PHYSICAL MECHANISMS LEADING TO HYPOXIA AND ANOXIA IN WESTERN LONG ISLAND SOUND

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Increased thermal and saline stratification during the summer exacerbate low dissolved oxygen (DO) concentrations in western Long Island Sound (WLIS). Occasionally, as in the summer of 1987, DO is depleted from the water column. In this study, the interaction of thermal and saline stratification and their influence on vertical mixing and DO concentrations in WLIS is elucidated. Diagnostic calculations involving a specified longitudinal density gradient are performed using a simple one-dimensional (vertical) mixed layer model. Numerical experiments are carried out under typical hydrographic, hydrodynamic, and atmospheric summer conditions in WLIS. Results illustrate intratidal and fortnightly variations of the vertical structure of density and DO subject to biological consumption. Modifications to the summer longitudinal density gradient in WLIS produce important changes to its hydrodynamic field and its water quality. Therefore, proposed water withdrawal from the Hudson River should be considered carefully.

INTRODUCTION

In semi-enclosed bodies of water, vertical mixing processes contribute to the exchange of properties between near-surface and near-bottom waters. This exchange tends to be inhibited by the development and strengthening of density stratification. In western Long Island Sound (WLIS) (Fig. 1), an extended period of stratification during the summer months isolates near-surface waters from those near the bottom through the development of a strong pycnocline (Jay and Bowman 1975). The prolonged stratification of the water column combined with biological and chemical processes can produce hypoxia below the pycnocline. Hypoxia is reached when dissolved oxygen concentrations (DO) are lower than 3 mg/L, thus, inducing stress or death on organisms. Hypoxia, according to the Long Island Sound Study (1990), is the most demanding priority problem in LIS because of its potential impact on the living resources. During late July and August of 1987, the hypoxia problem was so severe that DO was depleted (anoxia) from WLIS's bottom waters.

Western Long Island Sound communicates with the lower Hudson estuary through the East River tidal strait (Fig. 1). Longitudinal density gradients in WLIS drive a gravitational circulation with characteristic velocities on the order of 0.05 m/s (Riley 1952). Tidal currents with rms amplitude of approximately 0.30 m/s (Vieira 1990) contribute to vertical mixing below the halocline. Winds can produce significant surface mixing that
occasionally deepens or destroys the pycnocline. During the spring months reduced wind-induced mixing and increased surface heating contribute to thermal stratification and reduced vertical mixing in the interior of the water column. The brackish inflow from the East River and the fresh water discharge from sewage treatment plants in the area reinforce saline stratification. Fresh water inflow (via the Hudson River and treatment plants) also tends to strengthen the gravitational circulation in the system thus enhancing near-bottom water advection from eastern portions of the Sound.

Conditions that lead to hypoxia in WLIS are as follows. After heavy rains, sewage treatment plants are bypassed allowing water with large amounts of nitrogenated nutrients to enter WLIS. During the spring, these added nutrients enhance phytoplankton blooms which produce oxygen through photosynthesis. Dissolved oxygen starts decreasing near the bottom with the development of a halocline from the spring freshet. The onset of surface heating strengthens stratification; the developing pycnocline restricts surface DO from getting to the bottom. Below the pycnocline, DO is consumed by respiration and organic decomposition causing hypoxic conditions. These conditions are exacerbated by the decomposition of the organisms that thrived near the surface as a consequence of the spring eutrophication.

The objective of this paper is to explore a possible scenario of mechanisms that lead to lower-than-normal DO concentrations in WLIS. A specified longitudinal density gradient, surface heating and bottom tidal stress are combined in a simple one-dimensional (vertical) mixed-layer model that solves for DO concentrations.

PROCEDURE

To describe the transient behavior of [DO], a one-dimensional (vertical) mixed-layer numerical model is used. This model solves the momentum, temperature, salinity, and oxygen equations. The values of the horizontal velocity components $u$, $v$ (m/s), salinity $S$, temperature $T$ (°C), density $\rho$ (kg/m³), and dissolved oxygen $DO$ (mg/L), are estimated as a function of depth $z$ (positive upwards) and time $t$ at one vertical station with depth $H = 20$ m and subdivided into 30 equally spaced levels. The dynamic balances are evaluated in a rotating earth (Coriolis parameter, $f = 9 \times 10^{-5}$ s⁻¹) with time- and depth-varying turbulent (eddy) coefficients [$A_v$, $A_{vO}$, $A_D$, $A_T$ (m²/s)] obtained from closure (Mellor and Durbin 1975). The horizontal density and DO gradients are prescribed in light of hydrographic observations (Subramanian and Bokuniewicz 1991). They are chosen to be constant with depth and time.

