

THE PAST, PRESENT, AND FUTURE OF
RISING SEA LEVELS

An aerial photograph of a small boat in the middle of a stormy sea. The boat is surrounded by a massive, billowing splash of white water that obscures much of its upper structure. The surrounding water is dark and turbulent, with whitecaps visible. The sky is a pale, overcast blue.

THE

ATTACKING

OCEAN

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AUTHOR OF BEYOND THE BLUE HORIZON

The Attacking Ocean

THE PAST, PRESENT, AND FUTURE OF
RISING SEA LEVELS

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To

Atticus Catticus Cattamore Moose

*A splendid beast who did everything he could to stop this book
being written by dancing on the keyboard at inopportune moments.
And he never has to worry about sea levels.*

It came to the megacity at dusk, deceptively and unequally ... In the lowlands, near the ~~seashores, the harbors, the bays, the Sound, the river: apocalypse. The very ocean rose,~~ tsunami-like, relentless, terrifying, bringing devastation by flood and wind and wind-shipped fire, and for some ten million people in a swath a thousand miles wide and encompassing sixteen states, darkness and dread.*

—Hendrik Hertzberg on Hurricane Sandy,
The New Yorker, November 12, 2012

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Preface

Almost all my life, I've lived by the sea. I've also sailed thousands of kilometers along ocean coasts and across open water, even crossed the Atlantic Ocean. Some of my earliest memories are of lying awake on an English morning, listening to the rain from a southwesterly gale gusting against my bedroom window. Another early childhood experience sticks in my mind—a late 1940s vacation on Jersey, part of the Channel Islands, where the tides run fast with a range of over eleven meters at full or new moon. I remember watching the rising tide course over wide sand flats so fast that you almost had to run to keep ahead of the breakers—not that my father would have allowed me to do anything so rash. He was well aware of the power of a wave born by a powerful tidal stream. In later years, I sailed small yachts in northern European waters, where the direction of tidal streams and the height of the ebb and flood determine which direction you sail and when, and where you'll anchor. Lying aground on a sandbank at thirty-five degrees is no fun, especially if it's the middle of the night and you feel guilty for having misjudged the tide. All these cumulative experiences flooded into my consciousness as I delved into the complex history of rising sea levels over the past fifteen thousand years—since the Ice Age.

You cannot, of course, compare the experience of feeling your way down narrow channels between sandbanks in a small boat with the phenomenon of rising (or falling) sea levels. Tides rise and fall over short cycles of about six hours. In places like Brittany in northern France or the Channel Islands the landscape changes dramatically from high tide to low. A deep, wide river at high water becomes a narrow stream flowing between rocks and sandbanks at low. It's almost like sailing in a different world, just as it is when you traverse creeks and twisting waterways in the shallow tidal waters of eastern England, where sandbanks appear and vanish in minutes. The changing sea levels described on these pages are something quite different. We're talking here of gradual, cumulative changes in ocean levels that have risen and fallen for at least 750,000 years and probably much longer. This book is primarily concerned with sea level changes over the past 10,000 years or so and how they have affected humanity.

Think of walking on a sandy beach as the tide is rising. You start at low water as the flood begins. As you walk, you play with the encroaching breakers in bare feet. But, as the hours pass, you find yourself walking farther upslope, often on a much narrower beach. The rise is slow, inexorable, and sure. This is exactly what the gradual sea levels since the end of the Ice Age some fifteen thousand years ago were like, but with one significant difference. There was no ebb. The rise was slow, continual, and cumulative over centuries and millennia, caused by geological processes unfolding thousands of kilometers away.

For the most part, we're unaware of rising sea levels, unless we live along a low-lying coastline where even a small rise can spread water over a wide area—as happened in the Persian Gulf at the end of the Ice Age, and is the case in places like the Ganges River delta in Bangladesh today. Even in densely populated, threatened areas like the Mekong or the Nile deltas, decadal changes are almost imperceptible. The attacking ocean only enters our urgent consciousness when hurricanes like Katrina or more recently, Sandy, barrel ashore, bringing high winds, torrential rainfall, and catastrophic sea surges that uproot everything before them. Such sea surges have always assaulted low-lying coasts, but it is only within the past 150 years or so that these vulnerable coasts have become crowded with tens of thousands, even millions, of people.

The past fifteen thousand years have witnessed dramatic sea level changes, which began with rapid global warming at the end of the Ice Age. When the ice started retreating, sea levels were as much as 221 meters below modern levels. Over the next eleven millennia, the oceans climbed in fits and starts, sometimes rapid starts, reaching near-modern levels by about 4000 B.C.E., nine centuries before the first Egyptian pharaohs ruled the Nile valley. This sweeping summary masks a long and complex process of sea level rise, triggered by melting ice sheets, complex earth movements, and myriad local adjustments that are still little understood. By all accounts, these rapid sea level changes had little effect on those humans who experienced them, partly because there were so few people on earth, and also because they were able to adjust readily to new coastlines. Over these eleven thousand years, the world's population was minuscule by today's standards. Fewer than five million people lived on earth fifteen thousand years ago, almost all of them in the Old World. The global population numbered about seven million by six thousand years ago. By today's standards, the world was almost deserted. There was plenty of room to move away from encroaching breakers even in the most densely populated areas. But the marshes and wetlands that protected coasts from storms were still vitally important, not only as natural defenses against the ocean, but also as rich habitats for game, large and small, and also for birds, fish, mollusks, and plant foods.

