

The collapse of the marine ecosystems

By Howard Dryden

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Summary

Over the last 265 million years the ocean has passed through five great crises in which a large pulse of carbon, or in one case an asteroid impact, changed the chemistry of seawater. This report compares those past events with the ocean of today, using two measures: the aragonite saturation of surface water and the share of marine life that was lost. The comparison shows that the modern ocean started from a weaker chemical position than in any of the past events, that its chemistry is now changing faster, and that its animal life has already fallen by between about one half and two thirds since 1850.

1. Why aragonite saturation matters

Aragonite is the form of calcium carbonate that corals, pteropods, the larvae of many shellfish and other animals use to build their shells and skeletons. Scientists express how easily aragonite can form with the saturation state, Ω , which is calculated from the pH, carbon dioxide, alkalinity, calcium, temperature and salinity of the water (National Research Council, 2010). Aragonite starts to dissolve in seawater when Ω falls below 1.0.

Sensitive animals suffer well before the water reaches that point. The larvae of bivalves such as oysters and mussels respond at Ω values of 1.2 to 1.5 (Waldbusser et al., 2015), and shelled pteropods, a key food for fish, are harmed when Ω falls below about 1.5 (Hofmann Elizondo et al., 2024). For this reason, we treat Ω 1.6 as the upper edge of a marginal zone for sensitive shell builders (Dryden and Duncan, 2026a).

When the ocean absorbs carbon dioxide from the air, the pH falls and the concentration of carbonate ions falls with the pH, so the value of Ω declines as well. The fall in Ω is therefore a direct chemical measure of ocean acidification and of the stress that acidification places on shell-building life.

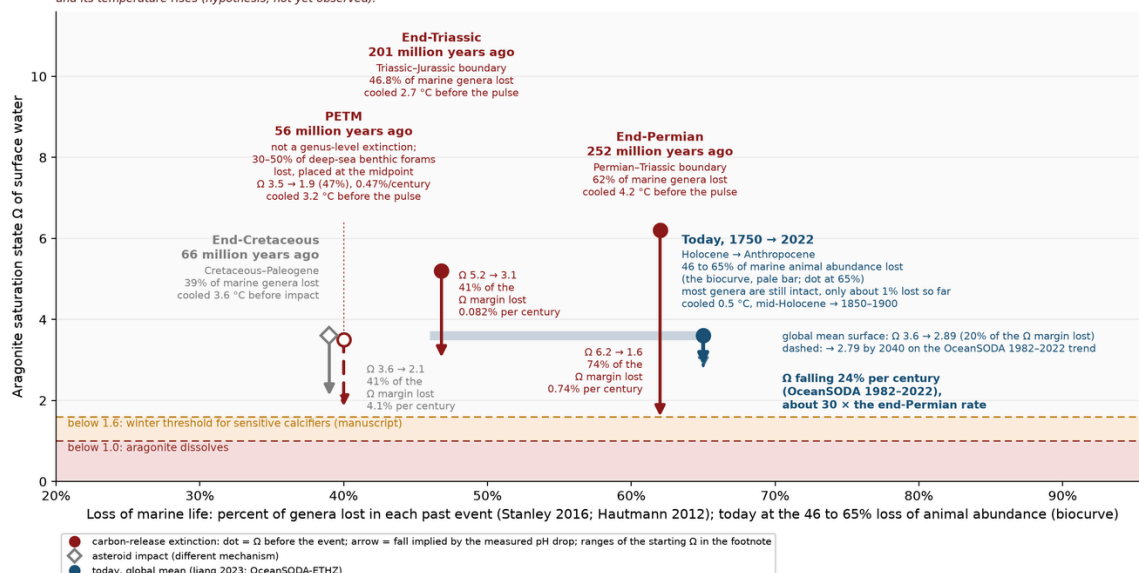
2. Five past crises compared with the ocean today

Figure 1 compares four past extinction events with the ocean today. For each event, it shows the aragonite saturation of surface water before and after the carbon pulse, set against the share of marine life that was lost.