Governing equations

The momentum balance includes a barotropic and a baroclinic pressure gradient in the along-channel direction $x$ and vertical mixing (vertical transfer of horizontal momentum):

$$ \frac{\partial \vec{U}}{\partial t} + \vec{u} \cdot \nabla \vec{U} = - \frac{\nabla P}{\rho_0} - f \vec{v} \times \vec{U} + \nabla \cdot \left( \vec{A} \cdot \nabla \vec{U} \right) $$

$\vec{U}$ is the velocity vector with components $u$ (along channel) and $v$ (across channel); $\Omega$ is the earth's angular velocity (s⁻¹); $\eta$ is the surface elevation; $g$ is the acceleration due to earth's gravity (9.8 m/s²), $\rho_0$ is an average value of the density $\rho$; and $A_v$ is the eddy diffusivity of momentum and is estimated according to the turbulence closure formulation of Mellor and Durbin (1975).

Transient $T$ and $S$ are determined by a balance between vertical mixing and horizontal advection with horizontal gradients specified to be constant with depth and time:

$$ \frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = \frac{\partial}{\partial z} \left( A_v \frac{\partial C}{\partial z} \right) $$

where C indicates the property of interest, i.e., $T$ or $S$, and $A_v$ represents the vertical eddy diffusivity coefficient. In this study, the vertical eddy diffusivity of heat, $A_v$, equals the vertical eddy diffusivity of salt, $A_{vO}$. Local density values are obtained from $T$ and $S$. The transient $DO$ behavior is also determined by an advection-mixing equation plus a reaction $R$ representing net degradation of oxygen (production minus consumption) during late summer:

$$ \frac{\partial DO}{\partial t} + v \frac{\partial DO}{\partial z} = \frac{\partial}{\partial z} \left( A_{vO} \frac{\partial DO}{\partial z} \right) + R $$

The vertical eddy diffusivity of oxygen, $A_{vO}$, is taken to be the same as $A_v$ and $A_{vO}$.

Boundary values for the governing equations

For the momentum equation, quadratic surface and bottom shears are specified in the form:

$$ A_v \frac{\partial \vec{U}}{\partial z} = C_{D} \vec{w} \ |\vec{w}| \text{ at the surface; and }$$

$$ A_v \frac{\partial \vec{U}}{\partial z} = C_{g} \vec{U} \ |\vec{U}| \text{ at the bottom.}$$
Fig. 1. Long Island Sound (LIS) location on the eastern coast of the United States.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Heat ( (^\circ \text{C} \cdot \text{m/s}) )</th>
<th>Wind ( (\text{m}^2/\text{s}^2) )</th>
<th>( \Delta S/\Delta x ) (psu/10 km)</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.00002</td>
<td>0</td>
<td>1</td>
<td>Intratidal</td>
</tr>
<tr>
<td>B</td>
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<td>0.00002</td>
<td>1</td>
<td>Intratidal</td>
</tr>
<tr>
<td>C</td>
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<td>0</td>
<td>3</td>
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</tr>
<tr>
<td>D</td>
<td>0.00001</td>
<td>0</td>
<td>1</td>
<td>Fortnight</td>
</tr>
<tr>
<td>E</td>
<td>0.00001</td>
<td>0</td>
<td>3</td>
<td>Fortnight</td>
</tr>
</tbody>
</table>

Table 1. Parameters for the different scenarios simulated.

\( C_D \) is a nondimensional surface drag coefficient (0.0015); \( \rho_a \) is the air's density (1.2 kg/m\(^3\)); \( \vec{w} \) is the wind velocity vector; and \( C_D \) is a nondimensional bottom drag coefficient (0.002).

For temperature, a vertical heat flux \( Q \) is specified at the surface and is negligible at the bottom. For salinity, it is assumed that there are no vertical fluxes of salt at either the air-water interface or the water-sediment interface. For DO, it is assumed to be saturated at the surface and that DO net production is negligible during the summer (Long Island Sound Study (LISS 1990)). Saturation values are estimated from Weiss (1970) for the \( T \) and \( S \) calculated with Eq. 2. The net vertical flux of DO from the water to the sediments obtained by Vigil (1990) for WLIS in August of 1988, is 1000 \( \mu \text{M} \) of \( \text{O}_2 \) per m per day (3.7\( \times \)10\(^4\) mg \( \text{O}_2/\text{L} \cdot \text{m} \cdot \text{s} \)). This value is used at the bottom boundary, i.e., \( A_{\infty} \partial(\text{DO})/\partial z = -3.7 \times 10^4 \) at \( z = -H \).