Global sea levels stabilized about six thousand years ago except for local adjustments that caused often quite significant changes to low-lying places like the Nile delta. The curve of inexorably rising seas flattened out as urban civilizations developed in Egypt, Mesopotamia, and South Asia. Imperceptible changes marked the centuries when Rome ruled the Western world and imperial China reached the height of its power. The Norse explored a North Atlantic identical to ours a thousand years ago; Christopher Columbus and the mariners of the European Age of Discovery sailed over seas that had changed little from the time of the pharaohs. But another variable was now in play, that of the world's population, which climbed rapidly after 4000 B.C.E. By the time of Christ, at least two hundred million people lived on earth. The number had reached a billion or so by the late eighteenth century, when the Industrial Revolution was under way. The densest of these growing populations lived in cities, many of them on river floodplains and low-lying coastal plains. With the rapid expansion of maritime and river-based trade, more and more people settled in strategic coastal locations that became important ports. Now the threat from the ocean increased dramatically, not because of rising sea levels, but from severe weather events like hurricanes and tropical cyclones with their violent sea surges. Tsunamis generated by deep-sea earthquakes assumed much more menacing proportions once people had settled in crowded cities close to the shore. Human vulnerability to a potentially climbing ocean has increased dramatically because there are now so many of us—today seven billion and climbing—at a time when sea level rise has resumed.

The new era of rising sea levels dates from about 1860, the height of the Industrial Revolution. Since then, the world has warmed significantly and the ocean is once again climbing inexorably. Without question, we humans have contributed to the accelerating warming of recent decades. The sea level changes are cumulative and gradual; no one knows when they will end—and the ascent's end is unlikely to come in any of our lifetimes. We live in a very different world from even that of 1860, with tens of millions more people living in coastal cities or farming land only a few meters above sea level. Even a rise of a meter or so will inundate thousands of hectares of rice paddies and major international ports—this before one factors in the savage destruction wrought by sea surges and tsunamis. Our sheer numbers and profound dependence on cargoes transported on the ocean have raised our vulnerability to rising sea levels to a point at which we face agonizing and extremely expensive decisions about flood-control works, sea defenses, or relocation questions that humanity has never wrestled with before.

The Attacking Ocean tells a tale of the increasing complexity of the relationship between human

and the sea at their doorsteps, a complexity created not by the oceans, whose responses to temperature changes and severe storms have changed but little. What has changed is us, and the number of us on earth.

LIKE MY OTHER BOOKS about ancient climate, *The Attacking Ocean* has many narratives and multiple story lines, for the tale covers fifteen millennia of human history, multiple continents, and a great variety of societies—ancient and modern, simple and complex. There is a somewhat chronological gradient in these pages, from earlier societies to later ones. Such an organization is a logical way to explore the tangled history of sea level changes over the past fifteen thousand years since post-Ice Age warming began. Once the stage is set in [chapter 1](#), which describes how sea levels rose and introduces the dangers of tsunamis and other extreme events, I've divided the story into three parts. "Millennia of Dramatic Change" covers the rapid sea level changes between fifteen thousand years ago and 4000 B.C.E. and their impact on human societies. Chapters 2 to 4 take us from northern Europe to the Black Sea, the Nile valley, and Mesopotamia, through coastal landscapes changed dramatically by fast-climbing sea levels. [Chapter 2](#) brings out a persistent theme—that of the importance of marshes and wetlands to both hunters and subsistence farmers, for these borderlands acted as dietary insurance when harvests fail or powerful storms attack low-lying coastlines. In [chapter 3](#) we explore the major environmental changes that resulted from climbing shorelines in the Dardanelles Strait between Europe and Asia. We describe how rising sea levels caused the ponding of the Nile, which led to the creation of the Nile delta, one of the breadbaskets for the Egyptian state. [Chapter 4](#) examines the complex relationship between the early Mesopotamians and a Persian Gulf that turned from a gorge-bisected desert into an arm of the Arabian Sea in a few thousand years, with momentous consequences for humanity. Again, we return to wetlands, this time between the Tigris and Euphrate Rivers, where the god Marduk "laid a reed on the face of the waters" and created one of the first civilizations.

These chapters reside firmly in the past, but the tempo and character of the history changes in "Catastrophic Forces," chapters [5](#) to [10](#). Now we are much closer to the present, telling stories of human vulnerability and of societies that often have direct relationships with those of today. Here, most chapters move seamlessly from the past into the present, for the same processes that shaped relationships with ancient sea levels still operate today. For instance, countless early Mediterranean ports had problems with natural sinking and also with accumulating river silt and severe storms. The same problems afflicted medieval Venice and continue to threaten its future today—which is why we journey from past into the present in this and other chapters. The same argument applies to chapters [9](#) and [10](#), which describe sea level changes in China and Japan. In all these chapters, the emphasis is more on major natural events, which bring catastrophe in their train, especially sea surges and tsunamis, the latter the dominant theme of [chapter 10](#). In the case of northern Europe and south Asia, we bring the story forward to later times, leaving the modern struggles with rising sea levels to later chapters.

