WILKO GRAF VON HARDENBERG

Our Bases Are Precarious!

Sea level rise has become a standard indicator of how humans are transforming the planet. But our ideas about sea level, why we measure it, and how it varies have changed radically over the centuries.

In a booklet published in 1931 titled *Marseille, ou la mer qui monte* (Marseille, or the rising sea), Auguste Bouchayer, an entrepreneur and engineer from Grenoble, reports on his hunt for the technical means by which the mean level of the Mediterranean Sea at the port of Marseille is determined. When Bouchayer arrives at the automated tide gauge, or "integrator," that was set up in the harbor in 1884, he realizes in horror that the data it's collected for almost 50 years has been corrupted. The wife of the gauge's warden, looking after the machinery while her husband is out fishing, reveals to Bouchayer and his companion—Louis Le Doyen, an amateur archaeologist working at the city's roads and water administration—that when the sea is too strong, they just close the lower basin. Then they can sleep without fretting that the float's cable might break. But by doing so they impede the gauge's ability to record continuous measurements. Bouchayer, dismayed, exclaims, "My dear Le Doyen, your integrator, marvel of mechanics, is rigged! Our bases are precarious!"

Precariousness is, in fact, intrinsic to all sea level measurements, as they depend on the constant changes experienced by the sea. Nonetheless, mean sea level is routinely used as a baseline for a variety of measures, including altitude; in most countries the official height reference framework refers to sea level in some way. The idea of sea level as a benchmark for elevation has been around for so long that it goes unnoticed—we mention it without pausing to consider what it means. We forget that sea level is far from a natural index, but a product of technically and culturally determined assumptions.

Establishing the level of the sea is part of a broader effort to reform and unify reference points and units of measure that has taken place since early modernity. The definition of the meter, the choice of a prime meridian, and the standardization of time are examples of this process. The use of sea level both as a baseline for measuring change and as a reference point for altitude is intertwined with a long-held perception of holocenic stability. And, paradoxically, sea level's use is also tangled with that perception's own recent upheaval, as climate change introduces new instability to our bases.

Methods of measure

It is common practice to provide the elevation of a place as part of its coordinates. Altimeters of varying precision are embedded in our phones, car navigators, and a multitude of wearables, making simple readings readily available. But extreme accuracy in determining heights was long seen as unnecessary. The first altitude recorded on a map appeared only in 1712, when the physician and mathematician Johann Jakob Scheuchzer indicated an approximate value for the height of the Steilerhorn peak in the Lepontine Alps on his famous map of Switzerland, the *Nova Helvetiae tabula geographica*. Scheuchzer assessed the elevation barometrically with respect to an unspecified location on the Mediterranean Sea. The conversion of barometer readings into altitude values was a recent scientific accomplishment and still rather imprecise: Scheuchzer gives the Steilerhorn's height as about 3,500 meters, while according to modern measurements its summit reaches just 2,980 meters. The formulas necessary to transform pressure values into heights with some precision took longer to develop. Crucial in this regard was the parallel improvement of methods and infrastructures for trigonometric surveys, which yielded reliable height assessments with which to compare barometric readings.

Although the principles of determining heights geometrically were known in early China as well as the Mediterranean world, elevations had not previously been shown on maps. Recording the difference in height between peak and valley bottom, or simply the fact that one place lay higher than another, appeared sufficient for most purposes. In many cultures, a focus on how human bodies reacted to changes in elevation was common: mere numerical height was generally deemed less important than the time and effort involved in a climb. In 1765, the French scholar Denis Diderot, famous for his *Encyclopédie*, criticized attempts made to derive a formula to transform the duration of a climb into a numerical value of altitude as subjective and imprecise: The time it takes to climb a mountain, he claimed, depends on multiple variables, including the climber's speed, the route chosen for the ascent, and the slope gradient.

