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Internal-Wave-Induced Upward Bias of pH on Coastal Submarine Slopes

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Abstract

Internal waves propagating on coastal submarine slopes can bias the nominal pH values found at fixed depths, increasing average pH by as much as 0.1 pH unit at 20-m depth. The quantitative bias depends on the amplitude of the waves, the sample depth, and the nominal pH gradient. Using temperature and pH time series data measured at the Dirk Burcham Scientific Mooring located near Two Harbors, Santa Catalina Island, California USA, we compute the pH bias for six deployments. The results are compared to a simple model relating the maximum potential bias derived from temperature models appropriate to the Southern California Bight.

Introduction: A series of measurements were taken to determine the baseline pH and its dynamics off Santa Catalina Island (Figure 1) between 2017 and 2022. The measurements were executed on both a mooring (Figure 2) where long duration time series could be obtained, and from sounding from a boat (Figure 3) that could profile the water column quickly. Data from the mooring are shown in Figures 4 and 5. pH is modulated by internal waves. All pH profile data are summarized in Figure 6 as a surface value and gradient.

Figure 1. Experiment Location: Santa Catalina Island, California USA

Figure 2. Experiment Setup: Mooring

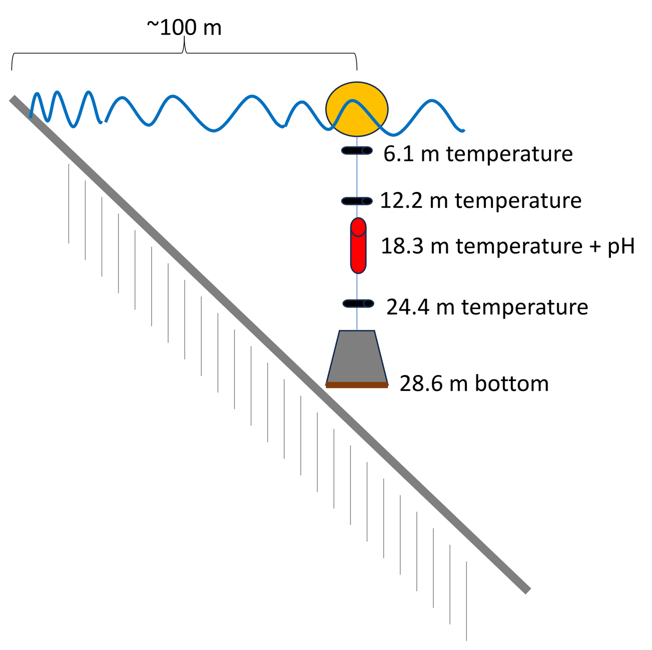


Figure 3. Experiment Setup: Depth profiling from boat

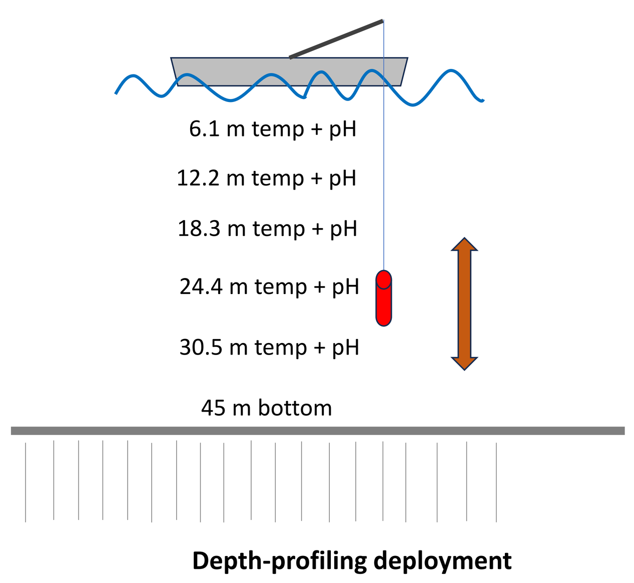


Figure 4. Mooring temperature (top) and pH (bottom) time series during stratification.

