MULTIPLE *stressor* considerations

Ocean acidification in a deoxygenating ocean and a warming climate

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The West Coast Ocean Acidification and Hypoxia Science Panel

Ocean acidification, deoxygenation, and warming are part of a system of interacting stressors facing marine ecosystems. Effectively ameliorating and adapting to changes ahead requires coordinated action by living marine resource, water, and air quality managers.

Changing Oceans

The ocean is a complex physical and biogeochemical environment. Primarily the purview of academic research over the last decade, ocean acidification has recently been thrust to the forefront of ocean conservation issues. However, ocean acidification is not an isolated change. Rather, it typically occurs against a backdrop of other changes including deoxygenation (resulting in hypoxic, or low oxygen conditions), warming, and cooling.

While our scientific knowledge is growing, the interactions of many natural and anthropogenic influences inhibits a detailed understanding of how ocean chemistry is changing and the many ways that species and ecosystems may be impacted. Yet, deepening our understanding and consideration of multiple interacting stressors, and the impacts on ocean resources, is critical for devising appropriate management and policy responses.

To support managers and policy-makers in considering ocean acidification as a multi-stressor issue, we provide an overview of acidification, deoxygenation, and temperature changes, the linkages between them, and potential perturbation scenarios projected for coastal oceans.

About this Document

This document highlights that ocean acidification, hypoxia, and warming are part of a system of interacting stressors facing marine ecosystems, and illustrates the need for coordinated action by natural resource, water and air managers and policy-makers.

This document was produced by a working group of the West Coast Ocean Acidification and Hypoxia Science Panel, with support from California Ocean Science Trust, as part of a suite of products to inform decision-making. The information provided reflects the best scientific thinking of the Panel.

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West Coast Ocean Acidification & Hypoxia Science Panel

California Ocean Science Trust

California Ocean Protection Council

Institute for Natural Resources

Interacting Stressors: Acidification, Deoxygenation and Temperature

'Hot, sour, breathless' is how some have described the impending future ocean. As the climate warms, much of Earth's retained heat is stored in ocean waters (hot), which are simultaneously losing dissolved oxygen (O_2; breathless) as they acidify (sour) (Gruber, 2011). Although this paints an effective picture at a global scale, it does not account for the complex spatial and temporal patterns that are predicted to occur on more local and regional scales, particularly within coastal oceans, bays, and estuaries. In addition, not all parameters of interest will exhibit a directional change with changing ocean conditions; an increase in variability and/or frequency of extreme events is likely.

In the most common definition of ocean acidification, the uptake of atmospheric carbon dioxide (CO_2) into the ocean (Fig. 1A) increases seawater pCO_2 and dissolved $CO_{2,aq}$, while pH, and aragonite and calcite saturation states (Ω_a, Ω_c) fall (Fig. 1B). However, numerous other factors also influence the oceanic carbonate system, including freshwater inputs, upwelling and/or downwelling intensity, and nutrient loading, especially in the coastal zone (Fig. 1D,H).

Deoxygenation and acidification can be coupled through biological activity: during the process of organic matter decomposition, O_2 is consumed and CO_2 is released into seawater via respiration (the opposite occurs during photosynthesis; Box 1; Fig. 1C,E). Thus, locations such as the coastal waters of the northeastern Pacific Ocean that suffer from hypoxia are also subject to enhanced acidification risk.

Changing temperatures add another element of complexity (Fig. 1F). Rising sea surface temperatures elevate rates of physiological processes. Moreover, warming of the global oceans will undoubtedly lead to changes in ocean stratification (reduced mixing) and circulation (Schmittner et al., 2008; Keeling et al., 2010; Rykaczewski and Dunne, 2010) (Fig. 1G) with consequent changes in nutrient supply, light availability, and the depth and intensity of respiration and photosynthesis. By reducing the solubility of O_2 and its resupply to the ocean interior, changes in ocean temperature, stratification and circulation will also enhance global deoxygenation trends.