Diderot's critique speaks to the quantitative turn scientific practices took in the second half of the eighteenth century. Mathematical methods increasingly influenced the description of the physical world, and measurements and debates about their accuracy gained importance in scientific discourse. Enlightenment scholars took their passion for measurement to heights around the world. Writing about his 1802 attempt to reach the summit of Chimborazo, in what's now Ecuador—then thought to be the highest peak in the world—the German polymath Alexander von Humboldt combined subjective and objective approaches to altimetry. On the one hand, he gauged elevation by recording how it affected his body; on the other, he stressed the imprecision and unreliability of altitudes defined on the basis of air pressure. He also noted how climbers "tend to overestimate the height they attain," then get annoyed when "confronted with correct measurements." The search for records and greater accuracy continued with the measurement of ever higher mountains and became embedded in the spirit of mountaineering throughout the nineteenth and twentieth centuries. Part of this search was the long series of expeditions to reach the highest peaks of the Himalayas, which contributed throughout the nineteenth century to a new perception of global verticality.

Yet measuring altitude required coordinated group efforts as much as heroic individual feats of exploration. A single effort could not determine altitude: measurements had to be repeated in order to ascertain the rate of error. Triangulating large areas and comparing the heights of mountains required signals and markers that could be seen from a distance. Each measurement thus took months or even years to accomplish. What had essentially been a hobby of some individuals now became a major undertaking requiring the kind of coordination, reiteration, and material support that only state agencies could offer. Accuracy and precision in establishing the heights of mountains were the products not only of technical improvements to instruments and tables, but of financial and political investments.

Making baselines

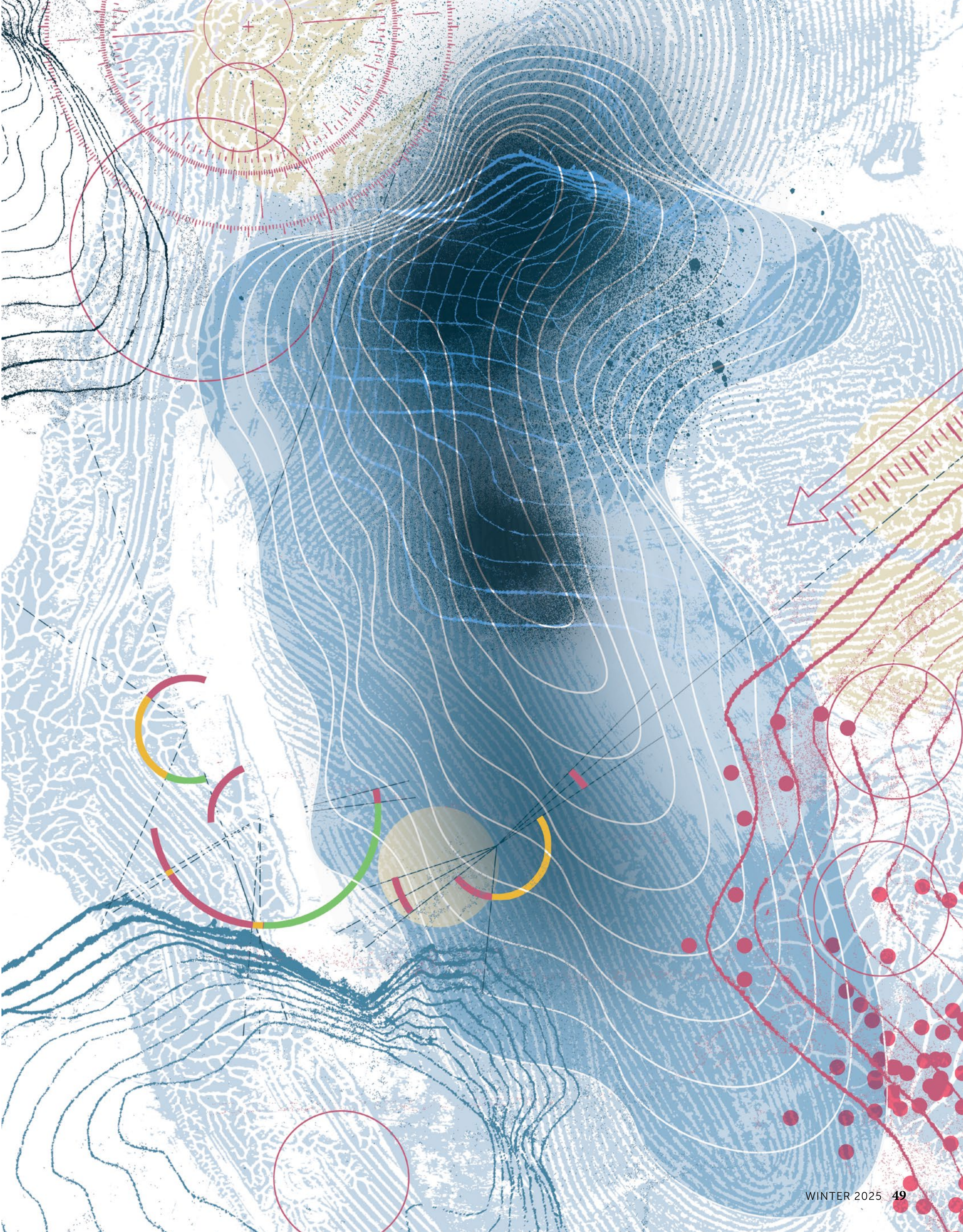
Despite the evident technical differences, barometric and trigonometric measurements have one thing in common: their accuracy depends on the choice of reference point or, to introduce a technical term, of *vertical datum*. Baselines for heights are invented, derived, and described rather than discovered. There is no progress to be found, no constant improvement of knowledge, no approach to a more "real" system of reference. The assessment of altitude is, instead, the outcome of specific material and historical practices.