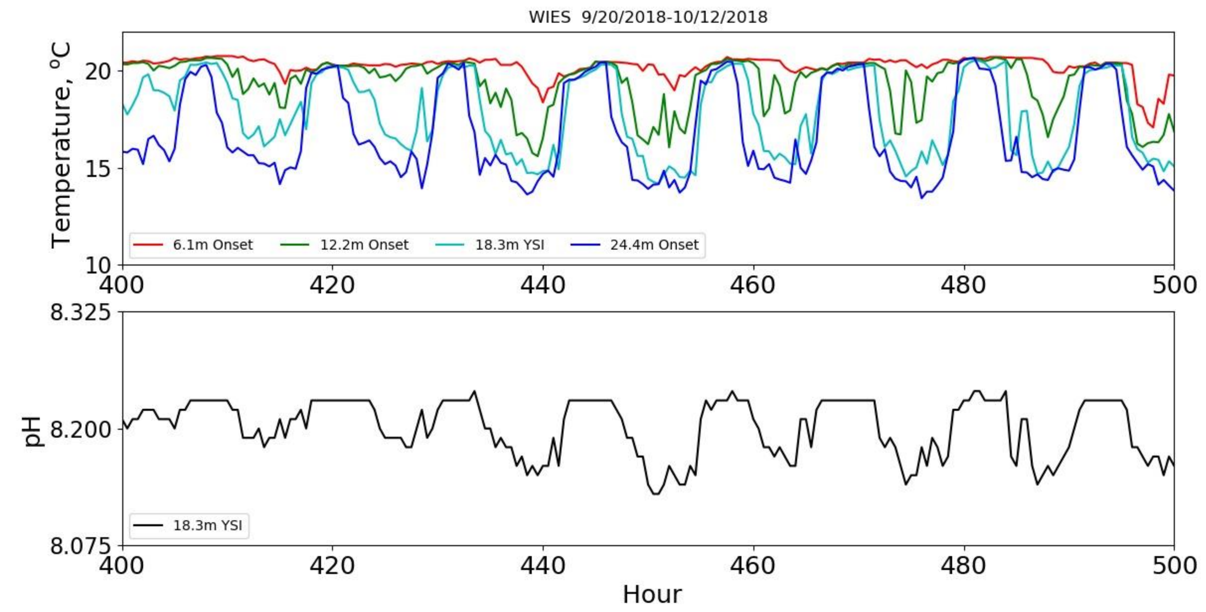


Figure 5. Mooring temperature (top) and pH (bottom) time series during little stratification.

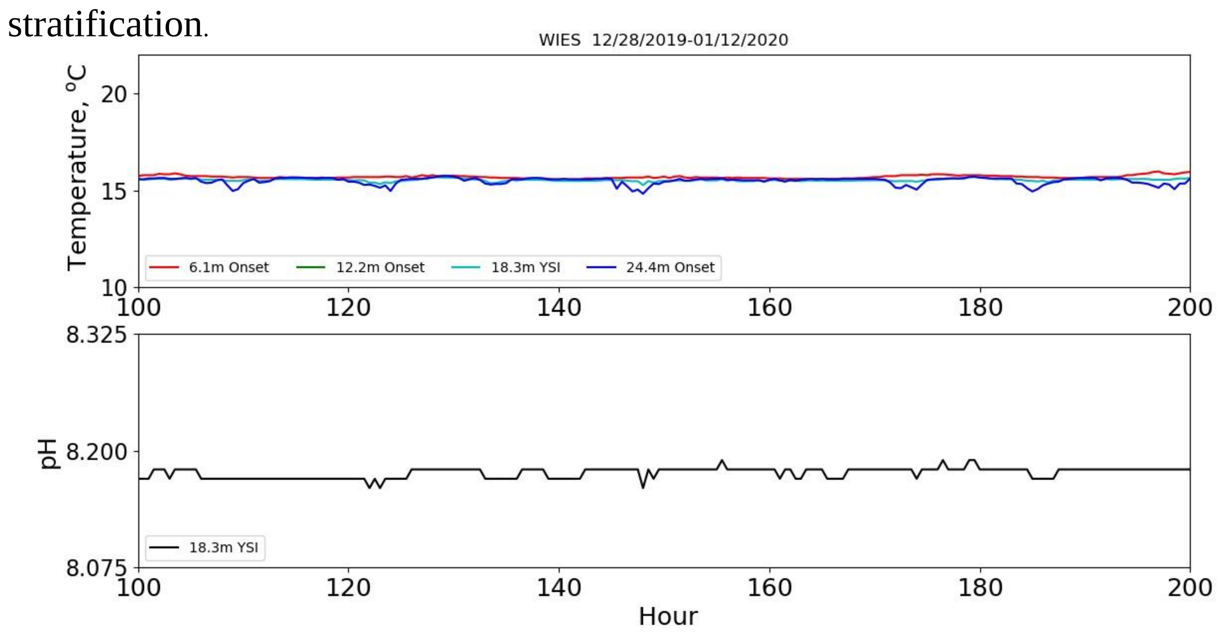
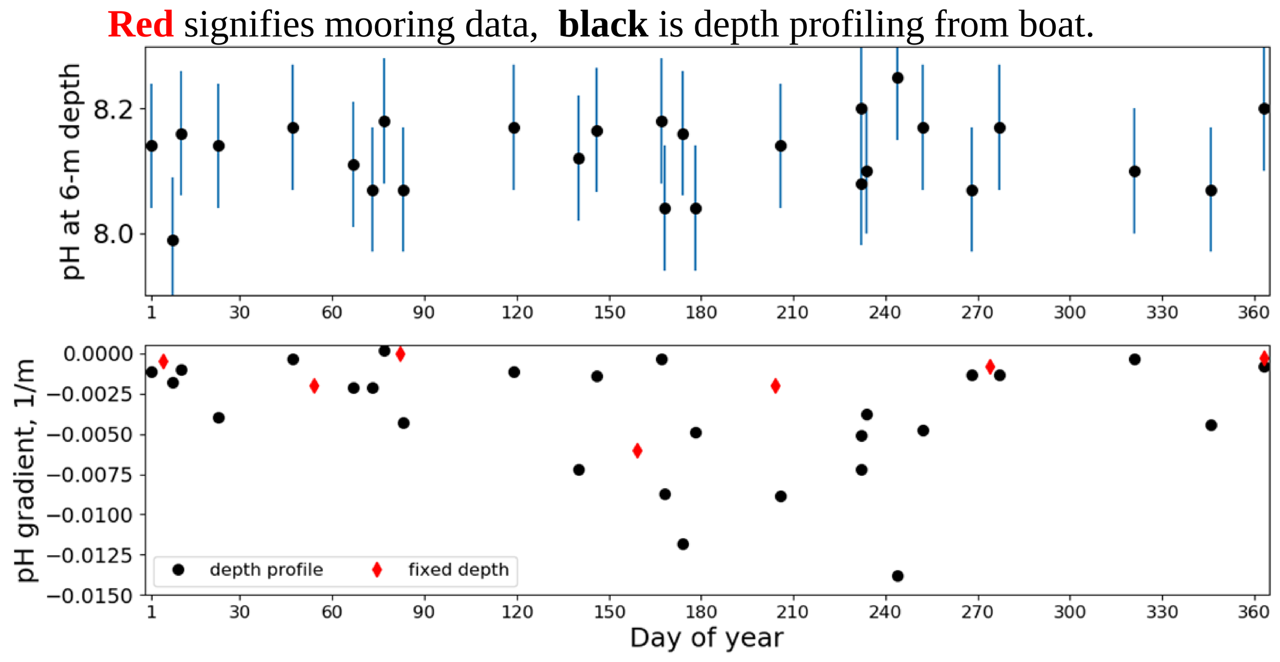