"Challenging Inundations" comprises the final five chapters, in which I describe some of the extraordinary challenges that confront us today. Again, the coverage is geographic, largely because each area has its own distinctive issues. [Chapter 11](#) describes the menacing difficulties that confront Bangladesh, where 168 million people live close to sea level with nowhere to go. Here, the long-term problem of environmental refugees raises its head, a global problem that is currently on few governments' agendas, although it should be. [Chapter 12](#), "The Dilemma of Islands" raises not only the issue of environmental refugees, but also the difficulties of relocating entire villages and small

island nations. “The Crookedest River in the World” takes us back deep into the history of the Mississippi and its peoples to a delta coast and modern cities threatened from both up- and downstream. This is a story of sea defenses erected in the face of extreme storms, unpredictable river floods, and rising sea levels. The Low Countries face the same dilemma as Bangladesh, lands walled off in an ultimate expression of human determination to resist the attacking sea to the death. The epilogue looks at the future and rising sea levels in the context of the United States, where millions of people live in houses but a few meters above today’s sea level. Hurricane Sandy, which devastated much of New York and the New Jersey Shore in October 2012, provided a sobering reminder of just how vulnerable we are to a future of more frequent extreme weather events and violent sea surges that can render tens of thousands homeless.

Everyone should start this book by reading [chapter 1](#), but thereafter you have choices. Brief summary statements introduce each section to help you on your way. You can follow the story chapter by chapter, moving from area to area as the narrative moves forward. If you find this confusing, especially the winding back of chronological narratives from one chapter to the next, you can explore different areas by jumping between widely dispersed chapters. An alternative table of contents on page xi guides you through this option. This is a particularly effective way of moving from past to present within specific geographies. Provided you end by reading chapter 15, you should leave the book with focused narratives of areas that interest you and with a general sense of the central messages of the book. If you choose this approach, your choices are open-ended. Using the notes at the end of the book, you can then delve more deeply into the enormous literature that surrounds each chapter.

Minus One Hundred Twenty-Two Meters and Climbing

On October 28, 2012, Hurricane Sandy, the largest Atlantic hurricane on record, came ashore in New Jersey. Sandy's assault and sea surge brought the ocean into neighborhoods and houses, inundated parking lots and tunnels, turned parks into lakes. When it was all over and the water receded, a huge swath of the Northeast American coast looked like a battered moonscape. Only Hurricane Katrina, which devastated New Orleans in 2005, was more costly. Katrina, with its gigantic sea surge, had been a wake-up call for people living on low-lying coasts, but the disaster soon receded from the public consciousness. Sandy struck in the heart of the densely populated Northeastern Corridor of the United States seven years later and impacted the lives of millions of people. The storm was an epochal demonstration of the power of an attacking ocean to destroy and kill in a world where tens of millions of people live on coastlines close to sea level. This time, people really sat up and took notice in the face of an extreme weather event of a type likely to be more commonplace in a warmer future. As this book goes to press, a serious debate about rising sea levels and the hazards they pose for humanity may have finally begun—but perhaps not.

Sandy developed out of a tropical depression south of Kingston, Jamaica, on October 22. Two days later, it passed over Jamaica, then over Cuba and Haiti, killing seventy-one people, before traversing the Bahamas. Come October 28, Sandy strengthened again, eventually making landfall about 150 kilometers southwest of Atlantic City, New Jersey, with winds of 150 kilometers an hour. By then Sandy was not only an unusually large hurricane but also a hybrid storm. A strong Arctic air pattern to the north forced Sandy to take a sharp left into the heavily populated Northeast when normally it would have veered into the open Atlantic and dissipated there. The blend produced a super storm with a wind diameter of 1,850 kilometers, said to be the largest since 1888, when far fewer people lived along the coast and in New York. Unfortunately, the tempest also arrived at a full moon with its astronomical high tides. Sandy was only a Category 1 hurricane, but it triggered a major natural disaster partly because it descended on a densely populated seaboard where thousands of houses and other properties lie within a few meters of sea level. Imagine the destruction a Category 5 storm would have wrought—something that could happen in the future.

The scale of destruction was mind-boggling. Sandy brought torrential downpours, heavy snowfall, and exceptionally high winds to an area of the eastern United States larger than Europe. Over one hundred people died in the affected states, forty of them in New York City. The storm cut off electricity for days for over 4.8 million customers in 15 states and the District of Columbia, 1,514,140 of them in New York alone. Most destructive of all, a powerful, record-breaking 4.26-meter sea surge swept into New York Harbor on the evening of October 29. The rising waters inundated streets, tunnels, and subways in Lower Manhattan, Staten Island, and elsewhere. Fires caused by electrical explosions and downed power wires destroyed homes and businesses, over one hundred residences in the Breezy Point area of Queens alone. Even the Ground Zero construction site was flooded. Fortunately, the authorities had advance warning. In advance of the storm, all public transit systems were shut down, ferry services were suspended, and airports closed until it was safe to fly. All major bridges and tunnels into the city were closed. The New York Stock Exchange shut down for two days. Initial recovery was slow, with shortages of gasoline causing long lines. Rapid transit systems slow

restored service, but the damage caused by the storm surge in lower Manhattan delayed reopening critical links for days.

