



The Effects of Coastal Downwelling on pH Exposure at Santa Catalina Island

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Abstract

We investigate the effects of internal-wave-induced downwelling on at-depth pH at Santa Catalina Island, CA USA using both measurements and models. We speculate on how climate change may affect pH exposure considering: how downwelling increases pH at depth because of the oceanic pH gradient is directed toward the surface; increasing atmospheric carbon dioxide will decrease mixed-layer pH; and the mixed-layer depth will change with stratification and expected increase in storm activity.

The location of the experiment, shown in Figure 1, was on the lee side of Santa Catalina Island, in the Southern California Bight. This area is known for little upwelling.

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

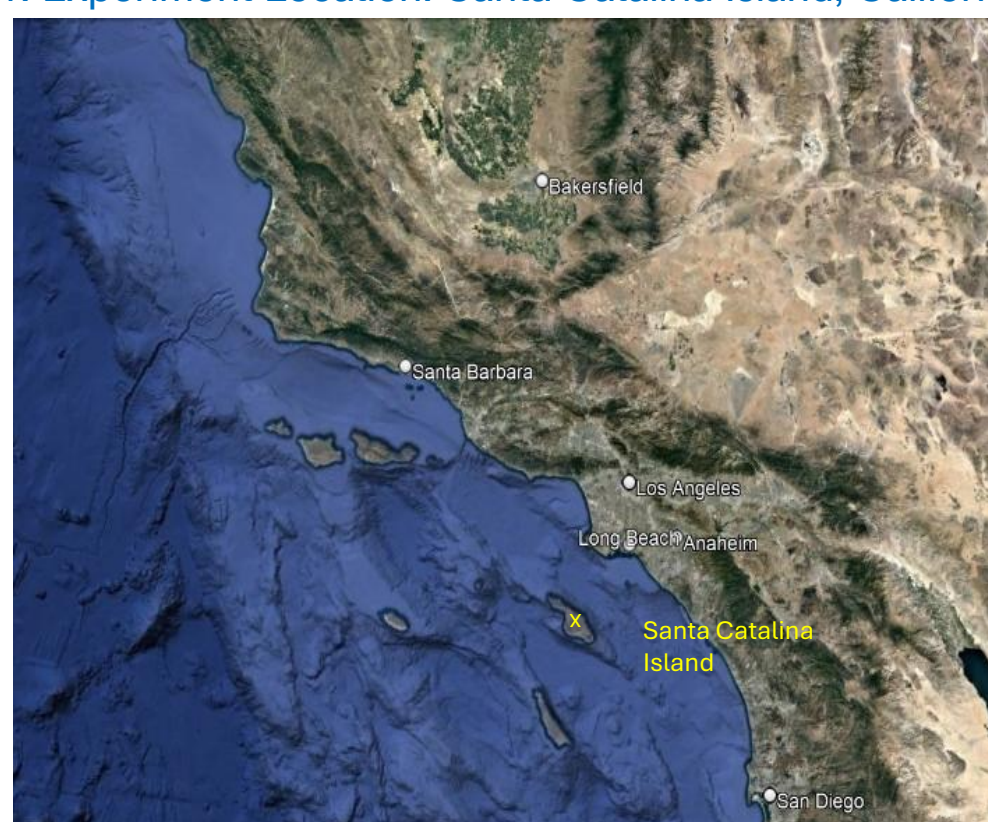


Figure 2. Experiment setup.