Figure 6. Synopsis of data. pH at 6-m depth (top) and gradient (bottom). **Red** signifies mooring data, **black** is depth profiling from boat.



Data Summary: Large-amplitude semi-diurnal internal waves (Figure 4) on the island's slopes advect the pH gradient, generating large modulations in pH at depth. These modulations are not correlated with biological frequencies or properties, e.g., solar cycle, or dissolved oxygen or chlorophyll subsurface maxima. There is no seasonal modulation in surface pH (Figure 6, top), but there is a large scatter in measured pH gradient Figure 6, bottom) during times of large stratification.

The modulations coupled with the nonlinearity of the gradient across the mixed-layer depth, introduces a bias in the average pH measured over time. The model below investigates this bias.

The time-average pH is the pH at the surface (assumed constant) and an integration of the pH gradient from the mixed-layer depth (MLD), $z_m(t)$, to the depth of interest, averaged over a wave cycle.

$$\langle pH(z)\rangle_{time} = pH(0) + \frac{1}{T}\int_0^T \int_{z_m(t)}^{z} \frac{\partial pH}{\partial z}\left(z', z_m(t)\right) dz' dt$$

The gradient is 0 above the MLD and constant below it.

$$\frac{\partial pH}{\partial z}(z) = \begin{matrix} 0, & z < z_m \\ C, & z > z_m \end{matrix}$$

The bias in pH is computed numerically after normalizing by the MLD and internal wave amplitude.

$$\hat{z} = \frac{z}{z_o}, \text{ normalized depth}$$

$$\hat{a} = \frac{a}{z_0}, \text{ normalized internal wave amplitude}$$

$$\hat{z}_m = \frac{z_m}{z_o} = 1 + \hat{a}\cos\omega t, \text{ normalized mixed layer depth}$$

