A stark future for ocean life

Model predicts a mass extinction event in the oceans if climate change is uncurbed

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The year 2021 marked the highest temperature and likely the lowest oxygen content for the oceans since human records began (*1*, *2*). These changes have put marine species on the front lines of climate change. For example, marine species' geographical ranges are shifting faster and experiencing more contractions than those of terrestrial species (*3*, *4*). However, whether climate change poses an existential threat to ocean life has been less clear. Marine species are often considered to be more resilient to extinction than terrestrial ones, and human-caused global extinctions of marine species have been relatively rare (*5*). On page XXX of this issue, Penn and Deutsch (*6*) present extensive modeling to reveal that runaway climate change would put ocean life on track for a mass extinction rivaling the worst in Earth's his- tory. Furthermore, they reveal how keeping global warming below an increase of 2°C compared with preindustrial levels could largely prevent these outcomes.

The topic of climate change and species extinction on land has been fraught with controversy. This is in part because of de- bates over suitable methods of predicting extinctions and in part because of the relatively few documented extinctions to date (*7*). The marine research community has largely avoided making projections of ex- tinction risk (*8*), even though experts widely see climate change as a major threat to the global oceans (*9*). This has left the watery 70% of Earth's surface as a giant blank spot in the future projection of life on Earth.

Penn and Deutsch modeled suitable habitats for marine species on the basis of well-described physiological processes that link metabolic demand for oxygen to the supply of oxygen to organismal tissues as a function of temperature. As warming causes the demand for oxygen to exceed supply in a given location, survival likely becomes untenable, causing extinctions. The authors calibrated their model against the oceanographic changes they reconstructed for the end-Permian mass extinction event, which was a period of extensive warming and deoxygenation 250 million years ago, colloquially known as the Great Dying. Although not a perfect analog to the current climate situation, the end-Permian mass extinction is one of the most cataclysmic periods in Earth's history for which there are records of extensive warming and extinction. Penn and Deutsch built confidence in their physiological model the same way climate modelers do—by integrating well-understood mechanisms and by demonstrating its ability to explain historical patterns.

The model predicts several key patterns in future extinction risk. For instance, the tropical oceans are expected to lose the most species as temperature and oxygen conditions exceed the ranges tolerable for most extant species today. However, many tropical species are expected to migrate and survive at higher latitudes as the global oceans warm up. This process mirrors the widespread range shifts that have already been observed on land and in the oceans (*3*). However, po- lar species are likely to go globally extinct as their suitable oceanographic conditions dis- appear entirely. Climate change is, in effect, walking species off the ends of the Earth. Widespread warming and deoxygenation in the end-Permian mass extinction had a simi- lar geographic signature (*10*).

The alternative scenarios explored by Penn and Deutsch illustrate the key choice that society is facing. Unabated greenhouse gas emissions would push radiative heating on Earth to 8.5 W/m^2 by 2100 and beyond in the centuries after. This future produces a doomsday scenario of end-Permian–like mass extinction by the year 2300. An alternative, consistent with the Paris Agreement (the 2016 international treaty on climate), is to limit or even reverse greenhouse gas emissions and keep radiative forcing to 2.6 W/m^2 by 2100. Doing so would keep climate change as a relatively minor threat to marine species' existence—lower than other more-direct threats, such as habitat loss or fishing—although the widespread extirpation of species from their historical locations will remain inevitable. Fortunately, greenhouse gas emissions are not on track for the worst-case scenario given policies to limit greenhouse gas emissions and the slower-than-projected growth of global economies (*11*). How close to the best-case scenario human society can hew, however, remains one of the most pressing questions for the future of life in the oceans.

The model of Penn and Deutsch also il- luminates key scientific uncertainties that surround the fate of marine life, including the degree to which species can expand into new territory as it becomes climatically suitable. Observations of rapidly expanding range edges make it clear that a pessimistic, no-dispersal scenario is unrealistic, but neither is it likely that all species will perfectly track suitable habitats in an optimistic, perfect-dispersal scenario (*12*). The transient dynamics of species expansion and contraction (*13*) will likely determine which species survive in the coming decades. Another key uncertainty is the percentage of habitat that species can lose before going extinct. Calibrating against end-Permian data, Penn and Deutsch predict that loss to be 50 to 70%. Although broadly consistent with the criteria published by the International Union for Conservation of Nature (*14*), very few data exist for marine species on which to calibrate these values because most hu- man-caused marine extinctions have been driven by overexploitation, not climate change (*15*).

The research of Penn and Deutsch also highlights key areas in need of investigation, such as metabolic traits for more marine species. Their modeling projects the future for all marine life using information from only a few dozen species, and future research will be needed to understand trait variation and correlation across life history strategies, habitats, and phylogenies. Other important extensions will include a better understanding of the role that microclimates and habitat refugia play in species survival, the potential for evolution of metabolic limits, the role of changing species interactions in promoting or impeding species survival, and the oceanographic dynamics in shelf and other coastal habitats that are currently not well represented by global climate simulations. Improved projections of these processes will refine the forecasts for marine biodiversity under climate change.

Not too long ago, canaries warned coal miners of toxic gas accumulation. Today, marine life is warning the world of a different and global gas accumulation. Staving off widespread biodiversity loss and the sixth mass extinction is a global priority. Because marine extinctions have not progressed as far as those on land, society has time to turn the tide in favor of ocean life. Exactly where the future falls between the best-case and worst-case scenarios will be determined by the choices that society makes not only about climate change, but also about habitat destruction, overfishing, and coastal pollution. With a coordinated approach that tackles multiple threats, ocean life as we know it has the best chance of surviving this century and far beyond. j

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