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Special Topic: Complex Marine Ecosystems and Planetary Boundaries

Revisiting the ocean acidification planetary boundary

Helen S. Findlay[1],* and Richard A. Feely[2]

Ocean acidification (OA) is one of the nine planetary processes recognized in the planetary boundary framework (PBF) that was established in 2009 [1]. The rapid uptake of carbon dioxide (CO_2) from the atmosphere into the ocean is causing a change in ocean chemistry, a process termed OA. Hydrogen ion concentration is increasing (increasing acidity, or decreasing pH), and carbonate ion concentration is decreasing, resulting in declining saturation states of important carbonate minerals like aragonite (Ω_{Arag}) that form the shells or skeletons of some calcifying organisms.

Mean global surface Ω_{Arag} was used as the control variable for the original OA planetary boundary, which was set at 80% of the pre-industrial mean value [1]. Up until 2024, the boundary was deemed not to have been crossed. However, in 2025, a reanalysis of the boundary, which added uncertainties, regionality, the sub-surface ocean, and additional biological thresholds, proposed that the boundary had in fact been surpassed in the early 2020s [2]. The analysis also showed that the 80% boundary did not actually satisfy the criteria originally used to justify its selection [2]. For instance, the first criterion was to keep the polar oceans from becoming undersaturated; however, regions of the Arctic surface and subsurface waters already experience undersaturation today. While these regions are now expanding because of OA, modelling suggests that some areas (e.g. the Siberian shelf and Chukchi Sea) may have experienced periods of undersaturation since pre-industrial times [3,4]. The second criterion was to keep warm-water coral reefs in conditions that are considered above marginal for growth, which again is not upheld by the 80% boundary—to keep all warm-water coral reefs in conditions considered 'good' for growth, would require the boundary to be set at 85% [2]. Despite this analysis [2], further development and potential integration with other factors is still needed to properly determine the boundary, and we discuss some of these issues below.

OA is a significant concern because of the potential impacts and consequences to marine ecosystem biodiversity and functioning, and ultimately the ecosystem services that a healthy ocean provides for our planet. There is a growing body of evidence that suggests marine ecosystems are now being impacted by OA (e.g. [5,6]). The sensitivity of these systems therefore needs to be considered to help set the OA boundary so that it is meaningful in realizing a safe operating space in the broadest context. That said, incorporating biological components into the OA PBF is not simple. Organisms show varied responses due to inherent population differences from acclimation and adaptation, and across life-stages. Biological or ecosystem indicators can be used to show how the system is changing, but attributing such changes solely to OA, or indeed warming or any other individual driver, is difficult in an ocean where multiple drivers are changing concomitantly. Biological indicators should therefore be focused on species or traits that are known to have sensitivity to OA [7], and further work in developing and evaluating these indicators is needed. Progress could be made by establishing a small suite of sentinel taxa and traits with well–documented OA sensitivities, developing corresponding biological thresholds from experimental and field evidence, and testing these candidate indicators within existing observing networks where chemical and biological data are already co–collected. Indeed, steps are being taken towards this, for example, within the Global Ocean Acidification Observing Network biology working group and associated projects. Examination of variability and associated OA responses [8] could also be a useful method to move from a single, somewhat arbitrary, boundary value to instead using a risk boundary defined by moving outside natural variability. These steps would allow potential indicators to be evaluated in a consistent and scalable way while retaining feasibility for integration into the PBF.

There is an ongoing debate within the OA community about the most appropriate control variable to use as an indicator, not only in the PBF but also more broadly, and across scales—global, regional, and national indicators. The UN SDG14.3.1 uses pH as an OA indicator, as does the WMO as part of its Global Climate Indicators. Ω_{Arag} was originally chosen

