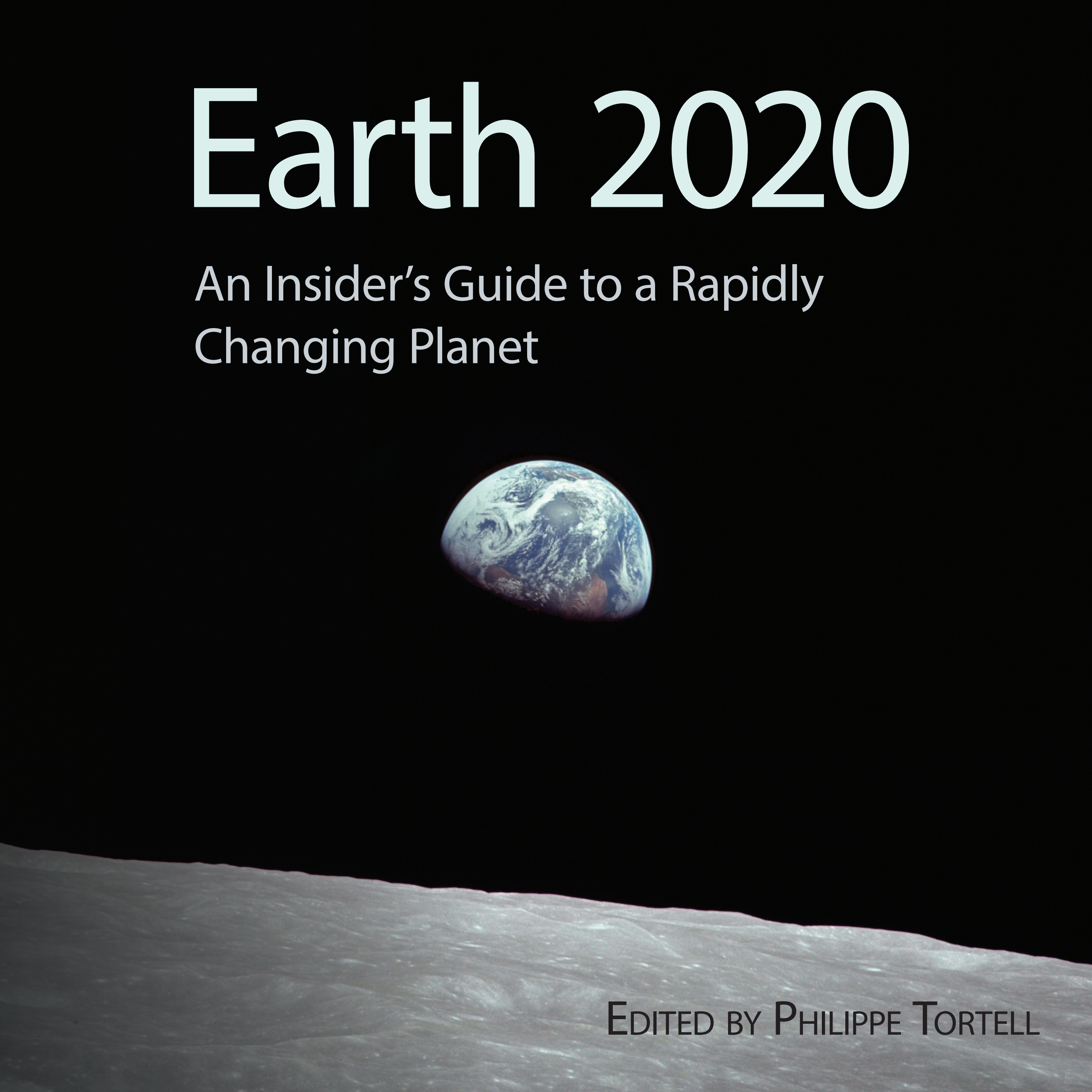
Earth 2020

An Insider's Guide to a Rapidly Changing Planet



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Sea Level Rise, 1970–2070
A View from the Future

Robert E. Kopp

Author's Note

The initial draft of this manuscript mysteriously appeared in my cloud drive on Earth Day 2020, with a time stamp fifty years later, April 22, 2070. It appears to have been written for a volume similar to this one, commemorating the Earth Day centennial. The description of the state of scientific knowledge through 2020 is accurate, and the discussion of future sea level and ice-sheet changes, as well as the challenges of adapting to rising sea level, are likewise consistent with current understanding. I have added endnotes, where appropriate, to support these descriptions. I cannot vouch for the accuracy of the depiction of the specific events of the next half-century, but leave these intact; they seem to me to represent one plausible future.