The New Jersey Shore, an iconic vacation area in the Northeast, suffered worst of all. For almost 150 years, people from hot, crowded cities have flocked to the Shore to lie on its beaches, families often going to the same place for generations. They eat ice cream and pizza, play in arcades once used by their grandparents, drink in bars, and go to church. The Shore could be a seedy place, fraught with racial tensions, and sometimes crime and violence, but there was always something for everybody, be they a wealthy resident of a mansion, a contestant in a Miss America pageant, a reality TV actor, a skinny-dipper, or a musician. Bruce Springsteen grew up along the Shore and his second album featured the song “4th of July, Asbury Park (Sandy),” an ode to a girl of that name and the Shore. “Sandy, the aurora is rising behind us; the pier lights our carnival life forever,” he sang. The words have taken on new meaning since the hurricane came.

Fortunately, the residents were warned in advance of the storm. They were advised to evacuate their homes as early as October 26. Two days later, the order became mandatory. New Jersey governor Chris Christie also ordered the closure of Atlantic City’s casinos, a decision that proved wise when Sandy swept ashore with brutal force, pulverizing long-established businesses, boardwalks, and homes. Atlantic City started a trend when it built its first boardwalk in 1870 to stop visitors from tracking sand into hotels. Boardwalk amusements are big business today, many of them faced by boardwalks that are as much as a 0.8-kilometer from the waves. Now many of the Shore’s iconic boardwalks are history. The waves and storm surge destroyed a roller coaster in Seaside Heights; it lay half submerged in the breakers. Seaside Heights itself was evacuated because of gas leaks and other dangers. Piers and carousels vanished; bars and restaurants were reduced to rubble. Bridges to barrier islands buckled, leaving residents unable to return home. The Shore may be rebuilt, but it will never be the same. A long-lived tradition has been interrupted, perhaps never to return. For all the fervent vows that the Shore will rise again, no one knows what will come back in its place along a coastline where the ocean, not humanity, is master.

As the waters of destruction receded, they left \$50 billion of damage behind them, and a sobering reminder of the hazards millions of people face along the densely populated eastern coast of the United States. Like Hurricanes Katrina in 2005 and Irene in 2011, Sandy showed us in no uncertain terms that a higher incidence of extreme weather events with their attendant sea surges threaten low-lying communities along much of the East Coast—from Rhode Island and Delaware to the Chesapeake and parts of Washington, DC, and far south along the Carolina coasts and into Florida, which escaped the full brunt of Sandy’s fury. There, high winds and waves washed sand onto coastal roads and there was some coastal flooding, a warning of what would certainly occur should a major hurricane come ashore in Central or Southern Florida—and the question is not *if* such an event will occur, but *when*.

ONE HUNDRED AND twenty meters and climbing: that’s the amount of sea level rise since the end of the Ice Age some fifteen thousand years ago. Slowly, inexorably, the ascent continues in a warming world. Today the ocean laps at millions of people’s doorsteps—crouched, ready to wreak catastrophic destruction with storm-generated sea surges and floods. We face a future that we are not prepared to handle, and it’s questionable just how much most of us think about it. This makes the lessons of Katrina, Irene, and Sandy, and other recent storms important to heed. Part of our understanding of the threat must come from an appreciation of the complex relationship between humanity and the rising ocean, which is why this book begins on a low land bridge between Siberia and Alaska fifteen thousand years ago ...

BETWEEN SIBERIA AND Alaska, late summer, fifteen thousand years ago. A pitiless north wind fills the air with fine dust that masks the pale-blue sky. Patches of snow lie in the shallow river valleys that dissect the featureless landscape. A tiny group of humans trudge down the valley close to water's edge, the wind at their backs, the men's eyes constantly on the move, searching for predators. They can hear the roar of the ocean in the shallow bay, where wind squalls whip waves into a white frenzy. A few days earlier, the women had trapped some arctic ptarmigan with willow snares, but the few remaining birds hanging at their belts are barely enough for another meal. A dark shadow looms through the dusty haze—a solitary young mammoth struggling to free itself from mud at river's edge.

The men fan out and approach from downwind, scoping out the prospects for a kill. The young beast is weakening rapidly after days in the muddy swamp. Nothing is to be gained by going in for the kill at the moment, so the band pitches camp a short distance away and lights a large fire to keep away predators. A gray, bitterly cold dawn reveals the helpless mammoth barely clinging to life, mired up to its stomach. A young man leaps onto the beast's hairy back and drives his stone-tipped spear between its shoulder blades, deep into the heart. He jumps off to one side, landing in the mud. The hunters watch the mammoth's death throes and thrust more spears into their helpless prey. Soon everyone moves in to skin the flanks and dismember the exposed parts. A short distance away, wolves lurk, ready to move in when the humans leave.

Back in camp, the men build low racks of fresh mammoth bone and lay out strips of flesh to dry against the ceaseless wind, while the women and children cook meat over the fire. Around them, the dusty, filled gloom never lifts, the wind blows, and the roar of the ocean never leaves their consciousness. The sea is never a threat, for their lives revolve around the land and they can easily avoid an encroaching waves by doing what they always have done—keeping on the move.

THIS IMAGINED MAMMOTH hunt unfolded at a time when the world was emerging from a prolonged deep freeze. The bitter cold of a long glacial cycle had peaked about seven thousand years earlier, the most recent of a more than 750,000-year seesaw of lengthy cold and shorter inter-glacial periods driven by changes in the earth's orbit around the sun, which had began 2.5 million years ago. Twenty-one thousand years ago, world sea levels were just under 122 meters below modern shorelines. The seas were beginning to rise fast, as a rapid thaw began and glacial meltwater flowed into northern oceans. Soon one would need a skin boat to cross from Siberia to Alaska and the mammoth hunters' killing grounds would be no more.