Carbonate margin against loss of life: what the ocean had, what it lost, and how many genera died

Each arrow runs from the aragonite saturation before the event to the level implied by the measured pH drop; the horizontal position is the share of marine life lost: genera for the past events, animal abundance (the biocurve) for today, since the modern event is in progress and the genus count has not yet moved. No past event on the boron record took the global-mean saturation below about 1.6; the end-Permian, the worst, reached that level. Today's ocean starts from the lowest calcium and highest Mg/Ca in 265 million years, its cold basins are already at 1.3 to 1.6 in winter (manuscript), and the fall is about 30 times faster than the end-Permian. After past events the chemistry recovered in tens of thousands of years; the biology took millions (Henehan 2019; Trudgill 2025).

Note (interpretation): the ocean entered the industrial era with the smallest carbonate margin of the last 265 million years, lowest calcium, highest Mg/Ca and cold icehouse water, so it was primed for an acidification extinction once a large carbon pulse arrived. Anthropogenic carbon supplied the pulse and compressed a change that took the end-Permian about ten thousand years into about two centuries. Because its aragonite saturation is so low, the ocean today is more sensitive to that pulse than at any stage in the last quarter of a billion years; chemical pollution adds a stressor that no past event carried. Marine life is heading for a mass extinction that could be more devastating than any previous event. A further hazard lies in the abyss: sediments 0.5 to 1.0 km thick covering about half the planet could start to ferment if the deep ocean loses its oxygen and its temperature rises (hypothesis, not yet observed).



Starting Ω and its published range: end-Permian 6.2 (2.4 to 6.2; Clarkson 2015 Science, Table S6, low- and high- CO_2 states); end-Triassic 5.2 (3.3 to 7.0; Trudgill 2025 Nat. Commun., calcite 5.0-10.7 converted with $D_{\text{calc}} = 0.65 D_{\text{arag}}$); end-Cretaceous 3.6 (3.0 to 4.0; Henehan 2019 PNAS pH and CO_2 with Horita 2002 calcium); PETM 3.5 (3.0 to 4.0; Tyrrell & Zeebe 2004). Genera lost: Stanley 2016 (PNAS); end-Triassic: Hautmann 2012 (eS); PETM benthic forams: Thomas 2007. Cooling before each event: PhanD stage medians (Judd 2024), the stage before the event minus the stage before that; today: Temp12k (Kaufman 2020). Falls: PyCO2SYS at constant alkalinity for each published pH drop, the instantaneous chemical response; weathering and dissolution feedbacks soften slow events such as the PETM. Rate = percent of Ω lost divided by the published duration, per century (end-Triassic 50 kyr, PETM 10 kyr, end-Permian 10 kyr, K-Pg 1 kyr); durations are upper limits, so palaeo rates are lower bounds. Today: Jiang 2023 (1750), OceanSODA-ETHZ (1982-2022); 2040: linear OceanSODA 1982-2022 trend. www.goesfoundation.com

Figure 1. Carbonate margin against loss of life in four past events and in the ocean today. Each arrow runs from the aragonite saturation of surface water before an event to the level implied by the measured fall in pH, and the horizontal position gives the share of marine genera lost in each past event, or the loss of animal abundance for today.

The end-Permian extinction, 252 million years ago. This event, known as the Great Dying, was driven by the huge volcanic eruptions of the Siberian Traps. About 62% of marine genera and about 81% of marine species were lost, which makes it the worst event in the fossil record (Stanley, 2016). Boron isotopes in fossil shells show a sharp drop in seawater pH of about 0.6 to 0.7 units during the second pulse of the extinction, in an acidification event that lasted about 10,000 years (Clarkson et al., 2015).

The end-Triassic extinction, 201 million years ago. Volcanic carbon from the Central Atlantic Magmatic Province, released as the supercontinent Pangaea began to break apart, drove this event. Nearly half of all marine genera, 46.8%, did not survive into the Jurassic (Hautmann, 2012). Boron isotopes in fossil oysters show that seawater pH fell by at least 0.29 units (Trudgill et al., 2025).

The Toarcian ocean anoxic event, 183 million years ago. Volcanic carbon from the Karoo and Ferrar provinces warmed the planet and stripped oxygen from large parts of the ocean. Boron isotopes in brachiopod shells show that seawater pH fell before and during the event, and carbonate production by marine life collapsed at the same time (Müller et al., 2020).

The end-Cretaceous extinction, 66 million years ago. An asteroid struck Chicxulub, on the coast of the Gulf of Mexico, and ended the age of the dinosaurs (Schulte et al., 2010). Between 38% and 40% of marine genera disappeared (Stanley, 2016). Surface seawater pH fell by about 0.25 units within a thousand years of the impact (Henehan et al., 2019).