One hundred years ago, at the time of the first Earth Day, in 1970, sea level rise was not a pressing global concern. While scientists had already been studying sea level change for over a century, it was mostly an intellectual curiosity. Nineteenth-century geophysicists had calculated how the growth and shrinkage of ice sheets reshape Earth's

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gravitational field, affecting sea level differently in different places. Early twentieth-century oceanographers had identified numerous processes leading to short-term variations in local sea level. In 1941, stitching together data from tide gauges around the world, Caltech geophysicist Beno Gutenberg identified a global average sea level rise of about 1.1 mm per year over the preceding half-century. But it wasn't until about three decades later that widespread scientific and public concern about a potential rapid acceleration of global sea level rise began.

Writing in the journal *Nature* in 1978, John Mercer, a glaciologist at Ohio State University, sounded an alarm about the potential melting of the West Antarctic Ice Sheet (WAIS) in response to modest levels of warming. The WAIS, he noted, sits with its base largely below sea level, and is buttressed by floating ice shelves around its perimeter; these factors make it potentially unstable in the face of the warming ocean and air. While the scientific understanding of ice-sheet physics has evolved, Mercer correctly identified the broad scope of the hazard we now see playing out, nearly a century later. He described the deglaciation of West Antarctica as a potentially 'disastrous result of continued fossil fuel combustion' that could lead to 'major dislocations in coastal cities, and submergence of low-lying areas such as much of Florida and the Netherlands'.[1] Indeed, at the turn of the twenty-first century, the WAIS contained enough water to raise global average sea level by 4.5 m, and there was active debate over whether some of the 3.5 m sea level equivalent of ice that sits below the ocean surface was already committed to collapse over the next couple centuries. Today, collapse is clearly underway in multiple sectors of the ice sheet.[2]

Fortunately, the planet's two other major ice sheets are so far proving more stable. The East Antarctic holds 53 m sea level equivalent of ice; of this, 19 m sea level equivalent sit with their base below the ocean surface and are potentially vulnerable to the same instabilities playing out in West Antarctic. But so far this ice sheet has only shrunk by a few centimeters and does not seem in imminent danger of collapse. The Greenland Ice Sheet contains enough water to raise sea level by 7.4 m. While geological records from past warm periods suggest we may already have warmed the planet enough to lose a substantial chunk of this ice sheet, it currently appears that its loss will take many millennia.[3]

While the ice sheets are the major (and most visible) driver of sea level change today, they aren't the only important factor. Indeed, as of the fiftieth Earth Day in 2020, they weren't even the dominant one. From 1993 — when the first satellite providing global sea level observations was launched — to 2020, global average sea level rose by about 8 cm. Of that 8 cm, about 40% was due to the thermal expansion of ocean water as it warmed, and another quarter to melting mountain glaciers.[4] The remaining 35% was due to accelerating ice losses from both Greenland and West Antarctica.[5]

That was the global story. Around the world, however, for a variety of reasons, different places experienced different rates of sea level change. For one thing, surface winds and ocean currents are important drivers of local sea level changes — indeed, the dominant driver on a year-to-year basis. Other factors also come into play. Over the twentieth century, many inhabited river deltas, such as the Mississippi Delta in Louisiana, experienced sea level rise several times greater than the global average. In these areas, which rest upon loosely consolidated sediments, the weight of the sediments can lead to a sinking of the land surface, and thus a relative sea level rise — a process accelerated when humans pump water, oil or gas out from between the sands. Conversely, other areas — such as parts of Alaska near melting glaciers — actually experienced a relative *drop* in sea level over the twentieth century, as a result of various geophysical processes. When a glacier or ice sheet melts, it exerts a weaker gravitational pull on nearby water bodies, leading to a local drop in sea level, and enhanced sea level rise farther away. The loss of glaciers also leads to a gradual 'rebound' of Earth's crust and mantle underneath the reduced load, further contributing to the relative drop in sea level. Thus, the actual changes in sea level experienced at any place on Earth can differ quite significantly from overall global trends.