In Europe and the Mediterranean world, premodern measurements of elevation would refer, generically, to the "lowest place on earth." That might mean a local, relative marker, such as the level of water in a nearby lake or river, or a customary location, such as a church's threshold. When sea level was used, it was often just because the sea was close by. In the eighteenth century, though, it became increasingly common to relate elevations further inland to sea level. Colonial administrations' need to conduct and compare land surveys across oceans, along with a growing fascination with the quantification of mountaineering achievements, made the possibility of a standardized reference framework increasingly desirable.

It remained unclear, however, what exactly was meant by "the level of the sea," and surveyors rarely explicitly clarified how they arrived at their "zero." The stability of the sea and its reliability as a point of reference was still a matter of debate. Myriad theories, many connected to the tale of the biblical flood, envisioned a sea that could change its level on local and global scale.

Mean sea level—like other height reference points—does not exist independently of cultural techniques for the appreciation of verticality, and its changes do not exist independently of the methods used to assess rates of change over time. But once created within a specific social and cultural setting as a tool to make the world more legible, sea level becomes quintessential in shaping the environment as we know it. Human cultural conceptions of what sea level is, which individual points should be singled out from the continuous curve of tidal movements, and how absolute and relative changes can be assessed are

Illustration by Shonagh Rae



historical constructs that have a substantial impact on how humans imagine and frame the environment.

Mean sea level is only one of many possible benchmarks, just as the meridian running through Greenwich, England, is one among many that have been historically used as a reference for longitude. Depending on their purposes, different sea levels have been selected and used as zero. When the relationship to the sea is primarily defensive, concerned with preventing storm floods and the like, the main interest has been to record the highest high tide, or the farthest inland point reached by the sea in its regular fluctuations. The average level of high tides is still customarily used on maps to mark coastlines—the extreme boundary of land in a strict sense. In the eighteenth century, most measurements in Europe referred to high water; these figures were easier to acquire than low-tide measurements and of more immediate import to dock operations. Ports, by their nature, are not supposed to experience low tide to its full extent—no port, that is, should ever be dry. Thus, while high water can easily be measured at a port entrance, measuring low water requires a second tide staff some distance offshore.

This does not mean, however, that low-tide levels have been ignored. When navigation is the focus, favor has been given to the lowest low tide, to indicate the minimum available depth of water and ensure that no ship runs aground when approaching the coast at any point in the tide cycle. In nautical charts, some iteration of the low-tide level has accordingly been used as the datum. The same reference point is also frequently used as the *hydrographic zero*, the starting point for the assessment of tidal movements, as it prevents the use of negative numbers.