> Locations that suffer from hypoxia are also subject to enhanced acidification risk.

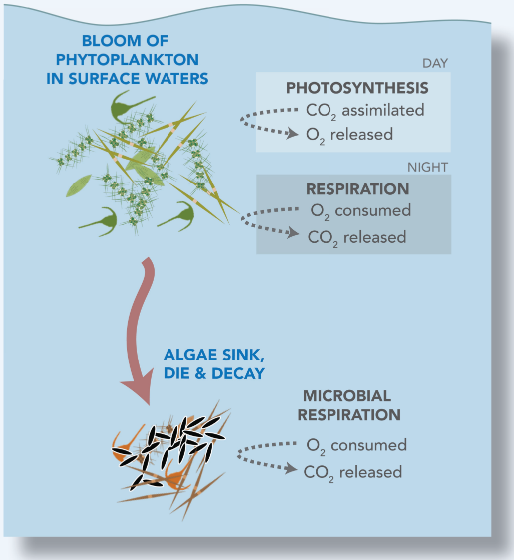
In coastal regions that experience increased upwelling from climate change (Fig. 1H), warming trends in surface waters will be punctuated by increased intrusion of cold, O_2-poor and CO_2- and nutrient-rich water from depth. Increased upwelling will also stimulate stronger surface phytoplankton blooms, and productive West Coast systems will face increased risk and intensity of hypoxic and acidified conditions as surface production eventually sinks to and is remineralized (respired) at depth.

While we focus here on the processes of acidification, deoxygenation and temperature, numerous other stressors are being exerted simultaneously (Fig. 1I). For example, habitat loss, marine debris and microplastics, invasive species, and overfishing will act concurrently on susceptible organisms, communities and ecosystems.

Actions taken to address these stressors – individually and collectively - may alleviate some of the the impacts on populations and ecosystems until global action on CO_2 emission reduction can be achieved.

BOX 1. METABOLIC COUPLING BETWEEN OCEAN ACIDIFICATION AND HYPOXIA

Ocean acidification and deoxygenation may be coupled though biological activity in some locations. Phytoplankton blooms in surface waters assimilate CO_2 and release O_2 into the water via photosynthesis (primary productivity) during the day. At night when sunlight is unavailable, the blooms undergo respiration (consume O_2, release CO_2). When blooms die, this dead material is eventually decomposed through microbial respiration. In the course of this decay, organic carbon material and O_2 are removed from the water and converted to inorganic CO_2. Thus, that water will simultaneously become low on O_2 (hypoxic) and elevated in CO_2, or acidified.



