 148 pp.
- , L. Boegman, and U. Piomelli, 2015: Evaluation of the inertial dissipation method within boundary layers using numerical simulations. *Geophys. Res. Lett.*, **42**, 1504–1511, <https://doi.org/10.1002/2015GL063147>.
- , A. Rouhi, and L. Boegman, 2016: Evaluation of the structure function method to compute turbulent dissipation within boundary layers using numerical simulations. *J. Geophys. Res. Oceans*, **121**, 5888–5897, <https://doi.org/10.1002/2015JC011608>.
- Keating, A., U. Piomelli, K. Bremhorst, and S. Nešić, 2004a: Large-eddy simulation of heat transfer downstream of a backward-facing step. *J. Turbul.*, **5**, N20, <https://doi.org/10.1088/1468-5248/5/1/020>.
- , —, E. Balaras, and H.-J. Kaltenbach, 2004b: A priori and a posteriori tests of inflow conditions for large-eddy simulation. *Phys. Fluids*, **16**, 4696–4712, <https://doi.org/10.1063/1.1811672>.
- Kundu, P. K., and I. M. Cohen, 2002: *Fluid Mechanics*. Academic Press, 759 pp.
- Lorke, A., 2007: Boundary mixing in the thermocline of a large lake. *J. Geophys. Res.*, **112**, C09019, <https://doi.org/10.1029/2006JC004008>.
- , and A. Wüest, 2005: Application of coherent ADCP for turbulence measurements in the bottom boundary layer. *J. Atmos. Oceanic Technol.*, **22**, 1821–1828, <https://doi.org/10.1175/JTECH1813.1>.
- , and S. MacIntyre, 2009: Hydrodynamics and mixing in lakes, reservoirs, wetlands, and rivers. *Encyclopedia of Inland Waters*, G. E. Likens, Ed., Elsevier, 505–514.
- , L. Umlauf, T. Jonas, and A. Wüest, 2002: Dynamics of turbulence in low-speed oscillating bottom-boundary layers of stratified basins. *Environ. Fluid Mech.*, **2**, 291–313, <https://doi.org/10.1023/A:1020450729821>.
- McGinnis, D. F., S. Sommer, A. Lorke, R. N. Glud, and P. Linke, 2014: Quantifying tidally driven benthic oxygen exchange across permeable sediments: An aquatic eddy correlation study. *J. Geophys. Res. Oceans*, **119**, 6918–6932, <https://doi.org/10.1002/2014JC010303>.
- Monin, A. S., and A. M. Yaglom, 1975: *Statistical Fluid Mechanics: Mechanics of Turbulence*. Vol. 2. MIT Press, 874 pp.
- Munk, W. H., 1966: Abyssal recipes. *Deep-Sea Res. Oceanogr. Abstr.*, **13**, 707–730, [https://doi.org/10.1016/0011-7471\(66\)90602-4](https://doi.org/10.1016/0011-7471(66)90602-4).
- Pope, S. B., 2000: *Turbulent Flows*. Cambridge University Press, 771 pp.
- Rao, Y. R., N. Hawley, M. N. Charlton, and W. M. Schertzer, 2008: Physical processes and hypoxia in the central basin of Lake Erie. *Limnol. Oceanogr.*, **53**, 2007–2020, <https://doi.org/10.4319/lno.2008.53.5.2007>.
- Saddoughi, S. G., and S. V. Veeravalli, 1994: Local isotropy in turbulent boundary layers at high Reynolds number. *J. Fluid Mech.*, **268**, 333–372, <https://doi.org/10.1017/S0022112094001370>.
- Sarkar, S., 2003: The effect of stable stratification on turbulence anisotropy in uniformly sheared flows. *Comput. Math. Appl.*, **46**, 639–646, [https://doi.org/10.1016/S0898-1221\(03\)90022-8](https://doi.org/10.1016/S0898-1221(03)90022-8).
- Sauvageot, H., 1992: *Radar Meteorology*. Artech House, 366 pp.
- Scalo, C., U. Piomelli, and L. Boegman, 2012: High-Schmidt-number mass transport mechanisms from a turbulent flow to absorbing sediments. *Phys. Fluids*, **24**, 085103, <https://doi.org/10.1063/1.4739064>.
- Scavia, D., and Coauthors, 2014: Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. *J. Great Lakes Res.*, **40**, 226–246, <https://doi.org/10.1016/j.jglr.2014.02.004>.
- Schwefel, R., M. Hondzo, A. Wüest, and D. Bouffard, 2017: Scaling oxygen microprofiles at the sediment interface of deep stratified waters. *Geophys. Res. Lett.*, **44**, 1340–1349, <https://doi.org/10.1002/2016GL072079>.
- Townsend, A. A., 1976: *The Structure of Turbulent Shear Flow*. 2nd ed. Cambridge University Press, 440 pp.
- Troy, C., D. Cannon, Q. Liao, and H. Bootsma, 2016: Logarithmic velocity structure in the deep hypolimnetic waters of Lake Michigan. *J. Geophys. Res. Oceans*, **121**, 949–965, <https://doi.org/10.1002/2014JC010506>.
- Valipour, R., D. Bouffard, and L. Boegman, 2015a: Parameterization of bottom mixed layer and logarithmic layer heights in central Lake Erie. *J. Great Lakes Res.*, **41**, 707–718, <https://doi.org/10.1016/j.jglr.2015.06.010>.
- , —, —, and Y. R. Rao, 2015b: Near-inertial waves in Lake Erie. *Limnol. Oceanogr.*, **60**, 1522–1535, <https://doi.org/10.1002/lno.10114>.
- , L. Boegman, D. Bouffard, and Y. R. Rao, 2017: Sediment resuspension mechanisms and their contributions to high-turbidity events in a large lake. *Limnol. Oceanogr.*, **62**, 1045–1065, <https://doi.org/10.1002/lno.10485>.
- Wiles, P. J., T. P. Rippeth, J. H. Simpson, and P. J. Hendricks, 2006: A novel technique for measuring the rate of turbulent dissipation in the marine environment. *Geophys. Res. Lett.*, **33**, L21608, <https://doi.org/10.1029/2006GL027050>.
- Yuan, J., and U. Piomelli, 2014: Numerical simulations of sink-flow boundary layers over rough surfaces. *Phys. Fluids*, **26**, 015113, <https://doi.org/10.1063/1.4862672>.
- Zulberti, A. P., G. N. Ivey, and N. L. Jones, 2018: Observations of near-bed stress beneath nonlinear internal wave trains in the ocean. *Proc. 21st Australasian Fluid Mechanics Conf.*, Adelaide, Australia, Australasian Fluid Mechanics Society.