An ascent of 122 meters is a long way for oceans to climb, but climb it they did, most of it with breathtaking rapidity by geological standards, between about fifteen thousand years ago and 6000 B.C.E. Most of the ascent resulted from powerful meltwater pulses that emptied enormous quantities of freshwater from ice sheets on land into northern waters and around Antarctica. This was not, of course, the first time that such a dramatic rise had transformed an ice-bound world, but there was an important difference fifteen millennia ago. For the first time, significant numbers of human beings—perhaps as many as hundreds of thousands of them, lived in close proximity to the ocean.

Some traveled offshore. Fifty thousand years ago, even while the late Ice Age was at its height, small numbers of Southeast Asians had already ventured into open tropical waters to what are now Australia and New Guinea. Well before twenty thousand years ago, people were living on the islands of the Bismarck Strait in the southwestern Pacific.² These voyages took place long before melting ice sheets and rising sea levels transformed the Ice Age world of *Homo sapiens*.

WE LIVE IN a rapidly warming world, where human activities now play a significant part in long-term climate change and have done so since the Industrial Revolution, when fossil fuels like coal came into widespread use. It's hard for us to imagine just how different the world was twenty-one thousand years ago. Much of it lay under thick ice. Two huge ice sheets covered virtually all of North America, from the Atlantic to the Pacific. The Cordilleran ice sheet, centered on the Rockies and western coastal ranges, mantled 2.5 million square kilometers. The enormous Laurentide ice sheet lapped the Cordilleran in the west and covered over 13 million square kilometers of what is now Canada. It was nearly 3,353 meters thick over Hudson Bay. Its southern extremities covered the Great Lakes and penetrated deep into today's United States. The Greenland ice sheet was 30 percent larger than today. Another smaller ice sheet linked it to the northern margins of the Laurentide.

In northern Europe, the Scandinavian ice sheet extended from Norway to the Ural Mountains over an area of 6.6 million square kilometers, may even have reached Spitsbergen, and flowed over much of the north German Plain. A smaller ice sheet covered about 340,000 square kilometers and reached halfway down the British Isles. Glaciers descended close to sea level in the Southern Alps. In Siberia and Northeast Asia, ice extended over at least ten times the area of the British ice sheet. Extensive ice sheets mantled the Himalayas.