The Paleocene-Eocene Thermal Maximum, 56 million years ago. A very large release of mostly volcanic carbon warmed the planet rapidly (Gutjahr et al., 2017). This event was not a mass extinction at the level of genera, but between 30% and 50% of the species of deep-sea benthic foraminifera were lost (Thomas, 2007). Surface pH fell by about 0.3 units, and the ocean stayed acidic for at least 70,000 years (Penman et al., 2014).

Ocean acidification is now linked by direct chemical evidence to three of the five largest extinction events in the history of the Earth (Trudgill et al., 2025). In each of these past events, the chemistry of the ocean recovered within tens of thousands of years, but the recovery of life and of the carbon cycle took far longer (Henehan et al., 2019).

The two kinds of loss in Figure 1 are measured in different ways. For the past events, the fossil record counts the share of genera that were lost. For the ocean today, the measure is the fall in the numbers of animals, because most genera still survive while their populations collapse. The International Union for Conservation of Nature records only 15 global extinctions of marine animal species in the past 514 years, compared with 514 extinctions of land animals over the same period (McCauley et al., 2015). The ocean is losing its animals long before it loses its species, a process that McCauley and colleagues call marine defaunation.

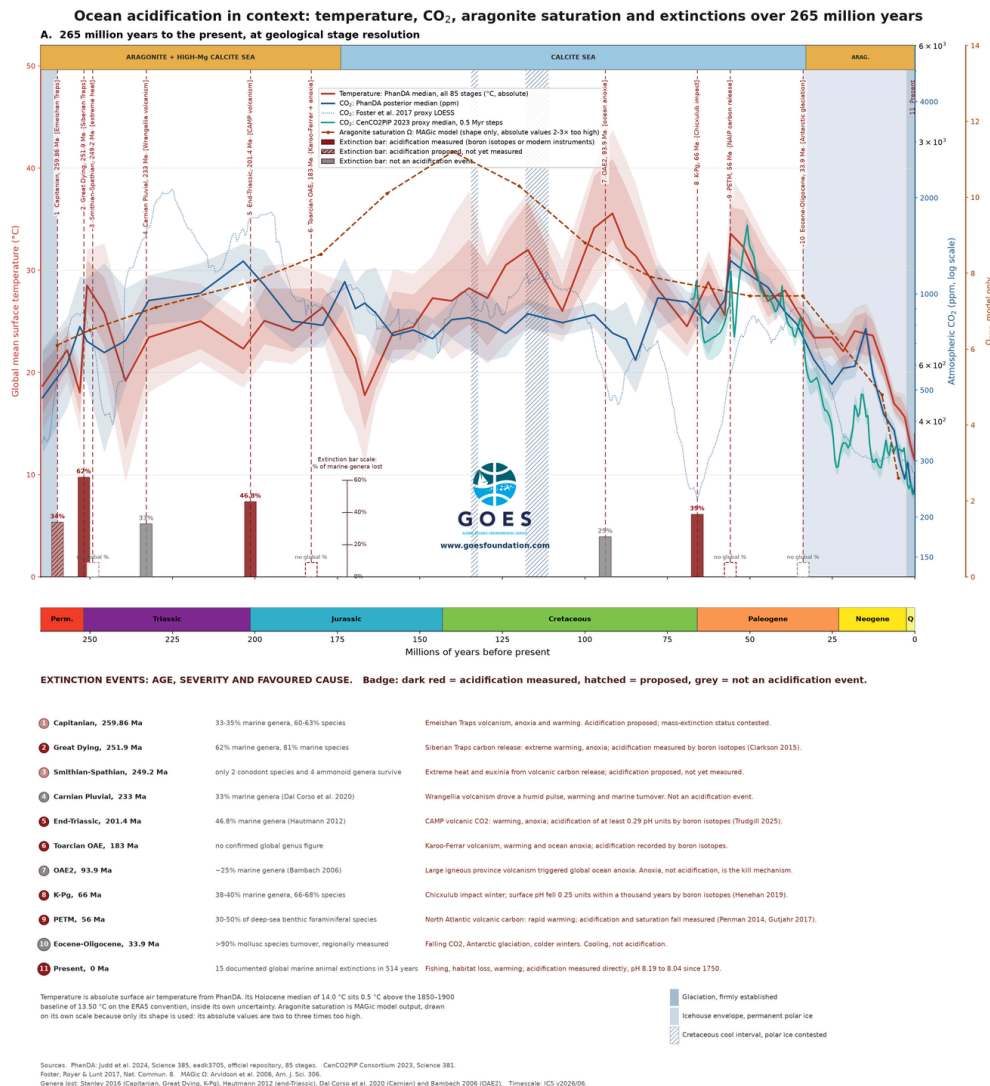


Figure 2. Ocean acidification in context over 265 million years, showing temperature, carbon dioxide, modelled aragonite saturation and the extinction events, with bars that mark whether acidification has been measured at each event.