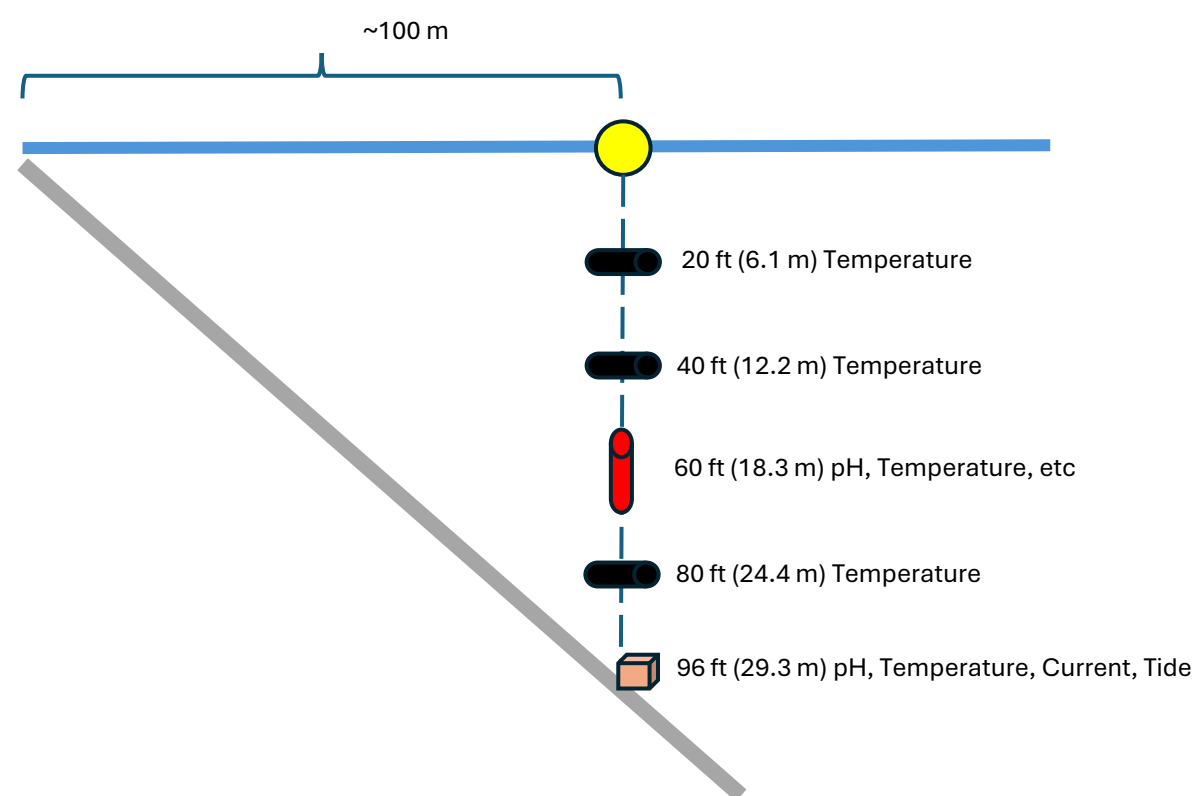
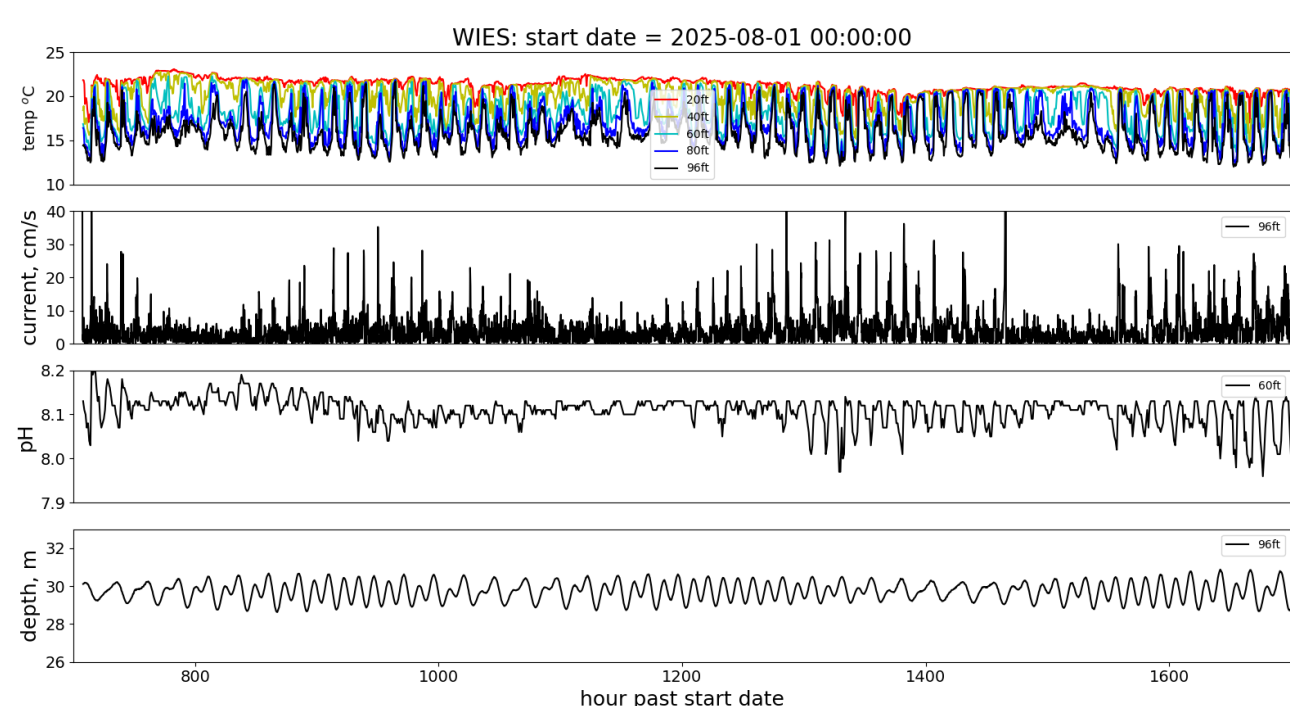


