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Editorial: Acidification and Hypoxia in Marginal Seas

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Editorial on the Research Topic

Acidification and Hypoxia in Marginal Seas

ACIDIFICATION AND DEOXYGENATION IN MARGINAL SEAS

Ocean acidification and hypoxia (dissolved oxygen $<2\,\text{mg L}^{-1}$ or $<62\,\mu\text{mol L}^{-1}$) are universal environmental concerns that can impact ecological and biogeochemical processes, including element cycling, carbon sequestration, community shifts, contributing to biodiversity reduction, and reducing marine ecosystem services (Riebesell et al., 2000; Feely et al., 2004, 2009; Andersson et al., 2005; Doney, 2006; Cohen and Holcomb, 2009; Doney et al., 2009, 2020; Kleypas and Yates, 2009; Ekstrom et al., 2015; Gattuso et al., 2015). While the stressors are global in their occurrence, local and regional impacts might be enhanced and even more accelerated, thus requiring even greater and faster consideration (Doney et al., 2020).

The driving mechanisms of acidification and hypoxia are inextricably linked in near-shore and coastal habitats. Along coastal shelf and its adjacent marginal seas, where the natural variability of multiple stressors is high, human-induced eutrophication is additionally enhancing both local acidification and hypoxia. For example, the well-known eutrophication of surface waters in the northern Gulf of Mexico caused hypoxic conditions that result in a pH decrease by 0.34 in the oxygen-depleted bottom water, which is significantly more than the pH decrease via atmospheric CO_2 sequestration alone (pH decrease by 0.11; Cai et al., 2011). Similar changes in coastal conditions involving biological respiration and atmospheric CO_2 invasion have also been observed in other marginal seas, urbanized estuaries, salt marshes and mangroves (Feely et al., 2008, 2010, 2018; Cai et al., 2011; Howarth et al., 2011). Other natural and anthropogenic processes, such as increased wind intensity and coastal upwelling, enhanced stratification due to global warming, along with more intense benthic respiration, more frequent extreme events, oscillation of water circulations, and variations in the terrestrial carbon and/or alkalinity fluxes, etc., all influence the onset and maintenance of acidification and/or hypoxia. For example, coastal upwelling brings both low pH and hypoxic water from below and enhances acidification and hypoxia in the coastal regions (Feely et al., 2008). Although acidification and hypoxia in the open oceans have received considerable attention already, the advances in our understanding of the driving mechanisms and the temporal evolution under global climate change is still poorly understood, particularly with respect to the region-specific differences, various scales of temporal and spatial variability, predictability patterns, and interactive multiple stressor impacts. Therefore, coastal ecosystems have a much broader range of rates of change in pH than the open ocean does (Carstensen and Duarte, 2019). The importance of understanding acidification and hypoxia for the biogeochemical and ecosystem implications in marginal seas is essential for climate change mitigation and adaptation strategy implementations in the future.

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The scope of this Research Topic is to cover the most recent advances related to the status of acidification and hypoxia in marginal seas, the coupling mechanisms of multi-drivers and human impacts, ecosystem responses, prediction of their evolution over space and time, and under future climate change scenarios. The authors of this Research Topic contributed a total of 35 papers covering a wide variety of subjects spanning from acidification and/or hypoxia (OAH) status, the carbonate chemistry baseline and trends, the impacts of OAH on the habitat suitability and ecosystem implications, and the long-term changes and variability of OAH in marginal seas.

Across many different temporal and spatial scales, the contributed papers highlighted the presence of acidification and hypoxia with their major controls in the marginal seas of the North Pacific, including the subpolar Bering Sea, the temperate China Seas of Bohai Sea, Yellow Sea and the East China Sea, Japanese coasts (Tokyo Bay and the coast of Hokkaido); the Atlantic, including the northern Gulf of Mexico, the Chesapeake Bay, and the Mediterranean Sea; the Arctic, including the Amundsen Gulf; the Indian Ocean, including the Arabian Sea, the Red Sea, etc.