3. The chemistry of the ocean today

The global mean aragonite saturation of the surface ocean has fallen from 3.51 before the industrial era to 2.90 in 2020, a decline of about 17% (Findlay et al., 2025). The same study shows that by 2020 the average ocean had already crossed into the uncertainty range of the planetary boundary for ocean acidification, and that more than 40% of the surface ocean and up to 60% of the upper 200 metres had crossed that boundary. Suitable habitat has fallen by 43% for tropical and subtropical coral reefs, by up to 61% for polar pteropods and by 13% for coastal bivalves (Findlay et al., 2025).

Over the four decades from 1982 to 2021, the global mean aragonite saturation fell by 0.071 per decade and the pH fell by 0.0166 per decade (Ma et al., 2023). At the present value of about 2.9, that trend removes about 24% of the saturation per century. During the end-Permian extinction,

the saturation fell from about 6.2 to about 1.6 over some 10,000 years, which is an average loss of less than 1% per century (Figure 1). The present rate of loss is therefore about 30 times faster than the average rate across the worst extinction event in the fossil record. The durations of the past events are upper limits, so the true peak rates in the past may have been higher than these averages suggest.

The global mean value hides the conditions in the most exposed cold waters. In the Iceland Sea, the winter saturation of surface water fell from about 1.6 to about 1.5 between 1985 and 2008 (Olafsson et al., 2009). Measured in winter against the threshold for each latitude zone, between 37% and 52% of the ocean surface already sits below its ecological reference threshold (Dryden and Duncan, 2026a).

The future of the ocean depends on the amount of carbon that we emit. On the high-emissions pathway SSP5-8.5, carbon dioxide in the air reaches 1135 ppm by 2100 (Meinshausen et al., 2020). On that pathway, nearly 95% of the surface ocean will have an aragonite saturation more than 40% below its pre-industrial level by the end of the century (Findlay et al., 2025).

4. Why the modern ocean is more exposed

The following points are our interpretation of the published record. The ocean entered the industrial era with the smallest carbonate margin of the last 265 million years. Three features of modern seawater and climate support this reading.

First, the modern ocean is a high-magnesium aragonite sea when compared with the geological record. Its molar ratio of magnesium to calcium is about 5.2, close to the highest value of the past 250 million years, and its calcium concentration is less than half of the value in the Cretaceous (Horita et al., 2002; Ries, 2010). Shells built from aragonite and high-magnesium calcite dissolve more easily than shells built from low-magnesium calcite (Ries, 2010).

Second, the present climate lies near the cold end of the range reconstructed for the last 485 million years (Judd et al., 2024). Cold water holds more carbon dioxide and has a lower aragonite saturation, so the cold, productive seas that feed much of the marine food web reach the danger zone first.

Third, the global mean saturation before the industrial era, 3.51, was no higher than the lowest starting value estimated for the past events in Figure 1, about 3.5 before the Paleocene-Eocene Thermal Maximum, and well below the value of about 6.2 before the end-Permian extinction. The estimates for the past events carry wide uncertainty ranges, which are listed at the foot of the figure. Anthropogenic carbon has supplied the pulse, and it has compressed into about two centuries a change that took the end-Permian about ten thousand years. Chemical pollution adds a further stressor that no past event carried.

5. The animal life of the ocean today

No census of marine animal life has ever been made, either today or in 1850. To set a baseline, we built the biocurve, an index that combines documented declines in groups of marine animals and sets the level in 1850 at 100% (Dryden and Duncan, 2026a). On the importance-weighted measure,

marine animal life stood at 69% of the 1850 level in 1950 and at about 35% in 2023, with an uncertainty band of 28% to 44%. A weighting by tonnage gives a higher value of 54%, so the loss since 1850 lies between about 46% and 65%. Most of this loss came from fishing, whaling, habitat destruction and pollution, long before the chemistry of the ocean began to shift.