The following section presents the results from intratidal and from long-term simulations (Table 1). Unless otherwise stated, \( T \) and \( S \) horizontal gradients equal 1\( \times \)10\(^{-4}\) \( ^\circ \text{C} \cdot \text{psu} \)/m, equivalent to a density gradient of 3.9\( \times \)10\(^{-4}\) \( \sigma \)/m, which is comparable to LIS's longitudinal density gradient (Kopelman et al. 1976; Subramaniam and Bokuniewicz 1991). The DO longitudinal gradient equals zero, and surface heat flux equals 0.0002\( ^\circ \text{C} \)/s for intratidal simulations and 0.0001\( ^\circ \text{C} \)/s for fortnightly simulations. Dissolved oxygen net degradation, \( R \), throughout the water column equals 1\( \times \)10\(^{-7}\) mg \( \text{O}_2 \)/L/s. All of the simulations start with vertically homogeneous \( T \) (17\( ^\circ \text{C} \)), \( S \) (27.5) and DO (7 mg/L). For the intratidal simulations, a forcing velocity with \( u \) and \( v \) amplitude components of 0.30 m/s and 0.10 m/s, respectively (Vieira 1990), oscillating at a frequency of 2\( \pi \)/12 h is specified. For the fortnight simulations, \( u \) \( (v) \) is 0.15 (0.05) m/s for both the \( M_1 \) and \( S_2 \) components, respectively. The results from the
intratidal simulations represent the fifth tidal period after four tidal cycles of "spin-up" time. The long-term simulations correspond to tidal cycles #5 to #32, after four tidal cycles of spin-up time.

**RESULTS**

The hydrographic and DO values obtained from the simulations agree with observations of Subramaniam and Bokuniewicz (1991) and Ranheim and Bokuniewicz (1991). Sigma-t at the surface is 17.5, with a stratified upper layer, and 19.5 at the well mixed bottom. Dissolved oxygen is stratified at the surface, with values in the vicinity of 7 mg/L, and well mixed at the bottom with values near 3 mg/L.

**Intratidal simulations**

For scenario A, density is uniform close to the bottom and a pycnocline develops close to the surface (Fig. 2b). The base of the pycnocline is located at ~7 m deep, which coincides with the depth where $A_t$ becomes nonzero, i.e., the upper limit of the vertical mixing range. Near slack periods, tidally induced vertical mixing is weak and the pycnocline migrates...
downward. Surface DO oscillates in time, according to the solubility allowed by $T$ and $S$ variations (Fig. 2b). Near the bottom, DO is well mixed due to vertical mixing and decreases in time due to the sediment oxygen demand. Higher DO values are stratified near the surface.

For scenario B, a surface density mixed layer, $-4$ m deep, develops as a consequence of increased near-surface vertical mixing, relative to scenario A, produced by the wind stress (Fig. 3a). The wind blowing in the direction of cbb tends to strengthen stratification and to weaken near-bottom vertical mixing. It also weakens flood speeds, which results in decreased vertical mixing during those tidal stages relative to scenario A. The pycnocline is weaker than in A and its base is forced downward to a depth of $-11$ m, thus producing a thinner bottom mixed layer than scenario A. Overall DO values are higher in scenario B than A (Fig. 3b) because wind stress induces greater vertical exchange of properties between nearsurface and near-bottom levels. Surface values fluctuate accordingly with the solubility permitted by $T$ and $S$ oscillations. A relatively well developed wind-induced surface DO mixed layer reaches a depth of $-4$ m. A bottom mixed layer ($-6$ m thick) is maintained by tidal mixing.

An increment to $\delta S/\delta z$ (scenario C) simulates additional buoyancy input to the water column up-steam of the station. Tidal mixing is greatly limited by
a thick stratified layer that extends from the surface to ~13 m deep and reaches 16 m at slack water (Fig. 4a). The pycnocline strength increases from 0.2 σ/m (scenario A) to 3 σ/m. The DO stratified layer increases and the layer of minimum oxygen is reduced (Fig. 4b). The DO vertical gradient in the upper layer decreases from 0.18 mg/L.m (scenario A) to 0.09 mg/L.m.

**Long-term simulations**

The long term simulations extend for 28 tidal cycles and feature spring-neap variability. The mean value of each 12-h tidal cycle (tidal residual) is used to represent that period. Scenario D (Table 1) illustrates the enhancement of density stratification due to the water column's buoyancy gain from atmospheric heat input (Fig. 5a). This simulation recreates the fortnight of net heat gain of the last week in July and the first week in August in WLIS. Sigma-t becomes increasingly stratified with time. A bottom-mixed layer of at least 7 m thick at neap periods (tidal cycle #10), when bottom mixing is small, is preserved throughout the fortnight. The bottom-mixed layer becomes thicker at periods of spring tidal stress (cycle #24). Dissolved oxygen decreases with time and depth and becomes strongly stratified toward the end of the fortnight (Fig. 5b).
Bottom DO falls from 6.0 mg/L to -3 mg/L and remains well mixed except at neap tidal periods, when weak bottom stratification occurs.