Figure 3. Illustrative data.



In Figure 3, note the increase in semi-diurnal temperature modulations with depth, the periodic spikes in current speed and modulations in pH that are highly correlated with temperature. Spikes and relaxations are assumed to be produced by nonlinear bores, Reference 1. Rectangular features are evidence of mixed layer advected to depth.

References

Reference 1: "Observations of Shoaling Nonlinear Internal Bores across the Central California Inner Shelf", J.M. McSweeney, J.A. Lerczal, J.A. Barth, J. Becherer, J.A. Colosi, J.A. MacKinnon, J.H. MacMahan, J. M. Moum, S.D. Pierce and A.F. Waterhouse, *J. Phys. Oceanography*, Vol 50, 2020.

Reference 2: "Seasonal temperature dynamics of the upper ocean in the Southern California Bight", C.G. Gelpi and K. E. Norris (2008), *J. Geophys. Res.*, 113, C04034, doi:10.1029/2006JC003820.

Model for pH is constant pH within the mixed layer in equilibrium with atmospheric CO₂ and constant pH gradient below mixed layer.

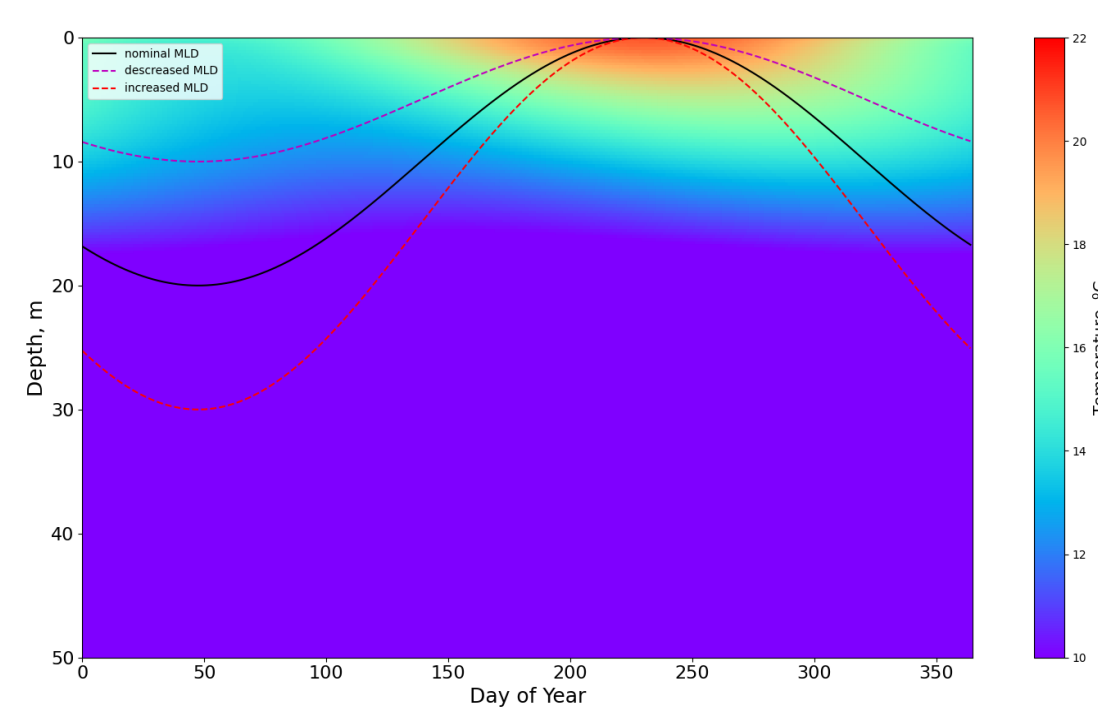
$$pH(z, t) = \int_{z_{mld}(t)}^z \frac{\partial pH}{\partial z} dz' + pH(z_{mld}(t))$$

The mixed-layer depth is modulated both seasonally by weather and semi-diurnally by bores.

$$pH(z, t) = \begin{cases} \frac{\partial pH}{\partial z} (z - (z_{mld0} + b(1 + \cos \omega t))) + pH_{surface}, & z > z_{mld}(t) \\ pH_{surface}, & z < z_{mld0}(t) + b(t)(1 + \cos \omega t) \end{cases}$$

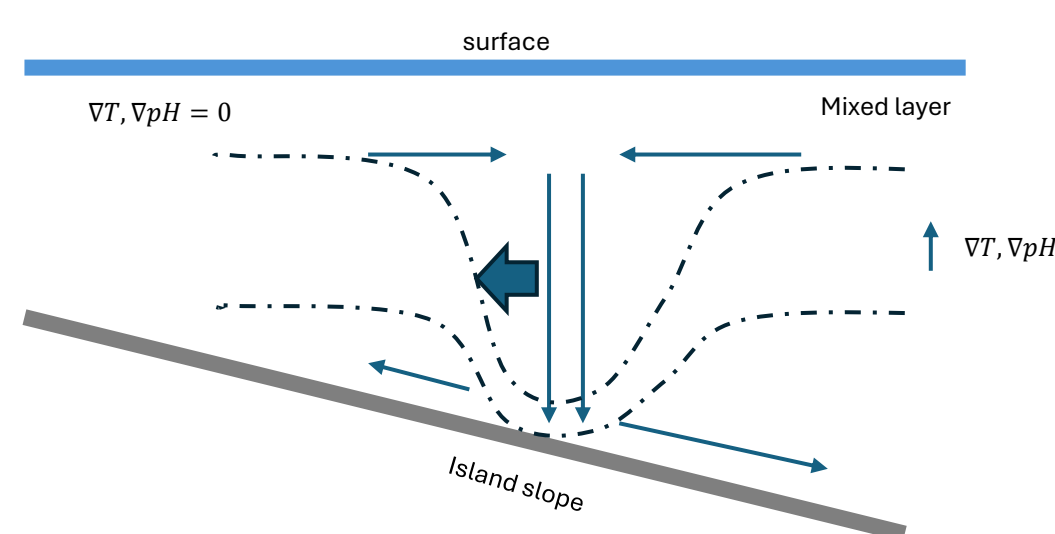
$$\langle pH(z) \rangle = \int_0^{year} pH(z, t) dt$$

Figure 4. Seasonal temperature and mixed-layer model.