Even back in 2020, sea level rise was having real — and increasingly costly —impacts. High-tide floods had become increasingly common in many areas. In coastal New Jersey, for example, impactful high-tide flooding increased from about one day in a typical year in the 1980s to more than five days in a typical year in the 2010s, with increases of similar magnitude occurring along much of the US Atlantic Coast.[6] Such increasingly frequent floods were starting to impact commerce, farming, property markets, sanitation and groundwater supplies in low-lying coastal areas around the world. In addition, coastal storms were causing more impactful flooding. During 2012's Hurricane Sandy, for example, higher seas meant that floodwaters reached the homes of more than 80,000 people who would not otherwise have been affected. Yet, adaptation efforts were quite limited: for example, in New Jersey in the five years after Hurricane Sandy, state-funded buyouts of flood-prone properties were outnumbered about five-fold by new houses built in the future flood plain.

From the vantage point of Earth Day 2020, the next couple decades of sea level rise were already set in motion, with the world almost unavoidably set for a global average rise of about 7 to 17 cm, sufficient to make high-tide flooding a multiple-weeks-per-year affair in many coastal communities.[7] Beyond the 2040s, however, there were two major drivers of sea level uncertainty: the future trajectory of global greenhouse gas emissions and ice-sheet physics. The former was a topic of urgent policy and diplomacy; the latter, a scientific story slowly being unveiled.

Had the world stuck to the aggressive temperature targets laid out in the Paris Agreement (drafted in 2015 and signed in 2016),[8] the additional global sea level rise over the last half-century (from 2020 to 2070) would most likely have been about 30 cm. The odds were quite good — about nine chances in ten, based on computer models — that sea level rise would have stayed below 50 cm.[9]

Unfortunately, the Paris Agreement was a very limited success. To be sure, intensified efforts in the 2020s did stabilize global greenhouse emissions, getting the world off the 'business-as-usual' path of growing fossil fuel consumption. But it took until the 2050s for global emissions to really start falling. In addition, an unexpected and rapid reduction in tropical cloud cover has accelerated the global temperature rise, with global average temperatures in 2070 now closing in on 3°C above nineteenth-century levels. The Paris Agreement's 1.5 and 2.0°C temperature targets are now a distant memory.

The world's lethargic approach to mitigation wasn't enough to slow cascading instabilities in the West Antarctic ice sheet. Global average sea level rise since the year 2000 has exceeded 60 cm, and it seems on track to double that by the end of the twenty-first century. By the 150th Earth Day in 2120, we may be nearing 2 m of sea level increase.[10]

And we may see even more dramatic changes over the longer term. Computer models and geological records of past warm periods suggest that 3°C of global warming would lead to about 10 m of total rise over the next two millennia if the planet were left to its own devices.[11] Such a drastic increase in global sea level would flood 2.6 million km^2 of habitable land surface — an area currently home to over 10% of the global population.

But it looks increasingly unlikely that the planet will be left to its own devices. While mid-century proposals from India and the Alliance of Small Island States to engineer the planet's climate with stratospheric aerosol pollution seem to have been quieted by threats from China's risk-averse leadership, efforts to artificially remove carbon dioxide from the atmosphere have seen rapid growth in the last decade.[12] It's quite possible that, by Earth Day 2120, the rate of deliberate removal of atmospheric carbon dioxide will match the mid-century rate of human emissions. If such efforts can be sustained, Earth's temperature may cool back to near its pre-industrial levels by the first half of the twenty-third century, with global sea level rise slowing to a more measured pace by the twenty-fourth century. Computer models suggest that such sustained emissions reductions efforts might be sufficient to keep the long-term global average sea level rise below 4 m.[13]

While the delayed benefits of climate change mitigation have yet to be seen by the world's coastal communities, there have been greater successes in adapting to the effects of sea level rise. In the once-laggard United States, for example, the 2020s saw some major steps forward. Following the devastating New Orleans flooding of 2023 — when levees built inadequately in the aftermath of Hurricane Katrina were overtopped during Hurricane Louis — the US president's major adaptation initiatives became one of the few elements of her proposed Green New Deal to win broad bipartisan support.

The centerpiece of these adaptation efforts was the Community And Regional Climate Adaptation Act (CARCAA) of 2024. This legislation provided federal support for states and public universities to work with communities in developing formal adaptation strategies, known as Community Adaptation Pathways (CAPs), and coordinating these strategies within and across state lines. CARCAA also set up an Adaptation Trust Fund to help finance the implementation of the CAPs, providing multi-year budgetary stability that was often missing in infrastructure projects in the US, and allowing lower-income communities to prepare in the same deliberate fashion as wealthier areas.

In coastal communities, each CAP considers four basic adaptations to sea level rise — accommodating more frequent flooding, defending against incoming waters, advancing into the ocean by elevating and extending the land, and relocating to safer ground. The CAPs evaluate the levels of sea level rise at which these four options would work, their financial costs, the resulting change in a community's risk profile, and the extent to which implementation would enable or hinder other options. And, importantly, the CAP must consider when and where relocation is the most viable remaining option.