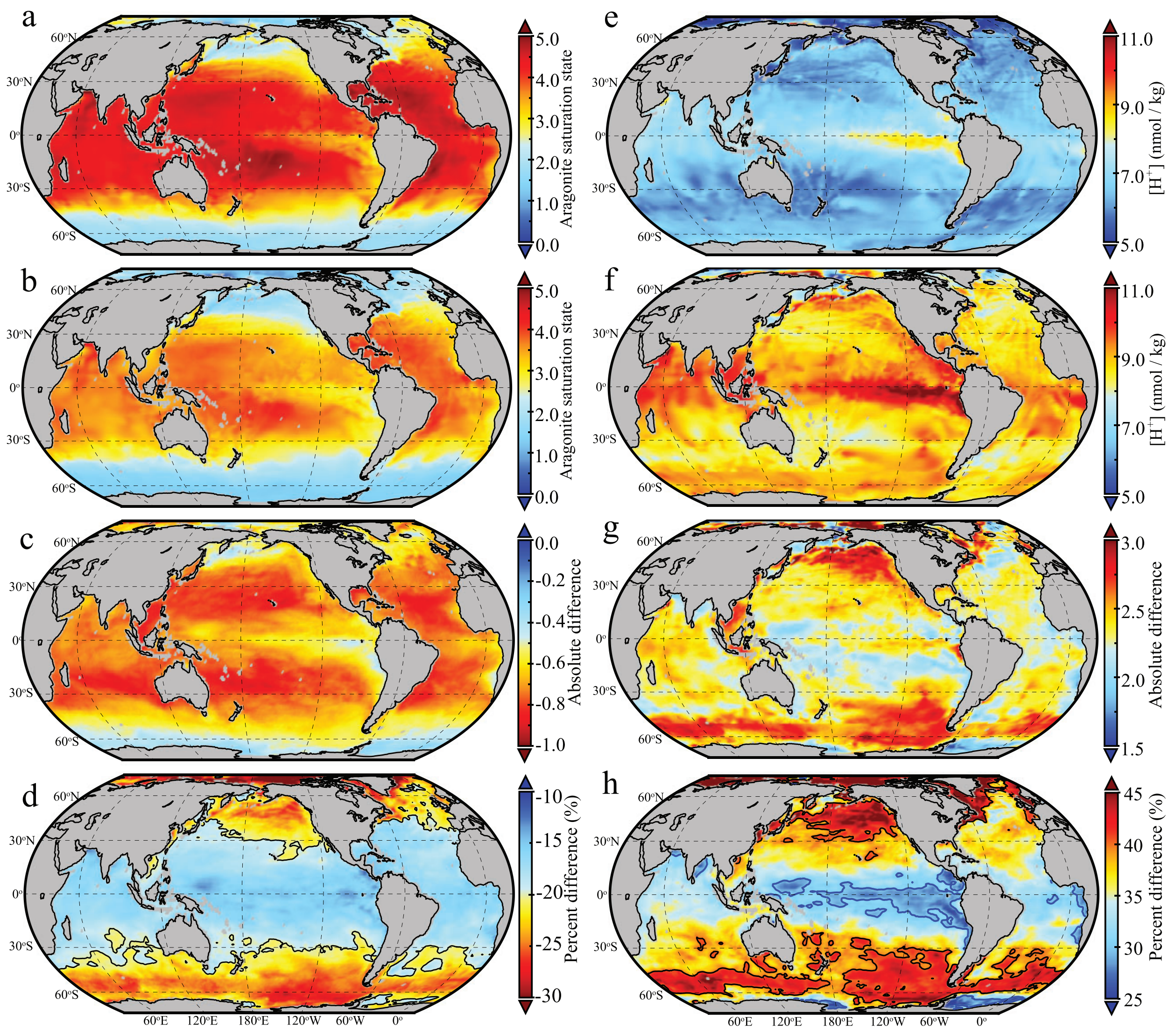

Figure 1. Maps of aragonite saturation state ($\boldsymbol{\Omega}_{\mathrm{Arag}}$) on the left (a–d) and hydrogen ion concentration ($[\mathrm{H}^+]$ in nmol kg^{-1}) on the right (e–h), showing (a) pre-industrial levels, (b) year 2020 levels, (c) absolute difference between year 2020 and pre-industrial, and (d) percentage difference between year 2020 and pre-industrial. Maps use model-data compilation outputs described by [15], produced using multi-model ensemble medians. Contour lines in the percentage difference maps represent 20% decline (black contour) for $\boldsymbol{\Omega}_{\mathrm{Arag}}$ (d), and 30% increase (blue contour) and 40% increase (black contour), respectively, for $[\mathrm{H}^+]$ (h).