An increase in δS/δx (scenario E) strengthens the overall stratification of the water column. The bottom density mixed layer is noticeably thinner than in scenario D (Fig. 6a). The concurrence of neap tides with reduced bottom mixing is not as straightforward as before (scenario D). Sigma-t increases markedly near the bottom suggesting an enhancement in the gravitational circulation. The bottom DO mixed layer is considerably reduced and there are no obvious spring-neap changes in its width. The overall DO field does not change much from scenario D except for the increased stratification throughout the water column and the slightly decreased DO values at the end of the fortnight (Fig 6b).

If it is assumed that the longitudinal distribution of DO in WLIS is not uniform and that the longitudinal DO gradient is 1 mg/L/10km under the increased density gradient of scenario E, then [DO] improves. The reinforced gravitational circulation (scenario E) advects near-bottom DO from the eastern, more oxygenated portions (Fig 6c). Bottom [DO] at the end of the fortnight increases from -3 mg/L to -4 mg/L.
DISCUSSION AND CONCLUSIONS

The results from the simulations presented here underscore the importance of different physical processes in determining the dynamics of DO in LIS. Heat input enhances stratification during late summer in WLIS thus increasing the possibility of hypoxic conditions by isolating bottom waters from surface waters with higher \([DO]\).

Large longitudinal salinity (density) gradient, greater than 1/10 km reinforces gravitational circulation. Reinforced gravitational circulation produces both increased exchange with bottom waters from the east, and greater stratification. In the case that hypoxia extends far to the east in LIS, an increased longitudinal density gradient will produce detrimental effects in the \([DO]\) as compared to the conditions with normal density gradient. If more oxygenated waters are found to the east than in WLIS, enhanced gravitational circulation should advect \(DO\) to WLIS. For example, assuming that the increased longitudinal density gradient from a station in WLIS produces a flow of 0.10 m/s and that \([DO]\) increases 1 mg/L/10 km, then \(DO\) would be advected at a rate of 8.64 km/d from the eastern Sound and degraded (by biological and sediment demand), during its transport, at a rate of 0.32 mg/L/d (10 \(\mu\)M/d). The water with higher \(DO\) (10 km to the east) would arrive at the station...
after 1.16 d and decrease by 0.37 mg/L. Therefore, \([\text{DO}]\) would increase approximately by 0.6 mg/L.d at the station. The three-fold increase in the longitudinal S gradient used for scenarios C and E is higher than expected in WLIS. Nonetheless, it illustrates the effects that an eastward increase in the longitudinal density gradient would have on the hydrodynamics and the water quality of this area. Hence, such an increase might be beneficial provided that the source of the increment (warmer water) does not also transport increased nutrient or carbon loads and that \([\text{DO}]\) are higher to the east.

Use of fresh water from the Hudson River would modify stratification and gravitational circulation in WLIS. Haline stratification would be reduced but thermal stratification would still persist and dominate. Also, gravitational circulation would decrease and consequently reduce advection of oxygenated water from the east. Therefore, proposed water withdrawal from the Hudson River should be considered carefully.

Aperiodic strong winds blowing in an east-west direction will provide sufficient vertical flux of momentum to break the summer pycnocline and restrict \([\text{DO}]\) depletion by mixing oxygenated surface waters with oxygen depleted bottom waters. Soon after the mixing period, \([\text{DO}]\) will continue its summer decline. In the New York City metropolitan area, however, summer winds blow predominantly from the south and southwest (Swanson and Zimmer 1990; Swanson and Valley-Levinson 1990), i.e., across WLIS. Therefore, generally, there is not a great enough fetch for the summer winds to develop strong stresses over the surface of WLIS and the water remains stratified.

In the simulations presented here, \([\text{DO}]\) decreases with time and reaches hypoxic levels in a fortnight (from 6.0 mg/L to 3.0 mg/L). At the degradation rate of 0.32 mg/d, \([\text{DO}]\) would be depleted in approximately one fortnight more. By that time, the water column may begin to lose heat due to the annual heating cycle, thereby destabilizing and allowing the mixing of surface \([\text{DO}]\) to the bottom. Therefore, a higher consumption rate is required for WLIS to go anoxic. Abnormally high organic matter decomposition combined with weakened gravitational circulation throughout the entire length of LIS and a lack of wind induced vertical mixing will cause lower-than-normal \([\text{DO}]\) in WLIS.

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