Earth 2020

An Insider's Guide to a Rapidly Changing Planet

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Oceans 2020

David M. Karl

I was born in 1950, at the beginning of the second half of the twentieth century, and just five years after the end of the Second World War. It was a time when rapid advances in science, technology and medicine were fundamentally changing the human experience on Earth, and not all for the better. As an eighteen-year-old high school senior, I read Paul Ehrlich's *The Population Bomb*,[1] a dire warning to humanity about the state of the global environment, with apocalyptic predictions about the future. I knew right then that we needed all hands on deck to deal with an impending crisis of our own making.

Two years later, in 1970, the first Earth Day was created to honor our planet and its diverse ecosystems. This event had its roots on college campuses across the United States under the leadership of then US Senator Gaylord Nelson, and it gained momentum and energy from the ongoing Vietnam War protests. I, too, was engaged in anti-war demonstrations, while at the same time pondering my own future. I was drawn to studies of environmental science and ecology, with a keen interest in aquatic habitats. Growing up in Buffalo, New York, on the heavily polluted shores of Lake Erie, I saw, firsthand, how industrial and municipal wastes were threatening the survival of all forms of aquatic life. In the late 1960s, oily slicks of toxic chemicals repeatedly caught fire in tributaries of the Lake, including the Buffalo and Cuyahoga Rivers.[2]

By 1971, environmental issues had already become more mainstream, and on April 21 of that year, I was invited to participate in 'Survival Day' — our neighborhood equivalent of

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the second Earth Day. My brother, Tom, was a high school teacher, and he helped organize this first-ever, local environmental event. Speakers included distinguished representatives from advocacy organizations, Health Department officials, university professors, as well as industry representatives from Allied Chemical Company, Bethlehem Steel and Niagara Mohawk — the regional energy provider. As a college student, without any fancy title or affiliation, I was listed in the program as 'Concerned resident of planet Earth'. And I was. My talk on the *Biogeochemical Effects of Bethlehem Steel on Lake Erie* was my first formal foray into the environmental movement — and from there, I never looked back. University degree in hand, I left Buffalo to begin my new career as an oceanographer, with an interest in understanding microbial processes in the deep blue sea, far removed from the influences of humankind. Or so I thought.

Exploration of the global ocean dates back many centuries, well before the European-led age of discovery or the Polynesian seafarers of the Pacific Ocean. Between the fifteenth and seventeenth centuries, explorers ventured far from their coasts to discover new lands, resources and wealth. The doctrine at that time, *mare clausum*, was one of exclusive ownership and navigational rights, even on the high seas. This policy changed radically in 1609 with the publication of Hugo Grotius' new principle of *mare liberum*, freedom of the sea,[3] which redefined the rules of sovereignty, and facilitated the growth of maritime activities including colonial expansion, commerce and scientific research. The great worldwide voyages of James Cook, Charles Darwin and James Clark Ross were partially motivated by scientific inquiry, but most scholars would agree that the four-year (1872–1876) worldwide voyage of HMS *Challenger* marked the true beginning of modern oceanography.

The first half of the twentieth century witnessed the expansion of marine laboratories and oceanographic research vessels worldwide. In 1927, the president of the US National Academy of Sciences (NAS) appointed a committee on oceanography to consider the worldwide scope of the discipline. The work of this committee was published over the next decade by Henry Bryant Bigelow and Thomas Wayland Vaughan,[4] among others, and served as the background and motivation for the classic treatise on oceanography by H. U. Sverdrup, M. W. Johnson and R. H. Fleming.[5] Key legacies of the NAS committee on oceanography were the establishment, in 1931, of the Woods Hole Oceanographic Institution, the creation of the Office of Naval Research, in 1946, and the establishment of public funding, in 1950, from the National Science Foundation for oceanographic research.