in the PBF because of its relationship between acidification and calcification/dissolution processes that can potentially impact marine calcifiers as Ω_{Arag} decreases. However, biologists generally agree that pH is more relatable to a broader suite of biological and physiological responses than Ω_{Arag}, and given that changes in acidity are the direct response of CO_2 uptake, it does seem the more pertinent choice as an indicator. That said, while reporting pH, it is important to consider that the comparison of trends in different locations with different initial pH values will reflect different absolute values in hydrogen ion concentration (H^+), and therefore H^+ is recommended to be reported instead of, or alongside, pH [9]. Examples of Ω_{Arag} and H+ as control variables are shown in Fig. 1. Other suggestions for an OA indicator include seawater $p\mathrm{CO}_2$ or dissolved inorganic carbon, which would give an indication of the carbon content of seawater, more directly relevant to the uptake of CO_2 and feedback to planetary dynamics such as the ocean carbon sink. Ultimately, the control variable needs to be observable both historically (to get the baseline Holocene value before the industrial revolution) and today. There are no widely accepted geochemical proxies for Ω_{Arag} for paleo-reconstruction; instead, Ω_{Arag} is calculated from other carbonate parameters. In contrast, there are direct geochemical proxies for reconstructing pH (e.g. boron isotopes) and pH is increasingly being measured *in situ*. Given this observability, pH (or H^+) is a strong indicator candidate, and next steps should focus on defining baseline values and variability, and integrating geochemical and biological indicators to define the boundary value.

While the 'solubility pump', i.e. the solubility of CO_2 and atmosphere–ocean gas exchange, driven by physical processes such as temperature, wind, and ocean currents, is the dominant process influencing direct uptake of 'anthropogenic' CO_2, biological communities play a significant role in the global carbon cycle. Biological activity provides important mechanisms for carbon uptake and transport from the atmosphere to the surface ocean, and from the surface ocean to intermediate and deep waters [10]. These biological processes (i.e. photosynthesis/respiration, calcification/dissolution and sedimentation) are important feedback mechanisms for ameliorating the impacts of releasing anthropogenic CO_2 into the atmosphere. Modelling studies of primary production and total alkalinity changes in the upper ocean indicate that these feedback mechanisms play a large role in controlling the atmosphere–ocean pCO_2 deficit and, consequently, the size of the ocean CO_2 sink and its variability over time [10,11]. Decreases in phytoplankton production resulting from increased water column stability from global warming reduce the air–sea pCO_2 gradient on seasonal and interannual time scales, causing reduced CO_2 uptake and carbon export. On the other hand, OA causes a decrease in near-surface calcification and enhances carbonate dissolution at deeper depths, both of which increase alkalinity on decadal and longer time scales [11]. The balance between these opposing feedback mechanisms will have measurable impacts on the ocean's future ability to sequester CO_2 from the atmosphere. Greater integration of satellite Earth observations with *in situ* monitoring and biogeochemical models could substantially improve our ability to constrain these feedbacks. This integrated approach would enable detection of ecosystem-scale changes in productivity, calcification, and carbon export, while providing spatially resolved assessments of how biological processes modulate the ocean's CO_2 uptake. These then could feed into the OA boundary by monitoring and detecting biologically driven changes in carbon uptake, identify emerging hotspots of vulnerability, and provide more robust estimates of when and where biological thresholds may be exceeded.

The combined effects of multiple stressors, including acidification, deoxygenation, and warming, that have been intensifying over the past century are now having profound, and potentially, nonlinear impacts on marine ecosystems. While OA is mainly caused by the uptake of anthropogenic CO_2 from the atmosphere, it also can be accelerated in subsurface open-ocean and coastal waters where the anthropogenic CO_2 combines with biological respiration-produced CO_2 to rapidly reduce the pH and increase pCO_2 to the point that the waters become undersaturated with respect to calcium carbonate [12,13]. These accelerated acidification processes are greatest at depths where the oceanic buffer capacity is decreasing rapidly during the summer and autumn months when respiration processes are at their maximum extent. Moreover, many marine organisms can also be negatively impacted by extremes in water temperature in surface and subsurface waters caused by marine heatwaves (MHW), downwelling, and intense El Niño Southern Oscillation (ENSO) events. Recent modelling and field studies have shown that prolonged periods of intense warming (caused by back-to-back MHW and ENSO events) followed by acidification events can cause significant changes in suitable habitat volume [14]. More research is needed to better understand the broad-scale consequences of these interactive effects and how they should be best incorporated into the PBF.

Assuming there will be continuing and sustained research on this topic and, consequently, our understanding of biological responses to OA and other multiple stressors continues to grow with time, our concepts of threshold criteria and appropriate control variables will need to be regularly reviewed and revised. These changes are necessary to respond to the challenges and complexities of the new scientific data and information. This is also true for most, if not all, of the other planetary boundaries that are described in this volume. Indeed, more planetary boundaries may be required to fully define the safe operating space for ensuring the sustainability of our marine ecosystems and their interactions with other components of the planetary system.

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Helen S. Findlay[1,*] and Richard A. Feely[2]
[1] Plymouth Marine Laboratory, UK and [2] NOAA Pacific Marine Environmental Laboratory, USA
***Corresponding author**. E-mail: hefi@pml.ac.uk

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