In the large river dominated East China Sea shelf, hypoxia occurs in bottom waters in summer (Li et al., 2002; Zhu et al., 2017). Circulation plays an important role in the biogeochemical processes including redistribution of nutrients, changes in stratification, water residence time and ventilation of the shelf water (Liu et al.). Furthermore, the impact of typhoons results in hypoxia demise with immediate extensive vertical mixing. However, the excess freshwater and nutrient loading during the typhoon period would boost the hypoxia restoration later on when the shelf waters are re-stratified (Liu et al.). With respect to coastal oxygen consumption, water, and sediment interactions contribute dynamically, and water-column respiration processes contribute to as much as 24–69% of total oxygen consumption beneath the pycnocline (Zhou et al.). Deconvolving the water column vs. sedimentary oxygen respiration in the oxygen depletion off the Changjiang estuary and East China Sea is an important advancement of our understanding of oxygen sinks.

From the perspective of a comparison between the northern East China Sea and the adjacent southern Yellow Sea, higher CO_2 solubility together with the biogeochemical CO_2 additions caused the colder Yellow Sea water generally to have lower aragonite saturation state index (Ω_{Ar}) than the warmer northern East China Sea water (Xiong et al.). Although marine organic matter is the major source of the oxygen-consuming carbon in the large river-dominated margins (Green et al., 2006; Wang et al., 2016), the maximum of hypoxia may come at a significant lag from the time of peak productivity. For example, bottom water hypoxia and acidification has a 2-month delay when compared with the maximum primary production in surface waters of the northern Gulf of Mexico (Huang W-J. et al.).

In addition to biogeochemical processes, upwelling also plays an important role in the status and distribution of hypoxia/acidification occurrence, such as in the well-known upwelling region off the California coast (Feely et al., 2008, 2016). The Chesapeake Bay is also impacted by upwelling-induced acidification, which will intensify with the wind-driven upwelling to cause low pH and "corrosive" water in the shallow shoals of the estuaries, enhancing large temporal pH and Ω_{Ar} seasonal fluctuations (Li et al.). Furthermore, non-local mechanisms may also be important in regulating the occurrence of hypoxia. For example, the Kuroshio intrusion into the northern South China Sea relieves the occurrence of hypoxia in the coastal zone (Lui et al.).

In the coastal seas without large river influence, OAH also occurs as a consequence of seasonal productivity and large-scale circulation processes. Along the Hokkaido coast, the highly euphotic Tokyo Bay, the Netarts Bay off Oregon, and the coastal habitat types on eastern Long Island, time series observations show the progression of seasonal OA and deoxygenation, often resulting in hypoxic conditions. In addition, high frequency pH and dissolved oxygen (DO) observations across sub-diel, diel and seasonal time scales across various habitat types (salt marsh, macroalgae, seagrass, open water) in the northeast US show the impact of ecosystem metabolism to modulate OAH (Wallace et al.). Comprehensive analysis of coastal observations suggests that pH and Ω_{Ar} decreased by 0.2-0.6 and 1–2, respectively, via circulation and biogeochemical processes, where Ω_{Ar} decreases can occur in the summer bottom waters and will be a common phenomenon in the near future in the eutrophic Tokyo Bay (Yamamoto-Kawai et al.). Fujii et al. and Fairchild and Hales separately showed that along the Hokkaido coast and in Netarts Bay along the Oregon coast, Ω_{Ar} sometimes decreases to values below the threshold for significant negative impacts on some calcifiers (e.g., 1.1–1.5 for bivalve larvae, 1–1.5 for pteropods, and pH values of 7.6-7.8 for echinoderms and decapods; Bednaršek, Ambrose et al.; Bednaršek, Calosi, et al.; Bednaršek, Naish, et al.; Bednaršek et al., 2019). Continued oceanic uptake of carbon dioxide will continue to decrease pH and Ω_{Ar}, with high-latitude surface waters expected to be fully undersaturated by the end of this century because of the natural low buffer capacity there (Feely et al., 2009; Steinacher et al., 2009).