Mixed-layer-depth model adopted from temperature model, Reference 2.

Figure 5. Model for bore based on Reference 1.



Non-linear bore propagates up slope with rapid downwelling and subsequent relaxation. Figure 5 depicts our model. Within the Mixed layer there are no gradients. The current spike of the bore forces the water column into downwelling, increasing pH and temperature. After the bore passes, the water column relaxes to original state.

Figure 6. pH versus depth and time of year without modulation.

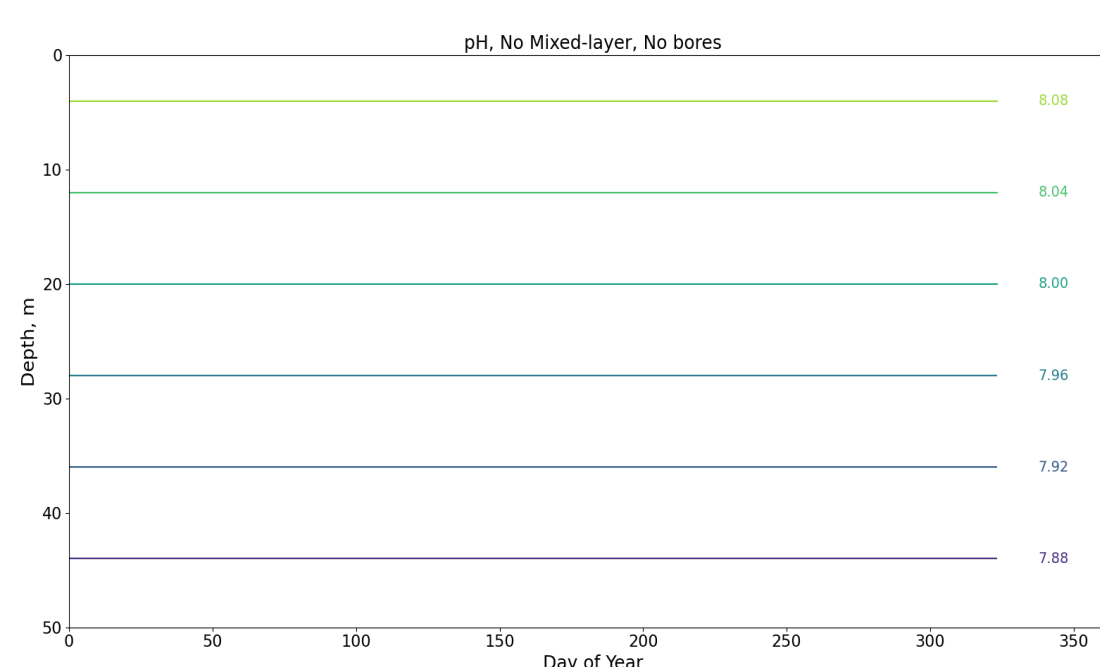
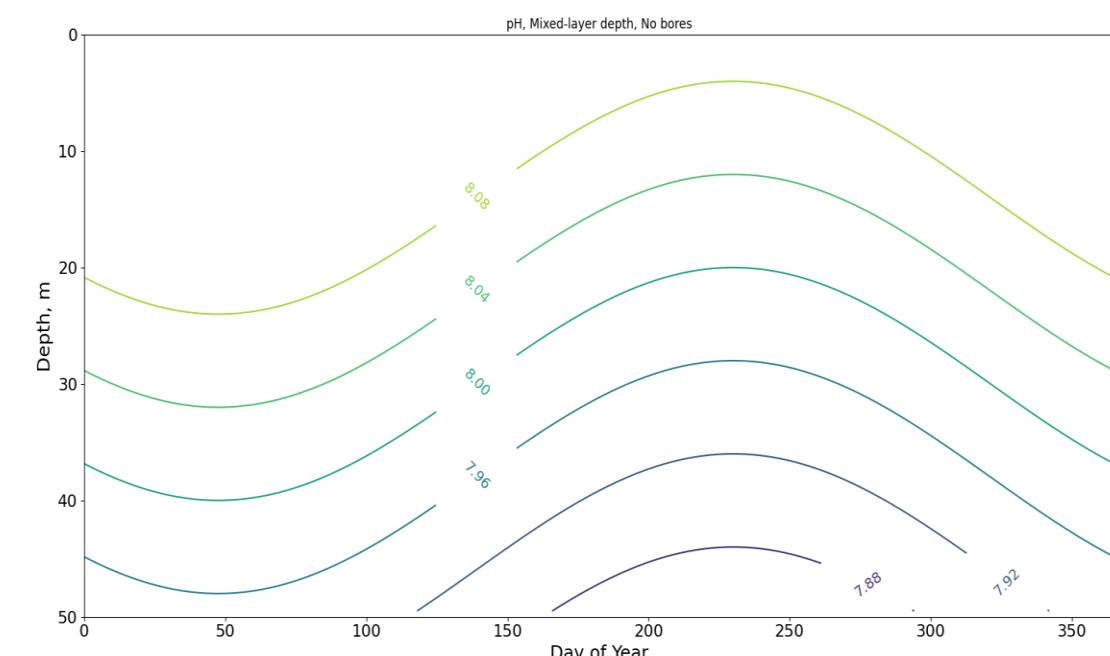
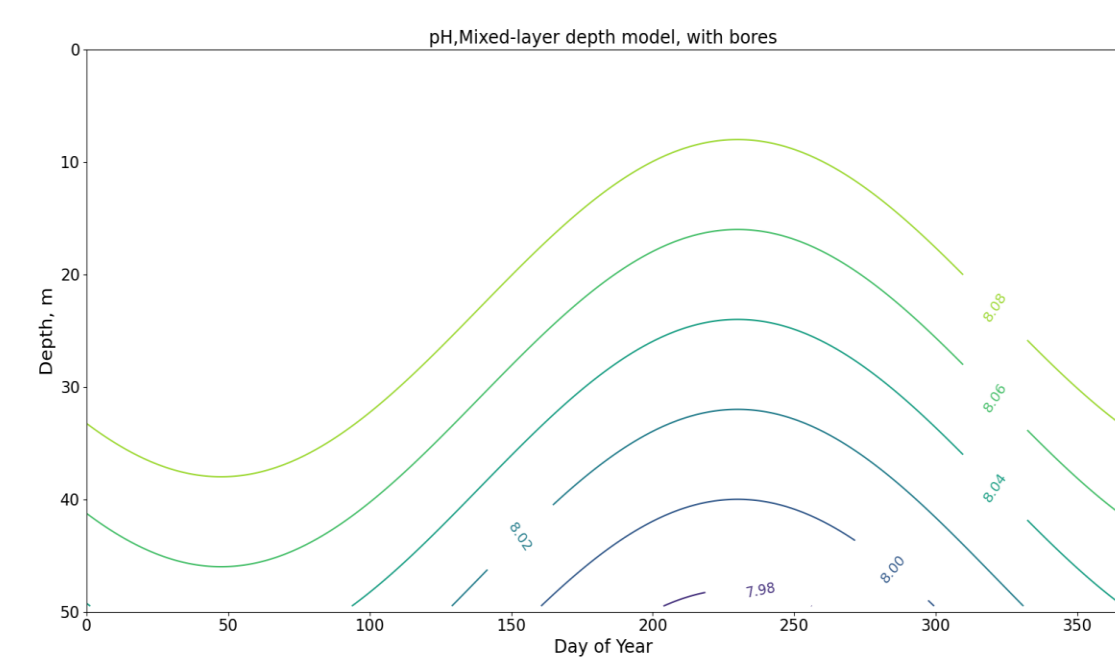


Figure 7. pH for seasonal modulation of MLD only.