By the early 1950s, planning was underway for what would eventually become the 1957–1958 International Geophysical Year (IGY), a comprehensive study of Earth and its oceans involving 30,000 scientists from sixty-six countries. One of the most important achievements of the IGY was the establishment, by the oceanographer Roger Revelle and his colleague Charles David Keeling, of a laboratory atop the Hawaiian volcano, Mauna Loa, for continuous measurements of atmospheric carbon dioxide (CO_2). These measurements soon revealed a regular seasonal pattern of CO_2, which reflected the net balance between planetary photosynthesis and respiration along with exchanges of atmospheric CO_2 with the upper ocean. After a few years, Keeling was able to document a small, but systematic, rise in the average atmospheric CO_2 from year to year, resulting primarily from fossil fuel combustion. Other CO_2 sampling sites were soon established at strategic locations worldwide, along with the creation of an international network of ocean weather ships, which, at its peak, included twenty-two Atlantic and twenty-four Pacific Ocean stations collecting oceanographic and meteorological observations. In the decades that followed, these long-term data sets would prove to be critical for detecting anomalous ocean conditions and for establishing baselines against which future ocean states could be compared.

In the decade that followed Keeling's early CO_2 measurements, scientific progress towards understanding the global oceans began to accelerate. In the US, the Stratton Commission, appointed by President Lyndon B. Johnson, developed a national ocean action plan[6] based on their comprehensive, long-range assessment of marine health and necessary research activities. Although the country was preoccupied with the Vietnam War and the developing space program, many of the recommendations of the Stratton Commission were eventually enacted, including the creation of the National Oceanic and Atmospheric Administration (NOAA) in 1970. Other important outcomes included the creation, in 1972, of the Coastal Zone Management Act, National Marine Sanctuaries Act, Marine Mammal Protection Act, and, in 1976, the Magnuson–Stevens Fishery Conservation and Management Act.

Throughout the 1970s, funding for oceanographic research increased significantly, with the International Decade of Ocean Exploration (IDOE) and other programs that stimulated large-scale, multi-disciplinary oceanographic research. These international programs began to view the ocean as an integrated system, and included studies to preserve the marine environment, improve environmental forecasting, develop advanced ocean monitoring systems and facilitate the worldwide exchange of oceanographic data.

Progress accelerated through the 1980s, with the establishment of the International Geosphere-Biosphere Programme (IGBP). In 1988, under the auspices of the Joint Global Ocean Flux Study (JGOFS) program, two ocean time-series stations were established: one in the North Atlantic near Bermuda, and the other in the North Pacific near Hawaii. Since that time, near-monthly observations have been conducted at these two open ocean sites, building on other existing time-series stations, including the location of the former weather ship at Ocean Station Papa in the Gulf of Alaska, where oceanographic measurements have been made since the 1960s.

The early ship-based oceanographic surveys and time-series stations were critical for providing important baseline observations. But given the vastness of the planet's oceans, these measurements could not even hope to cover all of Earth's marine waters. Fortunately, just as ship-based oceanographic programs were ramping up, ocean science entered into the satellite age. In 1978, the coastal zone color scanner (CZCS) was launched on the Nimbus 7 satellite, providing the first dedicated imagery of ocean color, which was used to measure the concentration of photosynthetic plankton in marine surface waters. Initially designed as a one-year proof of concept, the CZCS mission ran until 1986, and yielded unprecedented information on the spatial and temporal patterns of biological productivity across the oceans. Since that time, improved satellite remote-sensing of ocean color, temperature, salinity, wind, sea level, sea ice and other key environmental variables has revolutionized our understanding of oceanographic processes on regional-to-global scales.