Crossing these pH thresholds consistently occurs in salt marsh and seagrass habitats along with hypoxic conditions (Wallace et al.). Under the IPCC global warming and acidification scenarios, Ω_{Ar} in some coastal environments will drop below these thresholds by 2090, indicating that critical thresholds may be crossed more frequently in the future and severely damage calcifiers and impact overall fisheries production (Tai et al.).

OCEAN ACIDIFICATION AND HYPOXIA AT THE CHEMICAL-BIOLOGICAL INTERFACE

Under continuously decreasing pH and low dissolved oxygen conditions, there is a general concern that the local bottom waters and the underlying sediments could switch from hypoxic to anoxic conditions. For example, in the hypoxic northern Gulf of Mexico, low DO conditions in sediment did not promote anoxic diagenesis as anticipated, possibly linked to the reduction of bioturbation during the hypoxic spring and summer months (Rabouille et al.). In the hypoxic area of the Eastern Arabian Sea, strong denitrification results in large nitrogen loss, accounting for as much as 20–60% of the total annual fixed nitrogen loss in oxygen minimum zone of the Arabian Sea (Sarkar et al.). Methane emissions in coastal regions can also be very large, accounting for as much as 15% of the methane emission from the Arabian Sea (Sudheesh et al.). Moreover, sediment diagenesis plays a critical role in triggering and maintaining hypoxia of lagoon waters, and it may be enhanced by changes in regional climate conditions, such as the increase in frequency of summer heat waves (Brigolin et al.).

IMPACTS OF OCEAN ACIDIFICATION AND HYPOXIA ON MARINE ORGANISMS AND ECOSYSTEMS

OA and hypoxia are significant stressors for marine species, communities, ecosystems, especially when they act interactively and cumulatively. Studies show that harmful effects of OA on the marine calcifiers have already been observed. In the Arctic and subpolar Beaufort Sea, Bering Sea, and the Amundsen Gulf, corrosive water for aragonite induced extensive shell dissolution in ecologically important zooplankton, i.e., pteropods (Niemi et al.). Conducting a more comprehensive OA risk assessment, Bednaršek, Naish, et al. elucidated high exposure OA risk in combination with high sensitivity and low adaptive capacity for pteropods in the polar habitats of the Northern Hemisphere.

Thresholds are very useful tools to determine when the OA exposure can start causing negative physiological and organismal impairments. With the echinoderms and decapods being one of the most dominant as well as ecologically and economically important species, the application of the thresholds for these two groups can have important regional and global implications (Bednaršek, Ambrose, et al.; Bednaršek, Calosi, et al.). These thresholds provide the foundation for consistent interpretation of OA monitoring data or numerical ocean model simulations to support climate change marine vulnerability assessments and evaluation of ocean management strategies.

On longer time scales, model results indicate that OA amplifies multi-stressor impacts on global marine invertebrate fisheries, with the fish catch potential to decrease by 12%, with 3.4% being attributed to OA by the end of this century (Tai et al.). A comprehensive understanding of OA effects based on the thresholds and predictive sensitives allows for improved predictions of ecosystem change relevant to effective fisheries resource management, as well as providing a more robust foundation for ecosystem health monitoring of the negative OA impacts in the most sensitive OAH habitats. While OA can also significantly affect the range of responses in different zooplankton taxa, the study by Keil et al. found little association between empirical measures of *in situ* pH and the abundance of sensitive taxa as revealed by meta-analysis. The authors concluded that the mismatch between experimental studies and field observations should have some important ramifications for the design of long-term monitoring programs and interpretation and use of the data produced.

