

to pH_T levels of 7.7 and 7.4 for the West Coast and Gulf of Mexico, respectively. The oxygen concentrations associated with saturation states of 1 are similar to those associated with hypercapnia for the US West Coast: $110 \mu\text{mol kg}^{-1}$ at present and $260 \mu\text{mol kg}^{-1}$ under RCP 8.5. In the Gulf of Mexico, the aragonite saturation horizon occurs at oxygen concentrations of about $15 \mu\text{mol kg}^{-1}$ under the RCP 8.5 conditions.

Comparing the two ecosystems under the most severe RCP 8.5 scenarios, the large change in amplitude of hypercapnia indicates the probability of extensive habitat compression along the US West Coast, while the conditions in the Gulf of Mexico will be undergoing slower degradation. Nevertheless, the Gulf of Mexico will continue to provide habitats that are suitable for numerous calcifying and non-calcifying species.

While the direction of change is similar for both regions, the onset of key thresholds and the overall vulnerability will be felt more quickly in the cold-water regime of the West Coast. Since various OA parameters affect multiple impairment pathways, overlapping OA parameters actually represent multiple-stressor environments for marine organisms. This is especially important for the most sensitive organisms with low capacity for acid-base regulation.

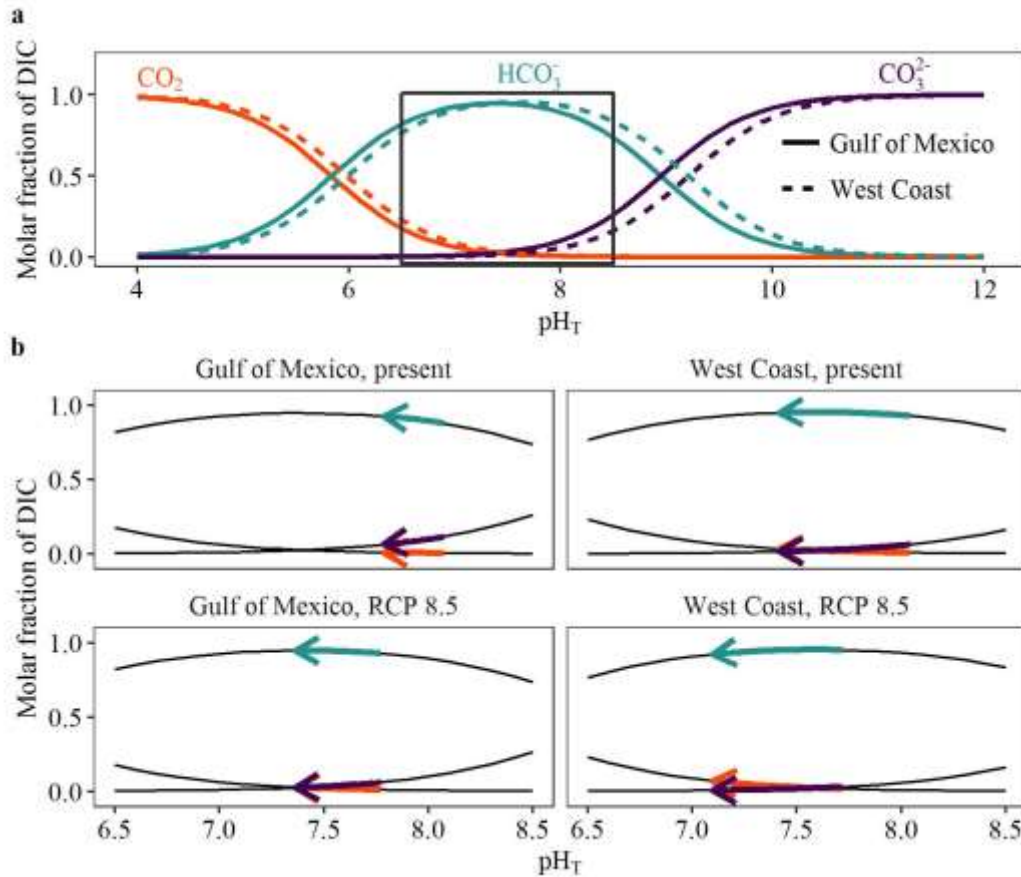


Figure 9. Bjerrum plots of the changes in chemical speciation of the carbonate system with increasing CO₂ concentrations for the Gulf of Mexico and US West Coast: (a) pH_T range from 4.0 to 12; and (b) pH_T range from 6.5 to 8.5. The arrows in bottom panels (b) indicate changes in carbonate chemistry from surface waters (arrow tail) to 0 μmol kg⁻¹ dissolved oxygen (arrow head) under present-day and RCP 8.5 scenarios (top and bottom panels, respectively).

8. Conclusions

The decrease in pH_T and aragonite saturation state, as well as the increase in *p*CO₂ of subsurface coastal waters, from the combined effects of “classical” ocean acidification and oxidative acidification (i.e., respiration processes) is significantly enhanced by the higher RF and the enhancement of the respiration process in the colder waters of the West Coast relative to the Gulf of Mexico. Consequently, in colder waters we should observe greater seasonal variability and more rapid response to critical thresholds of

acidification and hypercapnia under the higher CO₂ conditions that are expected to occur over the next several decades. These changes should be observable with continuous monitoring of our coastal waters for chemical and biological impacts.