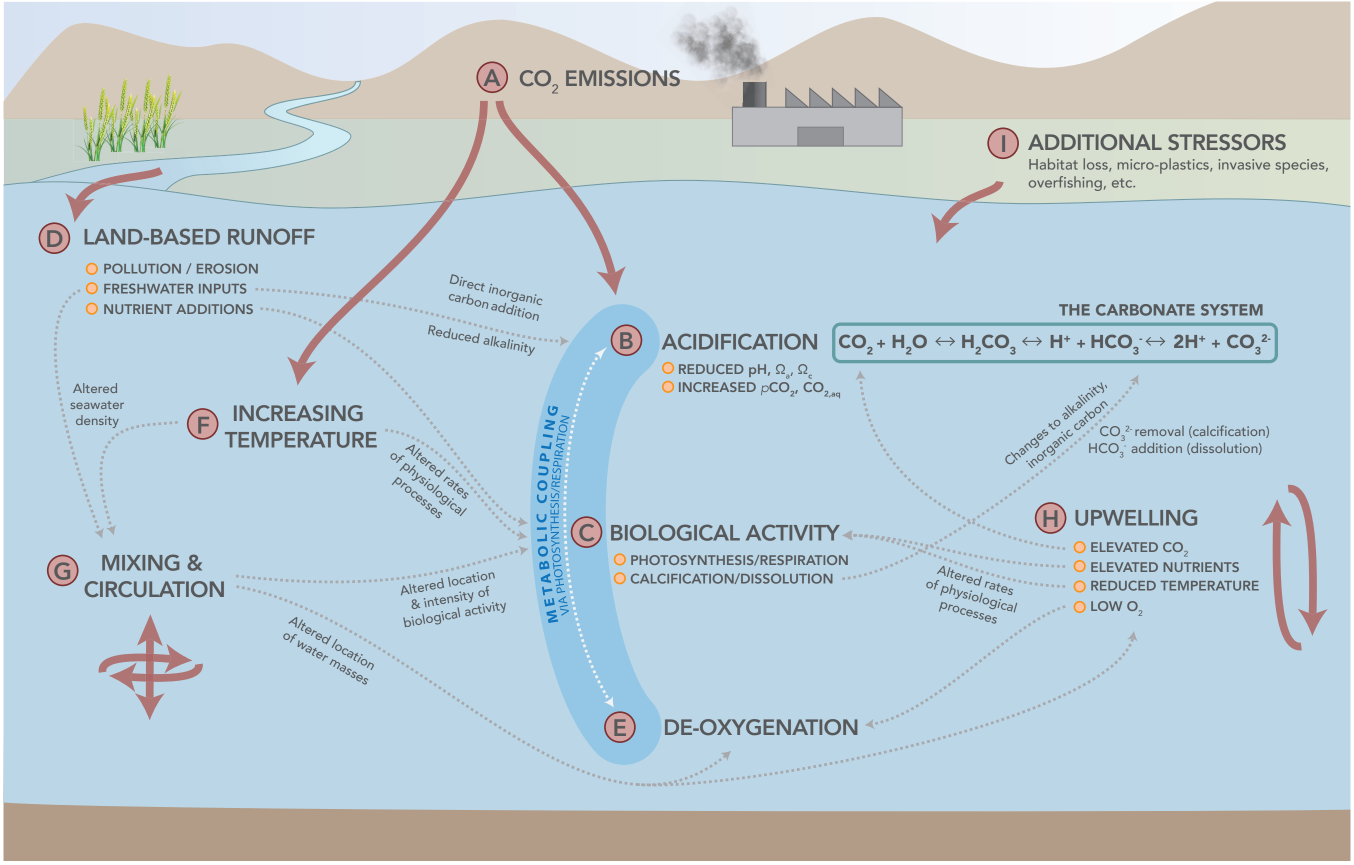


Figure 1. Overview of the major driving processes (and associated linkages among them) in coastal oceans. (A) Atmospheric CO_2-driven (B) acidification occurs against a backdrop of additional drivers of change in ocean conditions, including (D) land-based runoff, (E) deoxygenation, (F) warming, (G) mixing and circulation, (H) upwelling, and (I) other additional stressors. Processes can be accentuated in bodies of water with low circulation and mixing, for example tidal flushed bays and estuaries, as well as tidepools.

Note: Location of processes relative to one another does not denote actual location in the water column.

Potential Perturbation Scenarios in Coastal Oceans

Hypothetical perturbation scenarios illustrate the potential combinations of acidification, deoxygenation, and thermal responses of coastal oceans (Table 1), and highlight that these stressors may be coupled or counteracting.

It is often difficult to predict which scenario will manifest in a location. While we can examine the suite of underlying drivers, variability in biological responses to changing ocean chemistry contributes to uncertainty through feedback loops, notably those that govern removal of CO_2 or its release through organismal calcification and dissolution processes (Gangsto et al., 2008). Despite this uncertainty in future predictions, these scenarios begin to narrow the range of potential future conditions and can serve to focus management and policy action for greatest impact.

Increased atmospheric CO_2 levels are the primary driver of global ocean acidification. The first potential perturbation scenario focuses on this effect (Table 1, Scenario 1). However, the dynamics of coastal zones are complex and additional drivers of changing ocean chemistry, described below, are worth adding to the picture (Table 1, Scenarios 2 and 3).