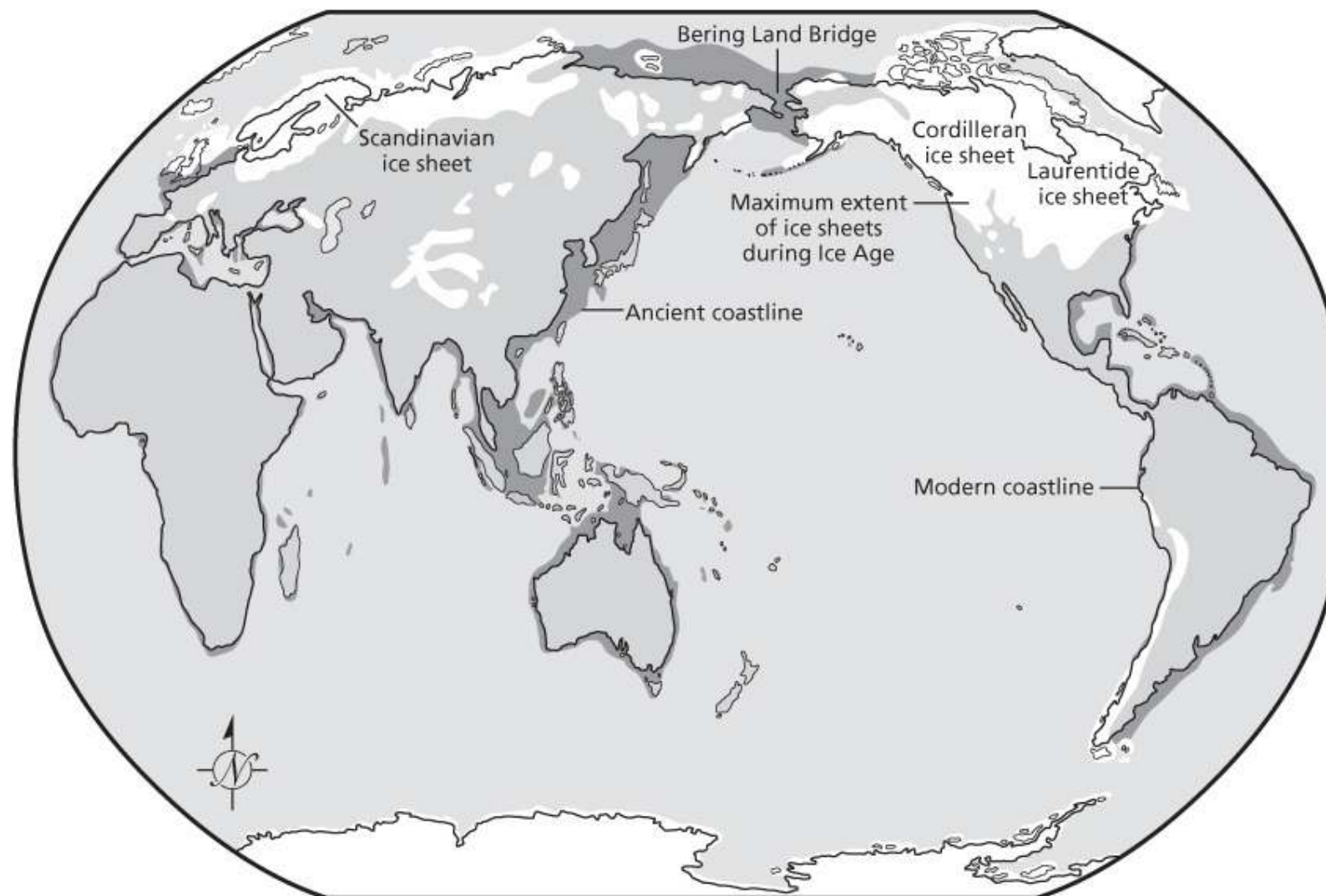


Figure 1.1 Map showing approximate extent of ice sheets and lower sea levels during the late Ice Age.

The Antarctic ice sheet was about 10 percent larger; seasonal sea ice extended eight hundred kilometers out from the continent. There were important ice sheets on the Andes Mountains, in South Africa, southern Australia, and New Zealand. Twenty-one thousand years ago, there was two and

half times as much ice on land as there is today. Of that, 35 percent was on North America, 32 percent on Antarctica, and 5 percent on Greenland. Today, 86 percent of the world's continental ice is on Antarctica, 11.5 percent on Greenland.

There was so much water locked up in glacial ice sheets and sucked out of the oceans that global sea levels were up to 122 meters below those of today. These much lower sea levels changed the shape of entire continents. Perhaps most significant historically was the bitterly cold and low-lying Bering Land Bridge that linked Siberia and Alaska, a natural highway that brought the first humans to the Americas. Dry land joined islands in Southeast Alaska and the Pacific Northwest of North America. Much farther south, San Francisco's Golden Gate channel was a narrow tidal gorge with fast-moving rapids. Continental shelves extended some distance off the Southern California coast, leaving between eleven kilometers of open water between the mainland and the Channel Islands close offshore.

On the other side of the Pacific, low sea levels joined the Japanese islands to Sakhalin Island in the north and brought them much closer to the Chinese and Korean mainland. In China, major rivers like the Huang He in the north and the Yangtze in the south flowed through incised, narrow valleys rather than broad floodplains. Rolling plains stretched far into the distance off Southeast Asia. Only short stretches of open water separated the mainland from Australia and New Guinea, which were a single landmass, now covered by the shallow Arafura Sea.

The configuration of the Indian Ocean was much different from today. Bangladesh lay far above sea level by modern standards, incised by the Ganges and other rivers that flowed much more rapidly to the sea. Sri Lanka's twenty-nine-kilometer-long Rama's Bridge, now a chain of limestone shoals, was a land bridge to India. The Persian Gulf was dry land, an arid landscape bisected by a narrow gorge that drained the highlands and plains at its head.

Had one looked down from a satellite at Europe and the Mediterranean eighteen thousand years ago, one would have surveyed unfamiliar landscapes. Continental shelves extended far into the Bay of Biscay. You could walk from Britain to France, had you possessed a canoe to carry you across an enormous estuary that carried the waters of the Rhine, Seine, and Thames Rivers of today. The southern North Sea was a land of shallow lakes and marshes. The Mediterranean was far smaller, with a narrow entrance at the Strait of Gibraltar scoured by fast-running currents. The northern Aegean Sea ended in a high barrier that isolated what is now the Black Sea from the ocean. The Euxine Lake, formed by glacial and freshwater runoff from the north, lay behind the natural berm. On the other side of the Mediterranean, the arid Nile delta with its sand dunes extended far into what is now open sea.

Everywhere large rivers like the Thames and the Rhine had lower courses and estuaries far different from those of today. The Nile flowed through a twisting, narrow gorge, where the annual flood for the most part remained close to the river channel rather than spilling over a wide floodplain as it did until the building of the Aswan Dam. In the Americas, the St. Lawrence River did not exist; it was under the Laurentide ice sheet. The Mississippi and Amazon Rivers cut far below their modern gradients, with almost none of the ponding and wetland formation that developed as sea levels rose.

Rapid, natural global warming transformed the late Ice Age world into what was effectively an entirely different place in less than ten thousand years. Within this brief time frame, the world's sea levels rose 122 meters.

EUSTACY AND ISOSTASY: the words used to describe sea level changes glide easily off the tongue but they mask very complex and still only partially understood geological processes. What does cause the world's sea levels to rise and fall? Isostatic changes result from local upward and downward shifts in the lithosphere, the uppermost layers of the earth. Such factors as earthquake activity and shifts

tectonic plates far below the earth's surface are important contributors to sea level change. Subsidence in river deltas, changes in glaciers, even sediment compaction—anything that adds to or subtracts from the weight of the earth's crust—all can cause isostatic sea level rises, such as are common in places like Shanghai.³

Eustatic, global sea level rise is completely different, a measure of the increase in the volume of water in the oceans expressed as a change in water height. Everyone knows that water expands as it heats. When the earth's atmosphere warms, the ocean absorbs much of the increasing heat and its waters swell. Thermal expansion is the major cause of global sea level rise since the 1860s, when the Industrial Revolution with its promiscuous use of fossil fuels added more carbon and other pollutants to the atmosphere—in other words, when humanly caused global warming began. At present, eustatic sea level rise advances at a rate of about two millimeters a year if calculated on an average of the past century. Over the past fifteen years, however, the averaged rate is around three millimeters a year, apparently a direct, accelerated response to global warming.