Accommodation to more frequent tidal- and storm-driven flooding serves as the first rung of a coastal CAP, and it has taken many forms. At its most basic, accommodation requires improving disaster response: for example, enhancing emergency communications and ensuring transportation networks function well during evacuations. Historical experience shows that mutual aid among the affected people plays a critical role in the immediate aftermath of a disaster, and large-scale preparedness exercises, modeled on the Great California ShakeOut, are one of the lasting legacies of CARCAA. Accommodation also includes physical changes to buildings and infrastructure, including traditional approaches like raising infrastructure, elevating buildings and wet-proofing basements to tolerate occasional flooding. More innovative approaches have also been developed, such as creating buildings that can safely float during a flood. In the aftermath of 2025's Hurricane Tanya, the rebuilding of the Naval Academy and the Naval Station Norfolk led to major innovations in this area, the legacy of which can be seen today across the world, from Washington, DC, to Guangzhou.

Coastal defense often takes the form of hard infrastructure: surge barriers that can be closed in the event of incoming high waters, as well as permanent levees and flood walls. It can also include softer infrastructure, such as periodically replenished beach dunes. Oyster reefs and salt marshes also provide substantial protection against waves, although they are generally less effective in protecting against longer-lasting storm surges and tides. Defensive structures that combine hard and soft elements in cities like New York and Boston have become a signature element of Green New Deal-era architecture.

Coastal advance involves reclaiming land from the sea and building it up to higher elevation. There are many historic examples. In the Netherlands, half of the country's land area is composed of polders, low-lying areas reclaimed over the course of centuries from marshland. In the aftermath of the Great Seattle Fire of 1889, streets that were originally near the tidal zone were elevated by about 12 ft, with the original first floors of buildings turned into basements. More recently, in the late twentieth and early twenty-first centuries, Shanghai increased its land area by over 6% by moving sand and using sea walls to capture sediment carried by the Yangtze River.

No defensive structures are failsafe, and in a world of rising sea levels, neither defense nor advance can be safely used without accompanying measures to accommodate flooding. Indeed, coastal defense and advance can create a false sense of security, allowing populations to continue to grow in areas with substantial flood exposure, as was demonstrated by the flooding of Lower Manhattan during Hurricane Susan in 2043. Twenty years earlier, following a pre-CARCAA plan developed by Mayor Bill de Blasio, New York City extended the southern portion of Manhattan to make space for new flood protection structures. But the condo developers followed quickly thereafter, putting more people in a vulnerable area. In the aftermath of Hurricane Rebekah, skepticism about coastal advance has significantly restricted its role in modern CAPs.

The fourth adaptation option — relocation — moves people out of harm's way. Unplanned relocation is often associated with the aftermath of a disaster. For example, New Orleans permanently lost about 15% of its population in the aftermath of Hurricane Katrina in 2005, and another 10% in the aftermath of Hurricane Lee in 2023. But perhaps the biggest success of CARCAA and follow-on measures was the widespread community deliberations about possible future relocation in the development of the CAPs. With gradual, community-driven transitions now mapped out in advance for vulnerable areas, there has been no large-scale disaster-driven population displacements in the US in over four decades.

A key to the success of the CAP process is that it is not imposed by the federal or state government; rather, these higher levels of government participate in a supporting role, providing funding for the process and incentives for participation, as well as identifying (and occasionally removing) barriers that might prevent options from playing out. Often, public universities — generally much more highly trusted than federal or state government, especially early on in the CARCAA era — play critical roles both as conveners and as sources of expert knowledge. The CAPs demonstrated that community voices could have real impact. They showed that communities, universities and higher levels of government working together could limit some of the damage of climate change's increasingly severe effects, and even create beauty in new public works.

Even so, efforts to cope with intensifying coastal flooding around the world have been less successful in lower-income countries. When freak hurricanes struck West Africa in the 2050s, millions of people were dislocated, and a substantial fraction of them sought refuge in the European Union. A similar wave of migration into the EU was kindled by Hurricane Milton's fierce landfall in England in 2062. With last year's Cyclone Kyarr sparking a similar dislocation in Myanmar and forcing the issue of disaster migration onto the Chinese agenda, it seems increasingly likely that a long-overdue examination of international migration law will be a key part of the global adaptation agenda in the 2070s.

Endnotes

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