Journal of Marine Systems 77 (2009) 397–408

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

A novel method for estimating vertical eddy diffusivities using diurnal signals with application to western Long Island Sound

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ARTICLE INFO

Article history:
Received 3 October 2007
Received in revised form 28 May 2008
Accepted 29 October 2008
Available online 6 November 2008

Regional terms:
USA
Northeast
Long Island Sound
Connecticut
New York

Keywords:
Dissolved oxygen
Eddy diffusivity
Hypoxia
Temperature
Turbulence measurement
Vertical mixing

ABSTRACT

We present an approach that allows the estimation of vertical eddy diffusivity coefficients from buoy measurements made at two or more depths. By measuring the attenuation and phase lag of a scalar signal generated periodically at the surface as it propagates downwards, the vertical eddy diffusivity coefficients can be calculated as $K_v = \omega\Delta z^2/2\ln^2(\alpha_2/\alpha_1)$, where α_2/α_1 is the ratio of the real amplitudes at frequency ω at the two depths separated by $\Delta z = z_2 - z_1$; as $K_V = \omega\Delta z^2/2\varphi^2$, where φ is the phase lag at the frequency ω; or as $K_v = i\omega\Delta z^2/\ln^2(U_2/U_1)$, where U_2/U_1 is the ratio of the complex signal amplitudes at the two depths. The method requires that horizontal fluxes be small at the ω frequency and that the signal-to-noise ratios at the two depths allow the determination of the amplitude and phase of ω.
Application of this method to summertime 2004 western Long Island Sound oxygen and temperature buoy measurements at two depths provides a time-series of two-day average vertical eddy diffusivity estimates. Using these eddy diffusivities in conjunction with measured vertical concentration gradients, we obtain a time-series of vertical transport rates for oxygen and heat and estimate mean downward fluxes for June and July as 150–260 mMol m^{-2} day^{-1} and 100–400 W m^{-2} respectively. These estimates are of a similar magnitude to sub-pycnocline O_2 and heat demands of 240 ± 200 mMol m^{-2} day^{-1} and 180 ± 60 W m^{-2} that we infer from simple budgets, implying that vertical transport is significant to both budgets.
The eddy coefficients obtained from the independent O_2 and temperature measurements have a 68% correlation, and the O_2 flux estimates show a correlation of 41% to measured rates of change in bottom dissolved oxygen levels. Our results indicate that extended time-series of eddy diffusivity coefficients can be obtained from in situ buoy measurements and the method shows promise as a way to constrain the vertical transport variability in budgets of dissolved materials in estuaries.

1. Background

Western Long Island Sound (LIS) bottom waters experience low dissolved oxygen (DO) levels in the summertime. This seasonal hypoxia is identified as a problem of special concern for the environmental management of the region. (NYDEC and CTDEP, 2000) Understanding the factors controlling the duration and extent of this summertime hypoxia in western Long Island Sound is also essential for the ecological modeling that guides environmental management. The seasonal rate of decline in DO levels is not constant, however, and there are intermittent increases in bottom DO levels that occur throughout the summer. (O'Donnell et al., 2008) Furthermore, measured rates of DO consumption would create anoxic conditions within 13–30 days whereas the observed rate of decline is on the order of 100 days. (Torgersen et al., 1997) This indicates that there is a positive flux of DO into western LIS bottom waters. Due to the turbidity of LIS, there is no internal O_2 production in bottom waters, so any flux of DO into western LIS bottom waters must be due to physical transport. Observations suggest that in

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doi:10.1016/j.jmarsys.2008.10.011

2004 the rate of decline of DO was influenced by synoptic scale variability in the vertical O_2 fluxes caused by physical mixing. (O'Donnell et al., 2008) Unfortunately, available technology is not capable of the direct measurement of these fluxes continuously for the several months needed to resolve this variability and quantitatively assess its role in determining seasonal trends.

Since 2004, the University of Connecticut has operated a network of buoys measuring water quality parameters in western LIS as part of the Long Island Sound Integrated Coastal Observing System (LISICOS). This system provides near-continuous high frequency observations of temperature, salinity, and DO at several depths that are suitable for the signal analysis methodology proposed herein. The Execution Rocks (EX) buoy is located in 22.6 m of water at the far end of western LIS near Execution Rocks at 40.88 N 73.73 W with YSI 6920 sensor packages located at −0.75 m, −7.5 m, and −15.5 m depths logging DO, temperature, and salinity. The western Sound (WS) buoy is moored in 19.8 m of water at 40.96 N 73.58 W with sensors at similar depths. Unfortunately, the mid-depth sensor of the WS buoy malfunctioned and did not provide data for 2004 making its record unsuitable for the eddy diffusivity estimation method outlined herein. We were, however, able to use its bottom record to calculate the horizontal gradients used in Section 4. Fig. 1 shows the locations of the EX and WS buoys.