Independent records of marine animal life point in the same direction. The marine Living Planet Index fell by 56% between 1970 and 2020, an average loss of about 1.6% every year (WWF, 2024), although a few populations in steep decline can pull such an index down strongly (Leung et al., 2020). The biomass of predatory fish in the world ocean has fallen by two thirds over the last 100 years, and 54% of that decline occurred in the last 40 years (Christensen et al., 2014). In the United Kingdom, the catch of bottom-living fish for each unit of fishing power fell by 94% between 1889 and 2007, so the modern fleet must work about 17 times harder for the same catch (Thurstan et al., 2010).

Figure 3 extends the biocurve beyond 2023 with a conditional decline scenario, which reaches about 13% of the 1850 level by 2040. This line is a scenario that shows where present pressures could lead, not a projection or a forecast (Dryden and Duncan, 2026a).

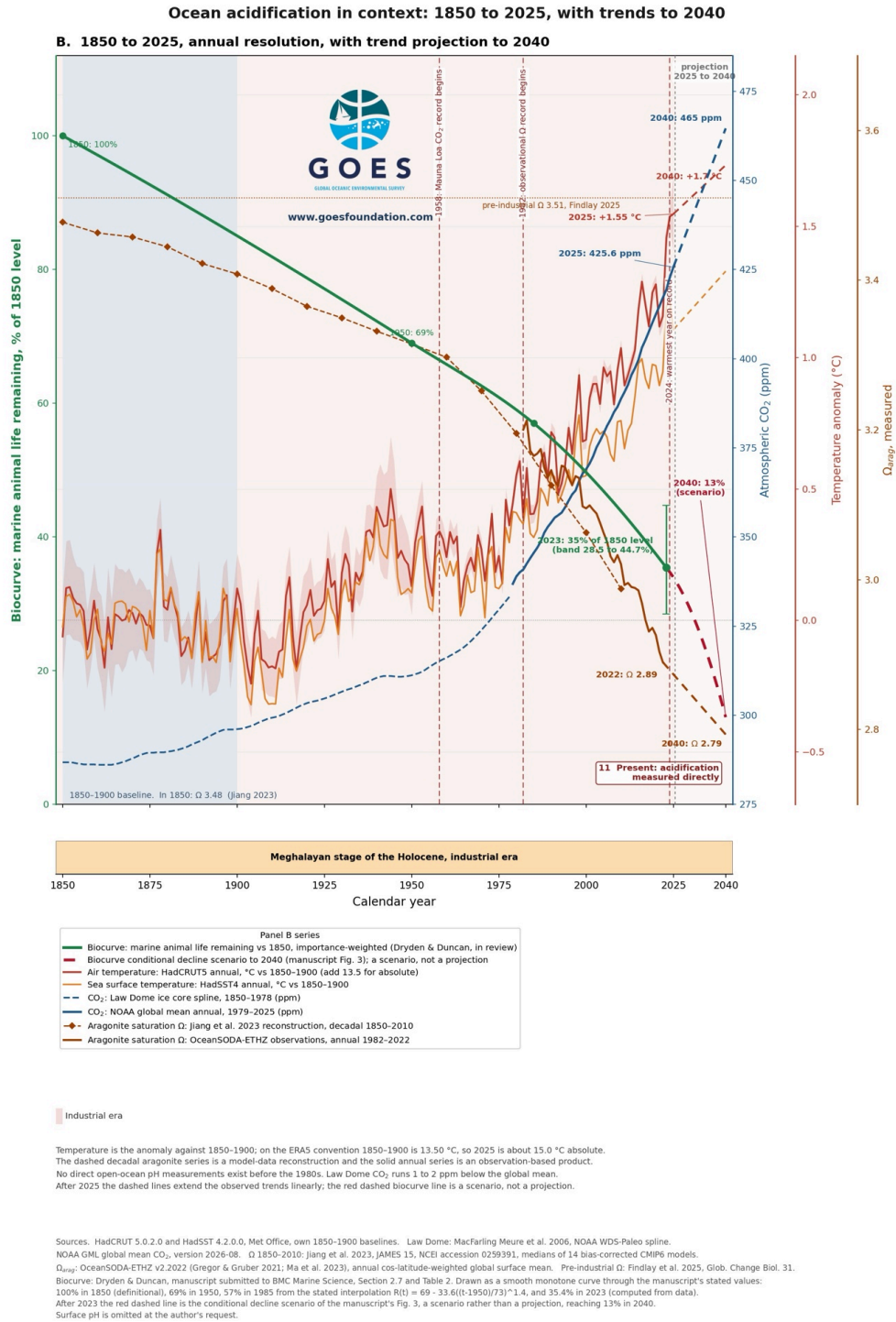


Figure 3. Ocean acidification in context from 1850 to 2025, with trends to 2040, showing the biocurve, air and sea temperature, carbon dioxide and aragonite saturation, together with the conditional decline scenario for the biocurve after 2023.