The development of marine science over the past half-century has coincided with a period of unprecedented human impacts on our oceans. Back in 1970, I (and others) believed that the oceans' vastness would serve to buffer any potential anthropogenic perturbations. Today we know that this is not the case. On a global scale, the oceans have warmed appreciably, as documented by successive reports of the Intergovernmental Panel on Climate Change (IPCC). This warming is largest near the sea surface (between 0 and 75 m depth), with a temperature increase of 0.11°C per decade since the first Earth Day, fifty years ago. This observed temperature trend has been documented with *high confidence*, in IPCC parlance.[7]

Rising ocean temperatures have both direct and indirect effects on marine ecosystems. For some species living at or near a temperature optimum, rising temperatures may approach or exceed physiological thermal tolerances, resulting in mass species migration. Indeed, the distributions and abundances of many marine organisms have already shifted poleward, or to deeper and colder waters as a result of ocean warming. Based on a fifty-year record from the North Atlantic Ocean, the range limit of warm water copepods (small planktonic animals eaten by fishes) has shifted north by ten degrees latitude. This poleward shift had led to seasonal mismatches in the growth cycles of primary producers, zooplankton grazers and predatory fishes, with significant ecosystem effects. Warming of polar regions is especially concerning owing to the narrow temperature ranges of many species, and the lack of colder water habitat refuges. In addition, organisms with limited ability to migrate, including tropical corals, face habitat loss, thermal-induced bleaching (loss of photosynthetic symbionts) and, possibly, extinction. The rate of temperature change in many marine ecosystems is unprecedented, so genetic adaptation and evolution are often unable to keep up.

The warming of surface ocean waters also has significant indirect effects on marine ecosystems. Rising temperature increases the density difference between the upper sunlit layers and the deeper, nutrient-rich waters below. This, in turn, reduces vertical mixing of water masses and the supply of nutrients for photosynthesis. This 'stratification' explains the deep blue color of tropical oceans, where low productivity ocean 'deserts' result from limited nutrient supply into the warm surface waters. Satellite observations of ocean color over the past several decades have revealed a significant global expansion of these oceanic deserts, and this trend is expected to continue in a warming future.

Ocean warming is also leading to the loss of sea ice as a critical habitat in high latitudes,[8] and changes in critical pathways of ocean circulation. Most notably, warming surface waters in the subpolar North Atlantic (near Greenland) could act to slow down the formation of cold and salty water masses, which sink into the ocean interior carrying nutrients and dissolved gases throughout the ocean depths. These sinking waters are closely coupled to the northward flow of the warm Gulf Stream current, which transports large amounts of heat to northern Europe. Should this circulation slow or even stop (as it appears to have done in the geological past), Europe could, counter-intuitively, experience less warming, or even some cooling, into the future. Moreover, sluggish ocean circulation, combined with lower gas solubility in warm waters is acting to decrease the concentration of dissolved oxygen (O_2) over much of the ocean interior. This is particularly problematic in regions that are naturally low in O_2, including large parts of the North Pacific, and in regions where additional anthropogenic nutrient inputs fuel excessive microbial O_2 consumption. In extreme cases, low O_2 conditions in some coastal sites have created so-called 'dead zones' leading to massive mortality of fishes and bottom-dwelling invertebrates.

Beyond its effect on global temperature, increasing atmospheric CO_2 concentrations are altering the chemistry of the surface ocean in a way that is negatively impacting many marine organisms. To date, approximately 25% of the CO_2 that has been emitted by human activities has been absorbed by the surface ocean.[9] On the face of it, this CO_2 enrichment might be expected to benefit ocean life by stimulating marine photosynthesis. The reality, however, is more complex. Perhaps most importantly, there is the problem of ocean acidification, which is a direct result of increasing ocean CO_2 levels, since dissolved CO_2 reacts with seawater to produce carbonic acid. Between 1988 and 2018, surface ocean acidity at the Hawaii Ocean Time-series Station ALOHA increased by 14%. This might not sound like a large change, but even very small changes in acidity can have profound consequences for the growth of many organisms. Marine species that produce calcium carbonate as a support structure, shell or skeleton (for example, shellfish and reef-building coral) will need to invest additional metabolic energy to form calcium carbonate. Furthermore, exposure of calcified structures to more acidic seawater will weaken or even completely dissolve the life-supporting calcium carbonate structures. In addition, water-breathing fishes may be impacted by increasing acidity in their bloodstream, creating an additional physiological stress beyond ocean warming and deoxygenation.