- **Upwelling**

  Gradients in coastal wind-driven upwelling strength - which brings cold, high CO_2, low O_2, and nutrient-enriched water to the ocean surface – occur along the west coast of North America. Coastal upwelling is generally assumed to enhance primary productivity (photosynthesis), with associated draw down of inorganic carbon and release of excess O_2 (Table 1, Scenario 2A; Bakun, 1990). However, recent research (Evans et al. 2015) suggests that the possible mismatch between the timescales of upwelling and biological responses can lead to the opposite effect (Table 1, Scenario 2B). In addition, reduced temperatures may lower metabolic rates, and high CO_2 concentrations can compromise integrity of calcium carbonate structures due to effects mediated through aragonite and calcite dissolution processes.

Table 1. Potential perturbation scenarios and the associated acidification, thermal, and deoxygenation responses for the North American Pacific coast. The table presents three scenarios that describe combinations of physical ocean processes, carbonate chemistry, and location. For each scenario, the acidification, deoxygenation and thermal response is provided. While interactions among these responses is likely, each is described separately to illustrate co-varying or counteracting responses. The table focuses on these three responses to illuminate broad scenarios, but additional factors (e.g., freshwater and nutrient inputs) may result in localized differences in observed responses. The term "WORSENING" describes increased acidification, higher deoxygenation, and increased temperature. "LESSENING" describes a smaller increase in acidification, smaller reductions in oxygen, and smaller increase in temperature. All responses are relative to mean present day (2015) conditions.

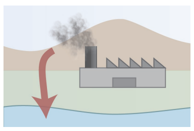
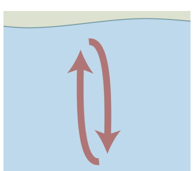
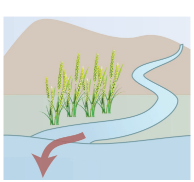
Perturbation Scenarios				Acidification Response	Deoxygenation Response	Thermal Response
1	**Enhanced atmospheric CO_2 and climate change** 	1A. SURFACE OCEAN		**WORSENING**	**WORSENING**	**WORSENING**
		1B. OCEAN INTERIOR		**WORSENING** Driven by elevated CO_2 in surface ocean and based on balance between organic particle sinking and transport of gases from the surface ocean.	**WORSENING** Based on balance between organic particle sinking and transport of gases from the surface ocean.	**WORSENING**
2	Scenario 1 with **Enhanced upwelling** (2A and 2B are alternative scenarios based on the time course of primary productivity) 	2A. **HIGH primary productivity** 	SURFACE OCEAN (Offshore, bays/ retention zones where blooms develop)	**LESSENING/MORE VARIABLE** Increased delivery high-CO_2 ocean interior water outpaced by CO_2 consumption by primary producers. Nighttime respiration associated with primary producers will likely make this more variable, rather than directional.	**LESSENING/MORE VARIABLE** Nutrient-stimulated primary productivity produces excess oxygen. Nighttime respiration associated with primary producers will likely make this more variable, rather than directional.	**LESSENING** Based on balance between rate of cool water upwelling and global average radiation budget. Possibly influenced by increased coastal cloud cover.
			DEEP OCEAN	**WORSENING** As surface-produced organic particles are delivered to and respired at depth (metabolic CO_2 production).	**WORSENING** As organic particles from the surface ocean are delivered to and respired at depth (metabolic O_2 consumption).	**UNCERTAIN** Potential warming as ocean interior warms
		2B. **LOW primary productivity** 	SURFACE OCEAN (Nearshore where upwelled water enters euphotic zone)	**WORSENING** Dependent on rate of upwelling relative to timescales of biological productivity. Increased delivery of high-CO_2 ocean interior water not balanced by primary productivity if water descends out of photic zone too quickly.	**WORSENING** As upwelling delivers low O_2 waters faster than productivity can produce O_2.	**LESSENING** Based on balance between rate of upwelling, global average radiation budget, possibly influenced by increased coastal cloud cover.
			DEEP OCEAN	**LESSENING** Low productivity in surface waters results in less organic material transported to deeper waters (reduced respiratory CO_2 production).	**LESSENING** Low productivity in surface waters results in less organic material transport to deeper waters (reduced respiratory O_2 consumption).	**UNCERTAIN** Potential warming as ocean interior warms.
3	Scenario 1 with **Enhanced Land-Based Nutrient Runoff** (3A, 3B, and 3C are concurrent scenarios in different locations in the water column) 	3A. SURFACE OCEAN		**LESSENING/MORE VARIABLE** Driven by nutrient-stimulated increase in primary production (photosynthetic CO_2 consumption). Nighttime respiration associated with primary producers will likely make this more variable, rather than directional.	**LESSENING/MORE VARIABLE** Driven by nutrient-stimulated increase in primary production (photosynthetic oxygen production). Nighttime respiration associated with primary producers will make this more variable, rather than directional.	**UNCERTAIN** Potential enhancement of global average warming via greater absorptivity of organic particle-rich waters.
		3B. OCEAN INTERIOR		**WORSENING** Driven by increasing respiratory load (metabolic CO_2 production) from surface-produced particles from scenario 3A settling out of the euphotic zone.	**WORSENING** Driven by increasing respiratory load (metabolic O_2 consumption) from surface-produced particles from scenario 3A settling out of the euphotic zone.	**UNCERTAIN**
		3C. SURFACE OCEAN (Offshore) DEEP OCEAN		**WORSENING** Driven by increasing respiratory load (metabolic CO_2 production) from surface-produced particles from scenario 3A traveling downstream and to depth.	**WORSENING** Driven by increasing respiratory load (metabolic O_2 consumption) from surface-produced particles from scenario 3A traveling downstream and to depth.	**UNCERTAIN** Potential enhancement of global average warming via greater absorptivity of organic particle-rich waters.