On the community level, the results of mesocosms-based experiments across various marginal seas, from the coastal East China Sea, Bohai Sea, coastal upwelling and riverine ecosystems in Chile, all agree that increasing partial pressure of CO_2 (pCO_2) can modulate plankton structure, composition and abundance, leading to altered biogeochemical cycles of carbon and nutrients, and carbon fluxes. Elevated pCO_2 mesocosm experiments in the East China Sea boosted biomass of diatoms, while impeding the succession of diatoms to dinoflagellates, and corresponds with increased abundance of virus and bacteria (Huang R. et al.). Such results appear to be region specific, because a different community response was demonstrated in the Bohai Sea, where high pCO_2 resulted in the decreased total diatom abundance, favoring the ratio of central to pennate diatoms. In addition, combined warming and OA significantly decreased the proportion of diatoms to dinoflagellates and caused the shifts in phytoplankton composition due to interactive and cumulative effect, ultimately resulting in carbon flux and sinking rate changes (Feng et al.). Another study in the coastal area off Chile, characterized by high natural variability, showed no response to high pCO_2 treatments; instead the changes during the incubations were related to other factors, such as competition and growth phase (Osma et al.). The study suggests that the pre-exposure to variable coastal gradients that structure local adaptation patterns could play an important role in determining responses of coastal phytoplankton communities to increased impact of OA. In the experiments combining various OA and light treatments conducted on 15 laboratory experimental generations of picophytoplankton, Bao and Gao showed that *Synechococcus* grew faster under the OA treatment with inhibiting light level only, suggesting differential picophytoplankton responses that are light dependent under various depth conditions.

Hypoxia is another stressor present mostly in the tropical and temperate marine ecosystems. In a tropical Caribbean reef, hypoxia had largest negative impact on the performance of a key reef herbivore. The interactive temperature and DO extremes with low pH led to impaired performance of the reef echinoderms (Lucey et al.).

The studies investigating the impact of carbonate chemistry variability in coastal regions demonstrate the importance on both biological and biogeochemical responses. Coastal and estuarine habitats are characterized by distinct temporal fluctuations in carbonate chemistry, ranging from sub-diel to diel to seasonal, which are expected to increase under projected scenarios even in the highly buffered systems (Urbini et al.). Extreme variability in hypoxia/reoxygenation seem to change the expression of the mitochondrial quality control pathways only of the species with high DO sensitivity, such as Pacific oysters *Crassostrea gigas*, but not blue mussels *Mytilus edulis*, elucidating the mechanisms of mitochondrial protection against hypoxia-reoxygenation-induced damage that might contribute to hypoxia tolerance in marine bivalves (Steffen et al.). In addition to eutrophication, marine heatwave might also contribute to triggering deoxygenation and biodiversity loss in the marginal seas. In a southwestern Atlantic coast, marine heatwaves, sewage and eutrophication combined to trigger deoxygenation and biodiversity loss (Brauko et al.).

LONG-TERM VARIABILITY IN OCEAN ACIDIFICATION AND HYPOXIA IN MARGINAL SEAS

In the marginal seas of the Indian Ocean (Persian Gulf, Red Sea and Andaman Sea), deoxygenation has been observed numerous times over the last few decades (Naqvi). Hypoxia in the East China Sea has become more severe since the 1960s mainly due to eutrophication, stronger stratification, and longer water residence times (Wang et al.). ENSO and global warming may also have indirect effects by regulating river discharge, stratification, and water residence time, etc. (Wang et al.). In the southwestern English Channel within the Northeastern Atlantic Ocean, time-series observations show that average $p\mathrm{CO}_2$ increases at rate of 2.95–3.52 μatm yr^{-1}, with a corresponding decrease in mean pH of 0.0028 yr^{-1} (Gac et al.), an acidification rate faster than the open ocean ($\sim$1.5 μatm yr^{-1} for $p\mathrm{CO}_2$ and $-0.0016 \sim -0.0017$ yr^{-1} for pH; Bates et al., 2014), and consistent with some other marginal seas, including the Mediterranean (Hassoun et al., 2015). Both atmospheric CO_2 absorption and climatic indices (i.e., North Atlantic Oscillation and Atlantic Multidecadal Variability) are responsible for this fast OA rate in the northern East Atlantic Ocean (Gac et al.).