As we reflect on the past fifty years of ocean change, we must also look to the future. The United Nations has proclaimed a Decade of Ocean Science for Sustainable Development (2021–2030) to address current and emerging threats to global marine ecosystems, including the insidious pollution by anthropogenic micro-plastics.[10] My generation is solely responsible for the global growth of plastics, a successful subsidiary of the oil industry. Of the long list of insults to marine ecosystems, plastic pollution might be the 'low-hanging fruit' for successful remediation, simply by enacting bans on single-use plastics, and increasing the effectiveness of recycling programs. The 2019 G20 summit in Tokyo released a joint declaration on the critical need for marine conservation, and the elimination of plastic waste. Equally concerning is the accelerated pace of proposals to mine deep ocean metal deposits. Since its inception in 1982, the International Seabed Authority has issued numerous leases for mineral exploration in the deep sea. The first commercial operation off Papua New Guinea had planned to mine mineral-rich hydrothermal vents from depths of 1.5–2 km, but financial problems forced it to file for bankruptcy in 2019. However, other nations and companies continue to map resources within their leased regions of the seabed, despite vocal and well-informed opposition by oceanographers and marine conservationists. The potential impacts on deep sea habitats are well documented, but these are pitted against the growing need for raw materials to sustain our current standard of living and future population growth. Who will referee the competing interests of humankind versus nature? And who will win?

In the face of significant challenges, we can take solace, and perhaps even inspiration, from the diverse marine microbial assemblages that have thrived on our planet for billions of years. These microorganisms possess enormous genomic potential and metabolic flexibility, and this has provided them with resilience in the face of environmental change. In the end, marine microbes will survive and adapt to climate change, although it is unclear how humankind will fare. Despite an ever-growing knowledge base concerning the sea around us built on observations, measurements and computer models, the ocean is still grossly under-sampled. Consequently, major uncertainties still exist regarding climate change impacts on the ocean and its inhabitants. Human influence on climate is indisputable and accelerating, and now, more than ever, we need to embrace a holistic view of the coupled Earth systems. Basic science is critical, but so too is fact-based education, aggressive advocacy for our planet and effective action.

Endnotes

1. P. R. Ehrlich, *The Population Bomb*, New York: Ballantine Books, 1968.
2. See also 'Fresh Water' by Janet G. Hering in this volume.
3. H. Grotius, *Mare Liberum, Sive De jure quod Batavis competit ad Indicana commercia Dissertatio* [The Freedom of the Seas, or a Disputation Concerning the Right Which Belongs to the Dutch to take part in the East Indian Trade], Leiden: Lodewijk Elzevir, 1609.
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5. H. U. Sverdrup, M. W. Johnson and R. H. Fleming, *The Oceans: Their Physics, Chemistry and General Biology*, New York: Prentice-Hall, Inc., 1942.
6. J. Stratton et al., *Our Nation and the Sea: A Plan for National Action*, Washington, DC: Commission on Marine Science, Engineering and Resources. US Government Printing Office, 1969.
7. IPCC, 'Climate change 2013: The physical science basis', in *Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Cambridge, UK: Cambridge University Press, 2013, 383–464, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf; IPCC, 'Climate change 2014: Impacts, adaptation and vulnerability, part A: Global and sectoral aspects', in *Contribution of the Working Group 2 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. by C. B. Field et al., Cambridge, UK: Cambridge University Press, 2014, 1–1131, https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf

8. See also ‘Ice’ by Julian Dowdeswell in this volume.
9. On oceanic uptake of CO_2, see ‘Carbon’ by David Archer in this volume.
10. See also ‘Earth and Plastic’ by Roland Geyer in this volume.