Photo credit: Ryan Meyer, Ocean Science Trust

- **Land-Based Runoff**

  Persistent and episodic inflows to the ocean from rivers, stormwater, and wastewater outfalls carry fresh water, nutrients and organic matter. In estuaries and areas of the coastal ocean that are affected by river run-off, these inputs have exacerbated localized acidification and deoxygenation. Terrestrial inputs can be diffuse, such as in parts of Oregon and Washington where numerous small rivers terminate at the coast, or these inputs can be concentrated where major river systems aggregate chemistry from large upland areas into major plumes.

  - **Nutrient additions:** Eutrophication stimulated via nutrient loading (i.e., elevated nutrients are assimilated by primary producers), particularly nitrogen and phosphorus, from land-based sources may create greater variability in carbonate chemistry through concurrent increases in primary production followed by respiration (Table 1, Scenario 3; Cai et al. 2011). These processes can be separated by space or time based on water mixing and circulation processes, among other considerations.

  - **Freshwater inputs:** Many river plumes are often more acidic than the ocean waters they combine with. Riverine freshwater inputs reduce receiving ocean alkalinity - the buffering of seawater – leading to large shifts in carbonate chemistry along the continental shelf (Salisbury et al. 2008). Low salinity-induced reduction in seawater density may alter water column mixing and circulation, with associated impacts to the location of biological activity. The timing and intensity of annual maximum freshwater fluxes is also likely to shift based on changes in annual precipitation and snowpack, especially in the northern California current system, adding further complexity.

In some cases, surface oceans may exhibit a lesser response to anthropogenic eutrophication that is magnified at depth as particles from the surface are respired (Table 1, Scenario 3A and 3B). In addition, water transport via ocean circulation (currents) and mixing can move water masses with high CO_2 and low O_2, resulting in offshore and deep locations with acidified, hypoxic conditions worse than one might predict based upon nearshore surface productivity.