6. Shifting baselines

Shifting baseline syndrome, a term introduced by Pauly (1995), describes how each generation accepts the depleted state that it inherits as normal. This syndrome has taken hold of our view of the ocean in a big way. When we sailed across the Atlantic Ocean, we saw no fish at all. In a later survey, crews on thirteen sailing yachts crossing the tropical Atlantic photographed seawater samples under a microscope and recorded very few animals at the surface (Dryden and Duncan, 2026b).

Historical records show how much richer the ocean once was. Overfishing began long before modern pollution and climate change, and it removed large animals from coastal ecosystems centuries ago (Jackson et al., 2001). Across all mammals on Earth the change is just as stark: humans now make up 36% and farm animals 60% of the mass of all mammals on Earth, while wild mammals make up only 4% (Bar-On et al., 2018).

7. Conclusion

The ocean began the industrial era with a smaller chemical margin than in any of the great crises of the last 265 million years, and it is now losing that margin about 30 times faster than during the end-Permian. Its animal life has already fallen by about one half to two thirds since 1850, although most species still survive. Aquatic foods supplied about 17% of the animal protein eaten worldwide in 2019 and more than 50% in parts of Asia and Africa, and around 600 million people depend on fisheries and aquaculture in some way for their lives and livelihoods (FAO, 2022).

Yet we still ignore the obvious and focus our attention on issues of far smaller importance. It is no longer enough to do no harm by stopping pollution, reducing carbon emissions and banning destructive fishing. We now have to do some good as well, and help the marine ecosystem to recover while recovery is still possible.

Further reading

Ocean acidification report and biocurve: <https://doi.org/10.13140/RG.2.2.34924.53123>

Anthropogenic pollution report: <https://tinyurl.com/yp9pmfer>

References

- Bar-On, Y. M., Phillips, R. and Milo, R. (2018). The biomass distribution on Earth. *Proceedings of the National Academy of Sciences* 115, 6506–6511. <https://doi.org/10.1073/pnas.1711842115>
- Christensen, V. et al. (2014). A century of fish biomass decline in the ocean. *Marine Ecology Progress Series* 512, 155–166. <https://doi.org/10.3354/meps10946>
- Clarkson, M. O. et al. (2015). Ocean acidification and the Permo-Triassic mass extinction. *Science* 348, 229–232. <https://doi.org/10.1126/science.aaa0193>