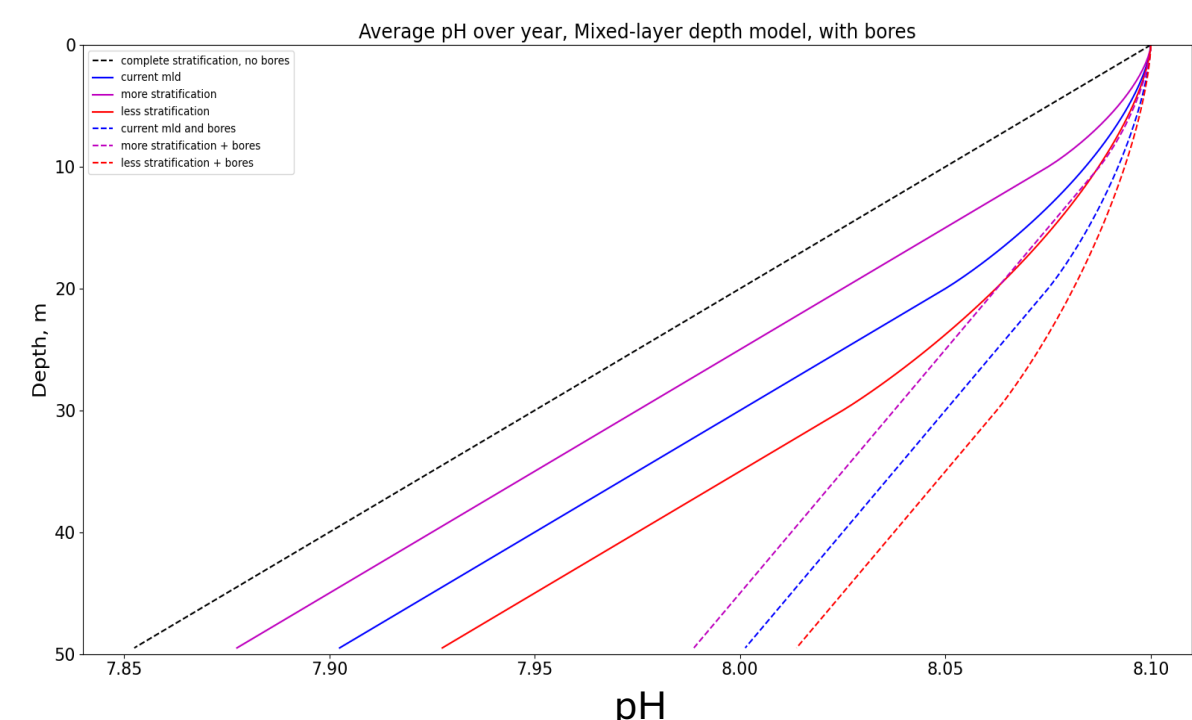
The seasonal change in MLD, deeper during the winter, mixes surface water to depth, increasing pH there, Figure 7. In the summer with a shallow MLD, pH is expected to decrease.

Figure 8. pH for seasonal and bore modulation of MLD.



As bores effectively increase downwelling, the phenomenon shown in Figure 7 will be larger.

Figure 9. Average pH, $\langle pH(z) \rangle$ vs depth with and without modulations.



Yearly average of pH as function of depth for various scenarios. Less stratification brought about by either larger MLD or larger bores, increases pH

Summary

The MLD modulation increases pH at depth by mixing high-pH surface water into the water column, nominally this increase is 0.05. Non-linear bores increase pH by a substantial 0.1. Decreasing MLD by half or doubling it changes the yearly-average pH by ~0.01 accordingly.

Acknowledgements

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