Deepening Understanding: Linking Chemical Changes to Biological Responses

Projections of change in multiple aspects of ocean chemistry have prompted an increase in multi-stressor experiments designed to elucidate the confounding effects of continued warming, deoxygenation, and acidification. Experimental approaches have recently isolated the specific carbonate-chemistry variables that drive some of the observed responses in marine organisms (Waldbusser et al. 2015a; b). These have confirmed that ocean acidification itself can be considered a multi-stressor problem. Even without considering the interacting effects of deoxygenation and warming, physiological processes are each influenced by different components of the carbonate system: pCO_2, dissolved $CO_{2,aq}$, pH, carbonate, and bicarbonate concentrations, and the saturation state of aragonite and calcite minerals (Ω_a, Ω_c; Waldbusser et al., 2015b).

As atmospheric CO_2 levels continue to rise, different biological thresholds will be crossed at different times – depending not only on the species, but also by the stressor and the specific physiological process being affected. This complexity will result in a mixture of observed impacts in time and space. Metabolic coupling of O_2 and CO_2 complicates the interpretation of responses to deoxygenation and acidification (Box 1). Are systems negatively impacted by the loss of oxygen during organic matter decomposition, or by the acidification due to the coincident carbon dioxide release, or by both?

> The complex responses to rising CO_2 concentrations will result in a mixture of observed impacts in time and space.

Temperature effects over time are also complex. Warming might not always be stressful, but can also serve as an enhancer for activities such as spawning that are dependent on warm-interval conditions, and as a mechanism that increases growth rates of some calcifiers, potentially alleviating the impact of acidification (e.g., Waldbusser et al. 2011, Kroeker et al. 2014).

Despite these complexities, evidence from past responses to temperature change, hypoxia, and other environmental shifts indicate that there will be strong ecological impacts due to variability in these parameters (Moffitt et al., 2015a,b). Multi-stressor experiments offer a path forward for linking complex ocean chemistry changes with responses by individuals, populations and ecosystems (McElhany and Busch 2013, Reum et al. 2014), while also considering the temporal covariance of extreme events and sensitive life history stages (Waldbusser and Salisbury 2014).

Viewing changing ocean chemistry as a multi-stressor issue illuminates the need for coordinated action by natural resource, water and air managers and policy-makers.

Supporting Policy and Management Action

Recent research has highlighted that ocean acidification, hypoxia, and warming are part of a system of interacting stressors facing marine ecosystems. While ocean acidification has garnered attention at multiple levels of government, viewing changing ocean chemistry as a multi-stressor issue illuminates the need for coordinated action by natural resource, water and air managers and policy-makers.

Looking forward, we can focus on research trajectories that increase our ability to predict future perturbation scenarios and likely impacts on ocean resources. Theoretical models offer the potential to forecast co-variance of suspected stressors (e.g. Rodgers et al. 2015), and have promise in identifying nearshore regions that may be future hotspots of, or refugia from, combined acidification, thermal, and deoxygenation stress (Fiechter et al. 2014). These locations present ideal candidates for experimental scenario testing. The potential for field and laboratory experimentalists to work with modelers in experimental design for meaningful future-condition simulation is still largely underutilized and is a growth area for future research.

New interdisciplinary science approaches can inform and support novel cross-jurisdictional policy action that acknowledges and holistically tackles changing ocean chemistry.