CONCLUSIONS AND PERSPECTIVES

OA and hypoxia often occur more severely in the marginal seas than in the open ocean globally, making the marginal seas species and ecosystems more vulnerable to future climate change related changes. Ω_{Ar} and pH conditions in some marginal seas are already below the thresholds that can induce negative biological responses for many marine calcifiers, especially in the rapidly changing polar/subpolar marginal seas or in coastal upwelling regions. In temperate marginal seas, subsurface water can be corrosive, which may be having an impact on fisheries and the ecosystem services they provide. For large river-dominated margins, there might be significant time lags of the bottom water hypoxia/acidification after the peak of the primary production. For coastal ecosystems in the margin systems characterized by the OA/hypoxia, we can expect differential effects and evolution across regional habitats, depending on the baseline and the physical and biogeochemical dynamics of local conditions. Understanding of such spatial and temporal variability is thus essential to start recognizing more sensitive habitats and conduct appropriate monitoring or management practices to protect and preserve ecologically and economically important ecosystems.

Marginal seas are productive areas essential for the human wellbeing and economic dependence, but insufficient awareness of biological and ecosystem responses and potential management strategies might be detrimental, especially in the developing countries. Although this Research Topic contributed to advance understanding of the chemical changes, the interpretation of biological responses in the marginal seas is still in need of more research. Such responses are complex, thus requiring a tight integration with the chemical and biogeochemical multi-scale parameters that can induce stress, community reorganization and shifts, biological interactions and others impacts.

An immediate need for enhanced understanding of multiple stressor effects as well as the effects of increased variability and unpredictability in the marginal seas systems is critical for developing better management strategies. While a single study indicates that multiple stressor extremes in the tropics lead to the physiological impairments, systematic studies are needed to reveal multiple stressor impacts on the marginal seas marine ecosystems. Equally, the projections of future conditions in dynamic coastal systems show enhanced variability and extreme values related to OA, which can be habitat specific and thus extremely variable, yet biological and biogeochemical implications of these impacts are largely unknown. In particular, a better understanding of increased amplitude variability and prolonged duration below thresholds for organisms and ecosystems is needed for the coastal-estuarine habitat. Various temporal scales of variability (from sub-diel to diel to seasonal) needs to be further examined to understand where and when the biological bottlenecks will first occur. The comparison of sensitivity and resilience of various marginal seas systems should be examined through the natural variability baseline to understand the extent of species plasticity and adaptation. Moreover, attention needs to be given to the temporal variation (autocorrelation and cross-correlations) that represents the framework of the "predictability" in the habitats (Bernhardt et al., 2020), which can also significantly structure biological responses. Extensive theoretical and empirical work shows that the predictability might in fact be a primary driver determining the biological responses compared to the variability, thus both, predictability and variability require more attention to assess their impact and trade-offs in the marginal seas.

The integrated results of this Research Topic carry important implications for variety of ecosystems and ecosystem services, including aquaculture practices, fisheries management, human wellbeing carbon sequestration, etc. Given enormous potential of ecosystems services in the marginal seas systems, much more comprehensive approaches are needed to assess the impacts and economic evaluation of their losses. The approach needs to be based on the integration of the chemical, biological and biogeochemical data, allowing to monitor changes over time, and developing management approaches to preserve the health and the biodiversity within the marginal seas in the face of the global climate change, including habitat restoration, protection of biogenic habitats, removal of anthropogenic nutrients, potential development of OAH habitat refugia, marine spatial planning, fishing practices and capacity of adaptation and resilience of the changing socio-ecological system. Special attention needs to be given to the "blue carbon" ecosystems given their role related to sequestering carbon and potentially slowing down the long-term changes at the local level while also exacerbating short-term variability. To this end, a spatially targeted evaluation related to different causes of OAH involving comprehensive interactions with local stakeholders is needed maximize the utility of smaller-scale policy recommendations.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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