In recent years, we've learned a great deal about the world's glaciers, thanks to satellite technology. We can now measure the elevation of glaciers, their growing and shrinking masses from space with satellite technology, a task hitherto accomplished by arduous fieldwork on the ground. We can also measure the velocity of moving ice and establish the grounding points of glaciers. All of this gives us a more complete overview of the world's ice. The new portraits show that the Antarctic and Greenland ice sheets have contributed only a tiny proportion to annual sea level rise—until recently. However, ice sheets are now contributing double the amount of water they did in the recent past. All the signs are that the rate is accelerating, perhaps dramatically.⁴

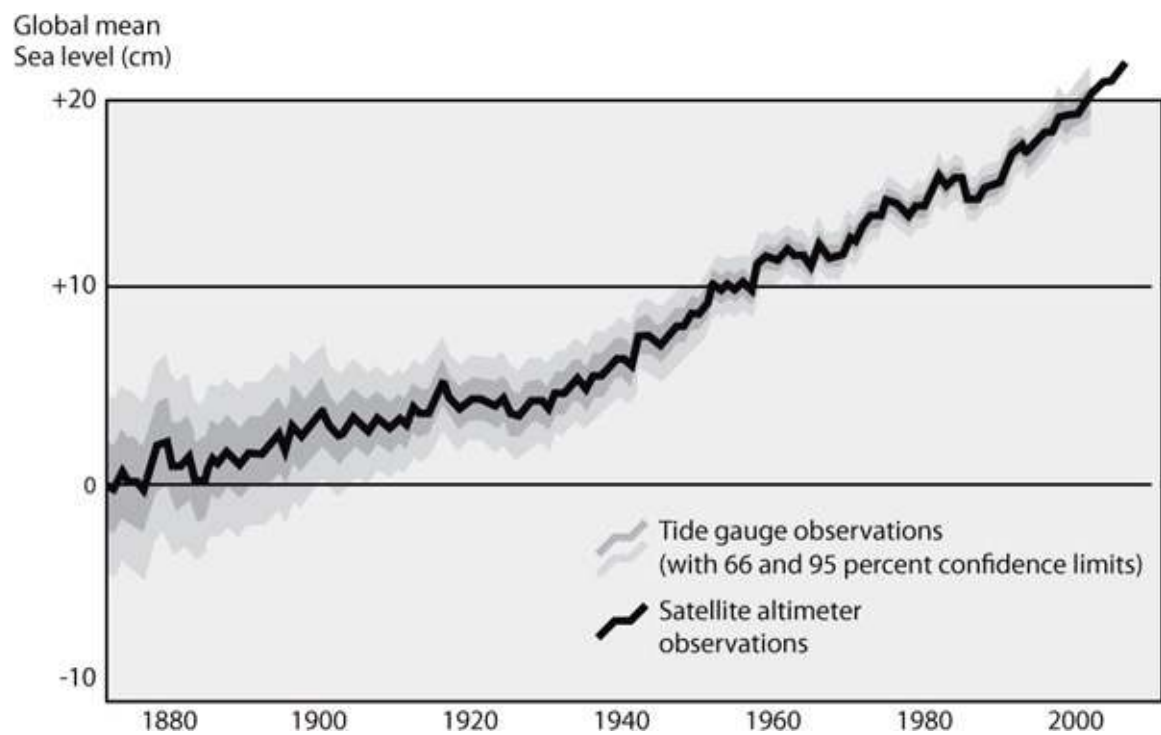


Figure 1.2 A global average of tide gauge data from 1870 to 2000. The new satellite altimeter data is superimposed from 1990. Data from both sources is very similar, chronicling a more rapid sea level rise since 1990. Courtesy: NASA.

Glaciers retreat most rapidly when they end in water. The Mendenhall Glacier near Juneau has retreated five kilometers since 1760 and a kilometer since 2000. Muir Glacier in Glacier Bay has receded ten kilometers since 1941, the Columbia Glacier in Prince William Sound by thirteen since 1981. The general retreat contrasts dramatically with that of the Little Ice Age (ca. 1350 to 1850 C.E.) when Alaska's mountain glaciers not only thickened but also advanced.

The Greenland ice sheet covers 4,550 million square kilometers. If this were to melt completely, global sea levels would rise by seven meters. Recent estimates using a variety of high-technology measurements and satellite data place the annual loss of Greenland ice at about 96 cubic kilometers in 1996, and almost three times that, at 290 cubic kilometers a year, in 2006. Most of this acceleration is occurring in the southernmost glaciers, but the melting is gradually moving northward. Were the entire Greenland ice sheet to melt, which has happened in the remote past, what is now a frozen continent would become an archipelago of islands surrounding a central sea—until crustal adjustments caused the continent to rebound from the weight imposed on it by the ice.