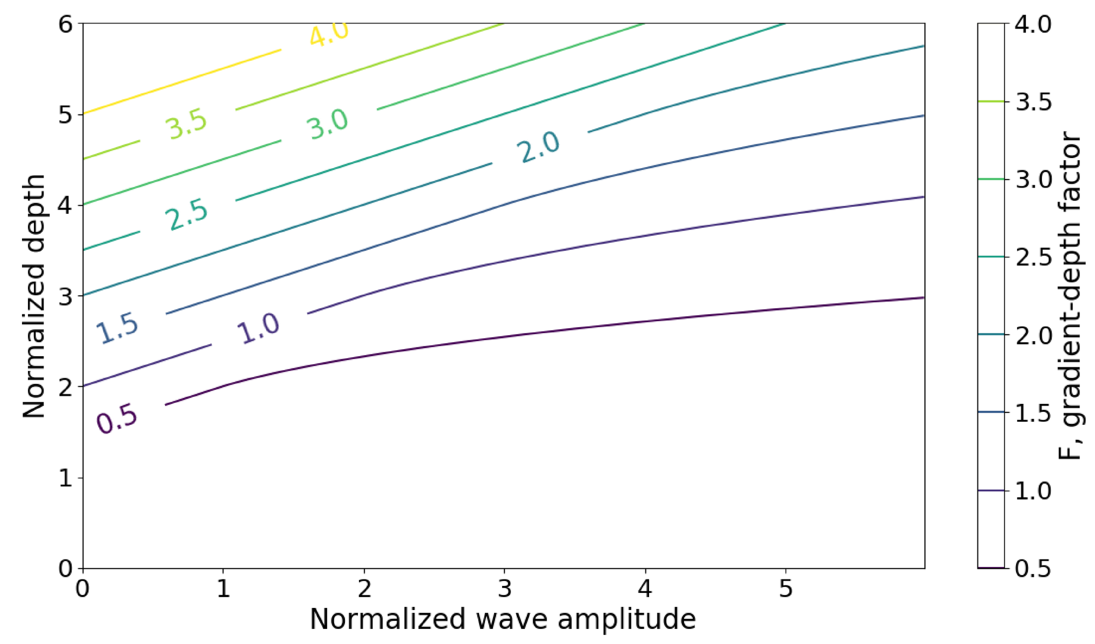
$$G(z, z_m) = \begin{matrix} 0, z < z_m \\ 1, z > z_m \end{matrix}$$

$$F(\hat{z}, \hat{a}) = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} G(\hat{z}, 1 - \hat{a}\cos\omega t)[\hat{z} - 1 - \hat{a}\cos\omega t]dt$$

$$\langle pH(z)\rangle_{time} = pH_0 + \frac{\partial pH}{\partial z} z_0 F(\hat{z}, \hat{a})$$

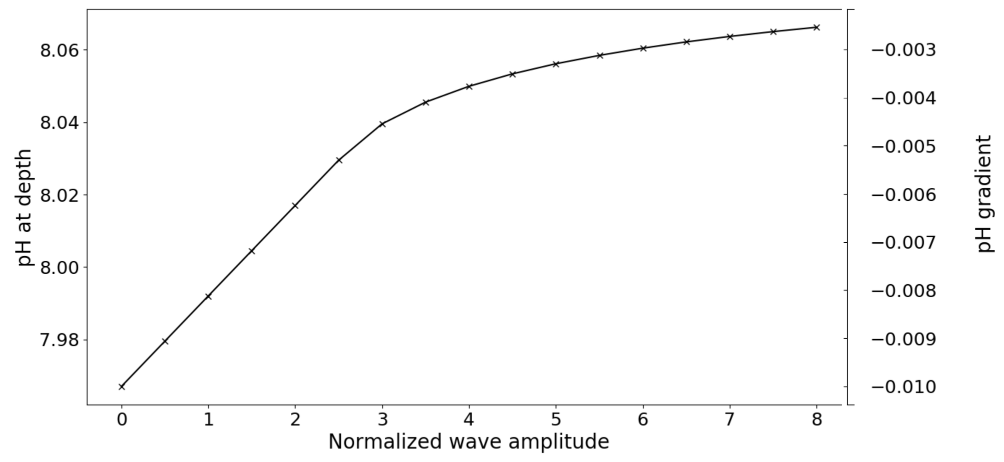
F is gradient depth factor, shown in Figure 7.

Figure 7. F



Concrete Example: MLD = 5 m, measurement depth is 18.3 m, mixed-layer pH = 8.1, pH gradient is -0.01/m. The bias in time-averaged measurements as a function of internal wave amplitude is shown in Figure 8.

Figure 8. pH and its gradient for conditions described above.



Conclusion: The internal waves on the island's slope biases the time average pH at depth, and reduces its gradient. This is consistent with the time-averaged gradients shown in Figure 6 (red dots).

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