- Dryden, H. and Duncan, D. (2026a). Ocean acidification and aragonite saturation compounding anthropogenic stressors on marine life. Research Square preprint, in review at BMC Marine Science. <https://doi.org/10.21203/rs.3.rs-11145455/v1>
- Dryden, H. and Duncan, D. (2026b). Near-absence of surface zooplankton and pervasive anthropogenic particles along a zonal North Atlantic transect: a multi-vessel citizen-science image survey. EGU sphere preprint. <https://doi.org/10.5194/egusphere-2026-3979>
- FAO (2022). The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation. FAO, Rome. <https://doi.org/10.4060/cc0461en>
- Findlay, H. S. et al. (2025). Ocean acidification: another planetary boundary crossed. *Global Change Biology* 31, e70238. <https://doi.org/10.1111/gcb.70238>
- Gutjahr, M. et al. (2017). Very large release of mostly volcanic carbon during the Palaeocene–Eocene Thermal Maximum. *Nature* 548, 573–577. <https://doi.org/10.1038/nature23646>
- Hautmann, M. (2012). Extinction: end-Triassic mass extinction. In: *Encyclopedia of Life Sciences (eLS)*. John Wiley and Sons, Chichester. <https://doi.org/10.1002/9780470015902.a0001655.pub3>
- Henehan, M. J. et al. (2019). Rapid ocean acidification and protracted Earth system recovery followed the end-Cretaceous Chicxulub impact. *Proceedings of the National Academy of Sciences* 116, 22500–22504. <https://doi.org/10.1073/pnas.1905989116>
- Hofmann Elizondo, U. et al. (2024). The impact of aragonite saturation variability on shelled pteropods: an attribution study in the California Current System. *Global Change Biology* 30, e17345. <https://doi.org/10.1111/gcb.17345>
- Horita, J., Zimmermann, H. and Holland, H. D. (2002). Chemical evolution of seawater during the Phanerozoic. *Geochimica et Cosmochimica Acta* 66, 3733–3756. [https://doi.org/10.1016/S0016-7037\(01\)00884-5](https://doi.org/10.1016/S0016-7037(01)00884-5)
- Jackson, J. B. C. et al. (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293, 629–637. <https://doi.org/10.1126/science.1059199>
- Judd, E. J. et al. (2024). A 485-million-year history of Earth's surface temperature. *Science* 385, eadk3705. <https://doi.org/10.1126/science.adk3705>
- Leung, B. et al. (2020). Clustered versus catastrophic global vertebrate declines. *Nature* 588, 267–271. <https://doi.org/10.1038/s41586-020-2920-6>
- Ma, D., Gregor, L. and Gruber, N. (2023). Four decades of trends and drivers of global surface ocean acidification. *Global Biogeochemical Cycles* 37, e2023GB007765. <https://doi.org/10.1029/2023GB007765>
- McCauley, D. J. et al. (2015). Marine defaunation: animal loss in the global ocean. *Science* 347, 1255641. <https://doi.org/10.1126/science.1255641>
- Meinshausen, M. et al. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development* 13, 3571–3605. <https://doi.org/10.5194/gmd-13-3571-2020>

- Müller, T. et al. (2020). Ocean acidification during the early Toarcian extinction event: evidence from boron isotopes in brachiopods. *Geology* 48, 1184–1188. <https://doi.org/10.1130/G47781.1>
- National Research Council (2010). *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*. The National Academies Press, Washington, DC. <https://doi.org/10.17226/12904>
- Olafsson, J. et al. (2009). Rate of Iceland Sea acidification from time series measurements. *Biogeosciences* 6, 2661–2668. <https://doi.org/10.5194/bg-6-2661-2009>
- Pauly, D. (1995). Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology and Evolution* 10, 430. [https://doi.org/10.1016/S0169-5347\(00\)89171-5](https://doi.org/10.1016/S0169-5347(00)89171-5)
- Penman, D. E. et al. (2014). Rapid and sustained surface ocean acidification during the Paleocene-Eocene Thermal Maximum. *Paleoceanography* 29, 357–369. <https://doi.org/10.1002/2014PA002621>
- Ries, J. B. (2010). Review: geological and experimental evidence for secular variation in seawater Mg/Ca (calcite-aragonite seas) and its effects on marine biological calcification. *Biogeosciences* 7, 2795–2849. <https://doi.org/10.5194/bg-7-2795-2010>
- Schulte, P. et al. (2010). The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. *Science* 327, 1214–1218. <https://doi.org/10.1126/science.1177265>
- Stanley, S. M. (2016). Estimates of the magnitudes of major marine mass extinctions in earth history. *Proceedings of the National Academy of Sciences* 113, E6325–E6334. <https://doi.org/10.1073/pnas.1613094113>
- Thomas, E. (2007). Cenozoic mass extinctions in the deep sea: what perturbs the largest habitat on Earth? *Geological Society of America Special Paper* 424, 1–23. [https://doi.org/10.1130/2007.2424\(01\)](https://doi.org/10.1130/2007.2424(01))
- Thurstan, R. H., Brockington, S. and Roberts, C. M. (2010). The effects of 118 years of industrial fishing on UK bottom trawl fisheries. *Nature Communications* 1, 15. <https://doi.org/10.1038/ncomms1013>
- Trudgill, M. et al. (2025). Pulses of ocean acidification at the Triassic–Jurassic boundary. *Nature Communications* 16, 6471. <https://doi.org/10.1038/s41467-025-61344-6>
- Waldbusser, G. G. et al. (2015). Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nature Climate Change* 5, 273–280. <https://doi.org/10.1038/nclimate2479>
- WWF (2024). *Living Planet Report 2024: A System in Peril*. WWF, Gland, Switzerland.