The points of low and high tide can be seen or touched as water lingers at the extremes of its cycle—what's called *slack tide*. In contrast, mean sea level is a pure mathematical abstraction of the tides, or what geographer Katherine G. Sammler calls a "temporal average meant to smooth the variability of shorter time scales." There is no strict boundary, despite the precise appearance of coastlines on maps. Neat distinctions between land and sea are relatively recent products of the modern age. As geographer Paul Carter explains, the coastline of modern Western cartography "is an artifact of linear thinking, a binary abstraction that corresponds to nothing in nature." Coasts are actually *ecotones*: spaces in which different ecosystems meet and interact; porous regions that are part land, part water.

Beginning in the late eighteenth century, these shifting coastal environments were conceptually split into discrete elements. The rise of capitalism, the first wave of industrialization, and the growing infrastructural needs of nation-states gradually divided land and sea into reciprocally alien worlds. Property, management, and control all require the subdivision of space into clear epistemic and legal categories. "The drawing of these lines of separation through technology and law," writes legal historian Debjani Bhattacharyya about the differential definition of land and sea in and around what is now Kolkata, India, in the nineteenth century, "also entails forgetting the soaking ecologies in order to embrace the dry cultures of land use."

But sea level is more than a mere boundary marker. It is increasingly an indicator of change, a material gauge of variations in the world's climate. "Because it integrates changes in several components of the climate system in response to external forcing factors and internal climate variability, sea level is one of the best indicators of global climate change," the French pioneer in space altimetry Anny Cazenave and her colleagues argue. It once marked change on a geological timescale, evincing shifts discernable only through long-term comparisons between, for instance, glacial and interglacial periods. These same changes are now significantly accelerated, showing, almost in real time, how humanity continues to transform the planet. Sea level rise is already encroaching on places as disparate as Miami, the Netherlands, Bangladesh, and the island states of the South Pacific, prompting a multiplicity of place-specific adaptive responses.

The dawn of data series

The earliest available data series on sea level relative to land began to be produced consistently almost five centuries ago in Amsterdam. Elsewhere, tide gauges, the tools necessary to collect sea level measurements, were installed in a disorderly, piecemeal fashion—and often used incorrectly, as Bouchayer indicated. Such haphazard and unbalanced development and the consequent unevenness of available series has produced biases in our historical understanding of sea level rise. Phenomena characteristic of the North Atlantic, where most early measurements were taken, were superimposed on all the seas under the assumption that processes such as sea level rise would be uniform across the globe. Recent research has shown how other factors, such as the gravitational pull exerted by land and ice masses, play a crucial role in the global distribution of seawater. The loss of attractive force caused by the melting of major ice masses, such as the West Antarctic and Greenland ice sheets, may counterintuitively result in a decrease in sea levels in the immediately surrounding areas. Sea level rise due to global glacial melt will thus affect the regions around the equator more significantly.

The preeminence of the North Atlantic in historic sea level data is a peculiar product of people's attempts to live and thrive in the littoral spaces of Western Europe. In Venice, for example, the epitome of a lagoon urban environment, the blackish-green line that marks the upper limit of algal growth on the foundations of the city's buildings has served, at least since 1440, as a benchmark for the depth soundings undertaken to assess the impact of siltation and sedimentation. This crucial effort contributed both to maintaining the city's role as a trading and seafaring port and to preserving the lagoon as a defense against possible attacks from land. In subsequent centuries, this natural marker, called the *comune marino* (sea average), was complemented by the carving of the letter "C" into the stone at the level marked by algae. However, these markers are of an extremely local nature and only record the level of the tide in a single canal on a specific *palazzo*. Given the peculiar conformation of the Venetian canal network and the time it takes the tide to reach different areas, this level varies to some extent from one corner of the city to another. As had been noted by the eighteenth century, the variability of this reference point made it impossible to assess changes over time in the relative level of the sea. A standard, mean level of high water—the *comune marino normale*—that could act as a baseline for future measurements and serve as a stable citywide datum was eventually selected in 1825.