Long Island Sound is close to resonance with the semidiurnal tidal constituents. Tidal height amplitudes increase and current amplitudes decrease towards the western end. Tides at EX are predominately M_2 with a mean range of 2.2 m. Fig. 2 shows the EX $[O_2]$ and temperature records from the surface and bottom sensors for the summer of 2004. The gap in the record in early August is a period during which the buoy data was unavailable. Our flux analysis will focus on the June and July portion of the record when the summertime DO decline occurs.

Fig. 2 clearly shows intermittent periods of bottom $[O_2]$ increases indicating significant horizontal and/or vertical transport fluxes at these times. O'Donnell et al. (2008) reason that if these increases were due to along-Sound transport, there would be contemporaneous decreases in bottom temperatures and increases in salinity since oxygenated eastern waters are colder and saltier; if, however, these increases were due to vertical mixing there would be corresponding increases in bottom temperatures and decreases in salinity since oxygenated surface waters are warmer and fresher. They find that in the vast majority of the 2004 DO increases there is also a temperature increase and salinity decrease, indicating that the majority of O_2 transport into western LIS bottom waters is likely due to vertical fluxes across the pycnocline. Measurements by Aller (1994) and Goebel and Kremer (2007) suggest a biological oxygen demand in the lower water column of $16 \pm 14\ \mu M\ day^{-1}$. This is similar to the maximal rates of decline seen in the 2004 buoy record. The intermittent $[O_2]$ increases observed in the buoy record are on the order of 20–50 $\mu M\ day^{-1}$, implying that the transport events provide a flux on the order of 500–1000 $mMol\ m^{-2}\ day^{-1}$ to the lower water column. Vertical $[O_2]$ gradients between the surface and the lower depths are on the order of 3–15 $\mu M\ m^{-1}$. If we assume that the $[O_2]$ increases are primarily due to vertical mixing, then these figures imply vertical eddy diffusivities for these transport events in the range of $4 \cdot 10^{-4}$ to $4 \cdot 10^{-3}\ m^2\ s^{-1}$ with diffusivities at other times below these values.

It is evident that vertical mixing is an important component of the bottom DO and heat budgets and that measurements of vertical eddy diffusivities should be

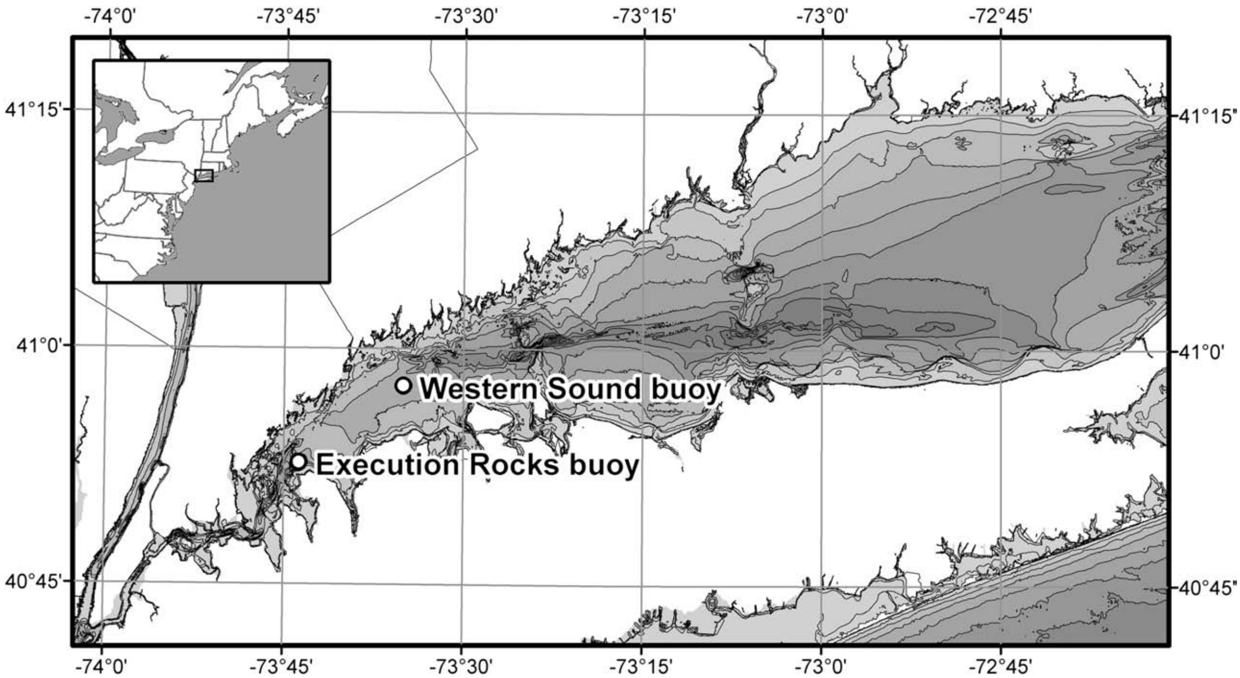

Fig. 1. EX and WS buoy locations. Bathymetry is contoured at 5 m intervals. Inset shows the location of LIS on the east coast of the United States.