9. Acknowledgements

The National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation sponsored this work. We specifically thank Libby Jewett and Dwight Gledhill of the NOAA Ocean Acidification Program, Dave Garrison of the National Science Foundation for their support. Nina Bednaršek was supported by the Pacific Marine Environmental Laboratory of NOAA and the NOAA Ocean Acidification Program. Wei-Jun Cai thanks NSF, NASA and NOAA support, Robert H. Byrne acknowledges support from the NSF. This is PMEL contribution number 4674. This research was supported by the National Oceanic and Atmospheric Administration, the National Science Foundation, and the National Aeronautics and Space Administration.

10. References

- Barton, A., Hales, B., Waldbusser, G., Langdon, C., Feely, R.A., 2012. The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification impacts. *Limnol. Oceanogr.* 57, 698–710, doi:10.4319/lo.2012.57.3.0698.
- Barton, A., Waldbusser, G.G., Feely, R.A., Weisberg, S.B., Newton, J.A., Hales, B., Cudd, S., Eudeline, B., Langdon, C.J., Jefferds, I., King, T., Suhrbier, A., McLaughlin, K., 2015. Impacts of coastal acidification on the Pacific Northwest

- Siedlecki, S.A., Kaplan, I., Hermann, A.J., Nguyen, T.T., Bond, N.A., Newton, J.A., Williams, G.D., Peterson, W.T., Alin, S.R., Feely, R.A., 2016. Experiments with seasonal forecasts of ocean conditions for the northern region of the California Current upwelling system. *Sci. Rep.* 6, 27203, doi:10.1038.srep/27203.
- Soetaert, K., Petzoldt, T., Meysman, F., 2015. marelac: Tools for Aquatic Sciences. R package version 2.1.5. <https://CRAN.R-project.org/package=marelac>
- Somero, G.N., Beers, J., Chan, F., Hill, T., Klinger, T., Litvin, S., 2016. What changes in the carbonate system, oxygen, and temperature portend for the northeastern Pacific Ocean: A physiological perspective. *Bioscience* 66, 14–26, doi:10.1093/biosci/biv162.
- Sunda, W.G., Cai, W.-J., 2012. Eutrophication induced CO₂-acidification of subsurface coastal waters: Interactive effects of temperature, salinity, and atmospheric pCO₂. *Environ. Sci. Tech.* 46(19), 10651–10659, doi:10.1021/es300626f.
- Thomson, R.E., Krassovski, M.V., 2010. Poleward reach of the California Undercurrent Extension. *J. Geophys. Res.* 115, C09027, doi:10.1029/2010JC006280.
- Turi, G., Lachkar, Z., Gruber, N., Munnich, M., 2016. Climatic modulation of recent trends in ocean acidification in the California Current System. *Environ. Res. Lett.* 11, 014007, doi:10.1088/1748-9326/11/1/014007.
- UNESCO, 1994. Protocols for the Joint Global Ocean Flux Study (JGOFS) Core Measurements. United Nations Educational, Scientific, and Cultural Organization, http://ijgofs.whoi.edu/Publications/Report_Series/JGOFS_19.pdf.

- Uppström, L.R., 1974. The boron/chlorinity ratio of deep-sea water from the Pacific Ocean. *Deep Sea Res. Oceanogr. Abstracts* 21, 161-162.
- van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: An overview. *Climatic Change* 109, 5–31.
- Waldbusser, G.G., Hales, B., Langdon, C.J., Haley, B.A., Schrader, P., Brunner, E.L., Gray, M.W., Miller, C.A., Gimenez, I., 2015. Saturation state sensitivity of marine bivalve larvae to ocean acidification. *Nature Clim. Change* 5, 273–280, doi:10.1038/nclimate2479.
- Weisberg, S.B., Bednaršek, N., Feely, R.A., Chan, F., Boehm, A.B., Sutula, M., Ruesink, J.L., Hales, B., Largier, J.L., Newton, J.A., 2016. Water quality criteria for an acidifying ocean: Challenges and opportunities. *Ocean Coastal Manage.* 126, 31–41, doi:10.1016/j.ocecoaman.2016.03.010.
- Wood, H.L., Spicer, J.I., Widdicombe, S., 2008. Ocean acidification may increase calcification rates, but at a cost. *Proc. R. Soc. B* 275, 1767– 1773.

Highlights

- In surface waters, the percentage change in the carbon parameters due to increasing CO₂ emissions are very similar for both regions even though the absolute decrease in aragonite saturation is much higher in the warmer waters of the Gulf of Mexico.
- In subsurface waters the changes are enhanced due to differences in the initial oxygen concentration and the changes in the buffer capacity (i.e., increasing Revelle Factor) with increasing respiration from the oxidation of organic matter, with the largest impacts on pH and CO₂ partial pressure ($p\text{CO}_2$) occurring in the colder waters.
- As anthropogenic CO₂ concentrations begin to build up in subsurface waters, increased atmospheric CO₂ will expose organisms to hypercapnic conditions ($p\text{CO}_2 > 1000 \mu\text{atm}$) within subsurface depths.