Venice was not the only place in Europe with a vested interest in keeping tabs on the relative position of land and sea. Amsterdam began to keep formal record of sea height by 1556, consequent to a court trial about the enlargement of the town walls. Based on these records, the locks allowing access to the new port area of Lastage would be shut when the sea surpassed a certain level, to prevent the city from being flooded. A thorough record of the highest level attained by the sea was essential to the operability and effectiveness of a port that, in those years, was radically improving its docks to become a node of intercontinental commerce. In 1675, the mean of these high-water levels—approximately 14 centimeters above mean sea level—was adopted as the town's official vertical benchmark, the baseline by which the minimum height of dikes would be determined. In 1818, due to both the European trend toward standardizing measuring units in the aftermath of the French Revolution as well as the increased infrastructural needs of the Dutch state, that baseline was adopted by King Willem I as the standard datum for the whole of the Netherlands, with the name *Amsterdam peil*, or Amsterdam ordnance datum.

Toward the mean

The Venetian and the Dutch efforts were exclusively concerned with recording the average high tide, which was easily registered. Much less intuitive is the recording of both low and high tides. Waves and wind constantly distort the data, making the level of the sea hard to ascertain in any given moment, even against the most accurate graduated rod. To overcome this churning, in 1665 Scottish natural philosopher Robert Moray proposed the use of a stilling well connected to the sea by a channel and thus isolated from disturbances produced by meteorological conditions. Moreover, he recommended a floating device, placed in the well, that would move a counterweight via a system of cables and pulleys. The level of the sea could then be read on a dial by means of a pointer connected to one of the pulleys. Moray was also the first to suggest that sea level should be read continuously, rather than just at tidal extremes. Although the scheme was never put into practice by Moray himself, it proved crucial in the scientific and technical developments that would contribute to making mean sea level the standard geodetic vertical datum.

Interest in accurate sea level measurements and the creation of new technical instruments may have also been stimulated in late seventeenth-century Western Europe by the lack of actual data to test new theories about the tides. In France, for instance, the need for data to test René Descartes's theory that tides were due exclusively to the influence of the moon led the French Academy of Sciences to circulate a formal protocol about how to gauge sea levels. This effort, the first coherent venture in tidal measurements by the central administration of a state, made use of stilling wells, as Moray had proposed, but radically simplified his apparatus. The outcome was a sudden increase in the amount of data available about the level of the sea along the coasts of France.

However, the potential of these scientific and technical improvements went unrealized. Measurements were taken discontinuously, in individual bouts separated by long periods of inactivity. And an idea prevalent among scholars during the eighteenth century, that the sea was steadily falling, made it harder to adopt sea level as a benchmark for heights. The growing debate of those decades, though, laid the groundwork for sea level's later designation as the standard vertical datum.

Over the last two centuries of the Holocene, human ideas about sea level and how it varies have changed drastically. In the eighteenth century, in continuity with older scholarly debates about the biblical flood, sea level was generally considered subject to continual decline. The earth, its mountains, and coasts were shaped primarily, many scholars affirmed, by the falling, over millennia, of a proto-ocean. From the turn of the nineteenth century, the stability of the sea and its use as the standard reference point for elevations became embedded into the Western scientific canon. And finally, in the last decades, the reality of a rising sea due to the impact of human activities on the geological scale has gained wide scientific acceptance.

To understand humanity's future challenges in an environment that is less and less comparable to the one that nurtured our species over millennia, we must read the history of both oceanic sciences and surveying in a way that clarifies their relationship with the environments they claim to study. New ways of understanding these relationships may be the necessary outcome of unprecedented environmental changes in the Anthropocene.

Wilko Graf von Hardenberg *is a historian of science and the environment. He currently leads the project "The Sound of Nature: Soundscapes and Environmental Awareness, 1750–1950" at Humboldt University in Berlin.* *This essay is adapted and excerpted from* Sea Level: A History *by Wilko Graf von Hardenberg, published by the University of Chicago Press.*