References

1. Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. Science, 247(4939), 198-201.
2. Cai, W.J., Hu, X.P., Huang, W.J., Murrell, M.C., Lehrter, J.C., Lohrenz, S.E., Chou, W.C., Zhai, W.D., Hollibaugh, J.T., Wang, Y.C., Zhao, P.S., Guo, X.H., Gundersen, K., Dai, M.H., Gong, G.C. 2011. Acidification of subsurface coastal waters enhanced by eutrophication. Nat. Geosci. 4:766-770.
3. Evans, W., B. Hales, P. Strutton, K. Shearman, and J. Barth. 2015. Failure to bloom: Intense upwelling results in negligible phytoplankton response and prolonged CO_2 outgassing over the Oregon Shelf. J. Geophys. Res.
4. Fiechter, J., Curchitser, E. N., Edwards, C. A., Chai, F., Goebel, N. L., & Chavez, F. P. 2014. Air sea CO_2 fluxes in the California Current: Impacts of model resolution and coastal topography. Global Biogeochemical Cycles, 28(4), 371-385.
5. Gangsto, R., M. Gehlen, B. Schneider, L. Bopp, O. Aumont, and F. Joos. 2008. Modeling the marine aragonite cycle: changes under rising carbon dioxide and its role in shallow water $CaCO_3$ dissolution. Biogeosciences, 5, 1057–1072.
6. Gruber N. 2011. Warming up, turning sour, losing breath: Ocean biogeochemistry under global change. Phil. Trans. R. Soc. A 369:1980-1996.
7. Keeling, R. F., Körtzinger, A., & Gruber, N. 2010. Ocean deoxygenation in a warming world. Annual Review of Marine Science, 2:199-229.
8. Kroeker K.J., Gaylord B., Hill T.M., Hosfelt J.D., Miller S.H., Sanford E. 2014. The Role of Temperature in Determining Species' Vulnerability to Ocean Acidification: A Case Study Using Mytilus galloprovincialis. PLoS ONE 9(7): e100353.
9. McElhany, P., and D. S. Busch. 2013. Appropriate pCO_2 treatments in ocean acidification experiments. Mar. Biol. 160: 1807-1812.
10. Moffitt S.E., Moffitt R.A., Sauthoff W., Davis C.V., Hewett K., Hill T.M. 2015b. Paleoceanographic insights on recent oxygen minimum zone expansion: lessons for modern oceanography. PLoS ONE 10(1): e0115246.
11. Moffitt, S. E., Hill, T. M., Roopnarine, P. D., & Kennett, J. P. 2015a. Response of seafloor ecosystems to abrupt global climate change. Proceedings of the National Academy of Sciences, 112(15), 4684-4689.

12. Reum J.C.P., Alin S.R., Feely R.A., Newton J., Warner M., McElhany P. 2014. Seasonal carbonate chemistry covariation with temperature, oxygen, and salinity in a fjord estuary: implications for the design of ocean acidification experiments. PLoS ONE 9(2): e89619.
13. Rodgers, K. B., J. Lin, T. L. Frölicher. 2015. Emergence of multiple ocean ecosystem drivers in a large ensemble suite with an Earth System Model. Biogeosciences, 12, 3301-3320
14. Rykaczewski, R. R., & Dunne, J. P. 2010. Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model. Geophysical Research Letters, 37(21).
15. Salisbury J., Green M., Hunt C., Campbell J. 2008. Coastal acidification by rivers: a threat to shellfish? EOS Trans Am Geophys Union, 89:513–4.
16. Schmittner, A., A. Oschlies, H. D. Matthews, and E. D. Galbraith. 2008. Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO_2 emission scenario until year 4000 AD. Global Biogeochem. Cycles, 22:GB1013
17. Waldbusser, G. G., and J. E. Salisbury. 2014. Ocean Acidification in the coastal zone from an organism's perspective: multiple system parameters, frequency domains, and habitats. Annual Review of Marine Science, Vol 6. p. 221-247
18. Waldbusser, G. G., E. P. Voigt, H. Bergschneider, M. A. Green, and R. I. E. Newell. 2011. Biocalcification in the Eastern Oyster (Crassostrea virginica) in relation to long-term trends in Chesapeake Bay pH. Estuaries Coasts 34: 221-231.
19. Waldbusser, G.G. B. Hales, C.J. Langdon, B.A. Haley, P. Schrader, E.L. Brunner, M.W. Gray, C.A. Miller, I. Gimenez. 2015a. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. Nature Climate Change 5:273–280.
20. Waldbusser, G.G., B. Hales, C.J. Langdon, B.A. Haley, P. Schrader, E.L. Brunner, M.W. Gray, C.A. Miller, I. Gimenez, G.Hutchinson. 2015b. Ocean acidification has multiple modes of action on bivalve larvae. PLOSOne

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