Estimating oxygen exchange across the air–water interface of a hypereutrophic lake

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Abstract

Patterns of estimates of oxygen flux (J) across the air–water interface of hypereutrophic Onondaga Lake, NY, U.S.A., are characterized for time scales ranging from diel to seasonal for an 8-month period. The analysis is supported by a high frequency (most often hourly) monitoring program, conducted with a robotic buoy, that included measurements of dissolved oxygen (DO), temperature, and fluorometric chlorophyll a in the lake’s surface waters, vertical profiles of DO through the epilimnion, and wind speed and solar radiance. The magnitude and direction of J is demonstrated to vary dramatically at diel, day-to-day, and seasonal time scales. Thus, large errors in estimates of J may result from extrapolating flux calculations made from short-term data to longer time periods. The variations in J were driven by variations in metabolic activity and meteorology, and were mediated by departures from equilibrium DO concentrations and wind-driven turbulence. Extended periods of high J values are shown to coincide with intervals of large departures from equilibrium DO concentrations, but day-to-day differences are driven mostly by variations in wind. A distinct diel pattern of J estimates is manifested for average conditions, with substantially higher J values during daylight hours. This pattern reflects the common diel patterns of the drivers of both higher DO oversaturation and wind speed over those hours. It is demonstrated that the magnitude of J is substantial relative to net changes in the epilimnetic DO pool, and thus must be accommodated accurately in estimates of primary production and community respiration that are to be based on diel monitoring of DO in the water columns of productive lakes.

Introduction

The exchange of gases across the air–water interface is important in regulating concentrations of various constituents of ecological and water quality concern (Broecker et al., 1980; Thomann & Mueller, 1987; Wanninkhof et al., 1991). This flux modulates deviations from equilibrium concentrations in surface waters of various relatively insoluble gases, including oxygen. The process has received particular attention in streams and rivers impacted by oxygen-demanding wastes, as a compensating source of oxygen (O’Connor, 1983; Thomann & Mueller, 1987). Oxygen exchange at the air–water interface is also important for lakes related to: (1) the need to accommodate this flux in estimating metabolic rates (primary production and community respiration) from changes in the dissolved oxygen (DO) pool (Vollenweider, 1974), (2) recovery from severe DO depletion in the upper waters of certain lakes (Gelda et al., 1996), and (3) support for mass balance calculations and models (Gelda & Auer, 1996).

The flux of DO at the air–water interface (J; g·m⁻²·d⁻¹) has been quantified according to

\[ J = K_L \cdot (C_s - C) \]  

where \( K_L \) is the liquid film transfer coefficient for oxygen (m·d⁻¹), \( C_s \) is the equilibrium, or saturation,
concentration of DO \( \text{g} \cdot \text{m}^{-3} \), and \( C \) is the DO concentration in the water proximate to the interface \( \text{g} \cdot \text{m}^{-3} \). Accordingly, oxygen is lost to the atmosphere when the upper waters are oversaturated \( C_s < C \), and inputs from the atmosphere (reaeration) occur when \( C_s > C \). The liquid side of the air–water interface controls exchange for substances such as oxygen that have low solubility and high vapor pressure (O'Connor, 1983). The accuracy of estimates of \( J \) depends on the accuracies of the specifications of the mass transfer coefficient, \( K_L \), and \( C_s \) and \( C \).

The value of \( K_L \) is regulated by internal turbulence, which in lakes is driven primarily by wind speed \( U \) (m/s); O'Connor, 1983. A number of expressions have been developed to estimate \( K_L \) for lakes and reservoirs from \( U \) (O'Connor, 1983; Bowie et al., 1985; Daniil & Gulliver, 1991; Gelda et al., 1996). The value of \( C_s \) is well specified by water temperature \( T \), salinity and pressure (elevation; APHA, 1992). Dynamics in \( C_s \) are driven primarily by changes in \( T \) in surface waters. Unlike the case for carbon dioxide for which substantial variations in overlying atmospheric concentrations, and thereby surface water equilibrium concentrations, can develop above productive lakes during intervals of low wind speed (Sellers et al., 1995), atmospheric concentrations of oxygen are not subject to substantial variations. However, substantial variations in \( C \) occur in the upper waters of productive lakes at time scales ranging from diel to seasonal associated with primary production and community respiration, that represent strong deviations from equilibrium concentrations (Wetzel, 2001). Variations in the extent of departure of surface DO concentrations from equilibrium \( C_s–C \), and \( U \), drive the dynamics of \( J \) [Equation (1)]. Recurring diel patterns are well known for \( C \) (Vollenweider, 1974) and have been demonstrated for \( U \) (Stauffer, 1980), suggesting \( J \) may also have a diel structure. Sellers et al. (1995) demonstrated with a data set of high frequency measurements for carbon dioxide and wind speed that large errors could result by extrapolating flux estimates for this gas from short-term data (e.g., daily) to longer intervals (e.g., weekly). Data sets necessary to support resolution of short-term patterns of \( J \) have generally not been available, particularly for \( C \), because of logistical problems and high costs. The advent of reliable remote monitoring devices has made these high frequency data sets more practical to collect (Bretts, 1998). This technology offers the opportunity to investigate the implications of frequency of measurements for quantifying \( J \) and its role in the overall oxygen budget of lakes.

This paper presents estimates of \( J \) for a hypertrophic lake for time scales ranging from diel to seasonal for an eight-month period. Time-series of supporting high frequency measurements of \( T \) and \( C \) for the near-surface waters of the lake, changes in the DO pool of the epilimnion, and \( U \) above the lake, are documented. Corresponding estimates of \( K_L \), \( C_s–C \), and \( J \) are presented for this period. Temporal patterns and variability of the measurements and estimates are characterized. The implications of the frequency of measurements for the estimates, and the relative roles of variations in \( C_s–C \) versus \( K_L \) (i.e., \( U \)) in driving the dynamics of \( J \), are described. The importance of the flux of oxygen at the air–water interface relative to the dynamics of the epilimnetic DO pool of the lake is demonstrated and discussed in the context of supporting estimates of metabolic rates.

**Methods**

**Test system**

Onondaga Lake is a hardwater alkaline, dimictic system, located in metropolitan Syracuse, NY. The lake has a volume of \( 131 \times 10^6 \text{ m}^3 \), a surface area of 12.0 km\(^2\), a mean depth of 10.9 m and a maximum depth of 19.5 m. The lake has two basins and a single outlet, and is largely unsheltered from wind driven turbulence. Onondaga Lake was oligo-mesotrophic before European settlement in the late 1700s (Rowell, 1996). The lake’s watershed (642 km\(^2\)) presently includes a population of \( \sim 450000 \).

Onondaga Lake is presently hypertrophic because of the very high phosphorus (P) loads received from an adjoining domestic wastewater treatment plant (Effler et al., 1996). The vast majority of the lake’s primary production is associated with phytoplankton, as rooted macrophyte growth in the lake is very limited (Madsen et al., 1996). Recurring manifestations of the lake’s hypertrophy include: (1) high concentrations of P (Connors et al., 1996), (2) occurrence of severe phytoplankton blooms (Matthews et al., 2001), (3) limited light penetration (Perkins & Effler, 1996), (4) rapid loss of DO from the hypolimnion (Effler et al., 1996), (5) subsequent accumulation of reduced by-products of anaerobic metabolism (Addess & Effler, 1996; Effler et al., 1988), and (6) severe lake-wide depletion of DO during the fall mixing period associated with the oxidation of these by-products (Gelda & Auer, 1996). Exodus of a large