Antarctica at the other end of the world is a vast desert continent, 98 percent of which is covered with ice. Until about 2000, the amount of Antarctic ice was slowly increasing. But recent satellite measurements show that the ice sheets are now losing mass. The East Antarctic ice sheet lies above sea level and is relatively stable. If it were to melt, the resulting sea level rise would be in the order of fifty meters. Much of the West Antarctic ice sheet is aground on the seabed, where changing ocean temperatures affect the stability of its foundations. When these decay, the upper parts of the ice sheet can detach and move seaward. Such melting occurred at the end of the last Ice Age and may well occur again in the near future. Should the entire West Antarctic ice sheet melt, world sea levels would rise by about five meters. If the sheet were to vanish within twelve hundred years, the ocean would climb about thirty to fifty centimeters per century. A five-hundred-year meltdown would cause sea level rises of as much as one hundred centimeters a century.

Predicting sea level changes is a game of geological poker. Unfortunately it is nearly impossible to establish whether changes in ice sheets are mere decadal events, part of normal fluctuations, or something that portends much more dramatic changes in the future. Many experts believe that a two-meter rise by 2100 should be the basis for future planning. Geoscientists Orrin Pilkey and Rob Young believe that “coastal management and planning should be carried out assuming that the ice sheet disintegration will continue and accelerate. This is a cautious and conservative approach.”⁵ Pilkey and Young are sober voices in what often becomes a morass of alarmism and sensationalist headlines. Unfortunately, impending (if probably fictional) climatological catastrophe makes for headline news.

WHAT, THEN, DO we know about sea level rise since the end of the Ice Age? So many local factors are involved that it's hard to provide anything more than a general portrait of global sea level change over the past fifteen thousand years—and even then the experts disagree. Here's a generalized framework, based on many data sources, which will provide a reference point for later chapters.⁶

When the great thaw began, ice sheets retreated precipitously by geological standards. Enormous volumes of meltwater cascaded into northern waters, much of it in dramatic accelerations in sea level rise (often called “pulses”) recorded in Caribbean corals and other sources. There were at least four major pulses, the first about 19,000 years ago, when the sea rose between ten and fifteen meters within a mere five centuries. Another major meltwater release, most likely from North American ice sheets, came between 14,600 and 13,600 years ago. This time the sea level rose between sixteen and twenty-four meters. These major sea level rises came before the onset of a 1,300-year cold snap, the so-called Younger Dryas of 10,800 to 9500 B.C.E. (named by geologists after a polar flower), when sea level rise slowed, only to resume sharply with another meltwater pulse between 9500 and 9000 B.C.E. A fourth meltwater pulse between 6200 and 5600 B.C.E. brought a minor rise, perhaps a meter or so.

By 4000 to 3000 B.C.E., global sea level rise had virtually ceased, except for local crustal adjustments as a result of melting ice sheets. Many islands and coastal areas far from glaciated areas experienced sea levels several meters higher than they are today. The earth's crust responded locally.

to changes in ice coverage and water loading by siphoning water away from equatorial ocean basins into depressed areas close to vanished ice sheets. At the same time, the weight of increased amounts of meltwater affected continental shelves by tilting the shoreline upward and lowering local sea level. Despite these changes, the rate of global sea level rise remained very low until the mid-nineteenth century C.E.

Now the situation has changed significantly. Data from coastal sediments, tidal gauges, and satellites tell us that sea levels have been rising once more since the late nineteenth and early twentieth centuries. Readings from the altimeter aboard the TOPEX/Poseidon satellite record an even higher rate of about 2.8 millimeters annually in recent years, hinting at a long-term acceleration of sea level rise.⁷ Satellites also tell us that the Greenland and Antarctic ice sheets are discharging ice into the oceans more rapidly. But with the kinds of temperature-rise projections of 2 to 5 degrees Celsius projected for the twenty-first century, the resulting virtually total meltdown would take several hundred years. Nevertheless, even with possible accelerated discharge from the West Antarctic ice sheet, it seems unlikely that the rate of sea level rise would exceed those of major post-Ice Age meltwater pulses.

Comforting words, perhaps, but the sea level rises of thousands of years ago came at a time when global populations were a fraction of those of today. Even as recently as five thousand years ago, the most concentrated urban populations in nascent cities like Uruk in Mesopotamia would have numbered less than ten thousand people. Elsewhere, in a world still peopled by small farming communities and hunting bands that were normally on the move, population densities never would have numbered more than a few people per square mile. The world was far from congested, and adjusting to rapid sea level rise was either a matter of shifting camp or of clearing new land for farming villages that were, in any case, often rebuilt or moved every few generations. Today, with cities in the millions and billions of coastal dwellers living at sea level or close to it, the long-term challenges of accelerated sea level rise are already making themselves felt in a much more vulnerable world. As many experts have testified, increased warming brings a higher incidence of extreme hurricanes and severe gales, and also of tropical cyclones and their sea surges, quite apart from the terrible consequences of tsunamis triggered by earth movements on the ocean floor that devastate coastal settlements. These may be short-term events, but they are deadly. Witness the notorious Lisbon earthquake and tsunami of 1755.

LISBON, PORTUGAL, NOVEMBER 1, 1755. All Saints' Day was the most important religious holiday in the calendar. Everyone—rich and poor, young and old—flocked to cathedrals and churches for not to attend was to open oneself to accusations of heresy, no light matter in eighteenth-century Portugal.⁸ People jostled for space; overflow crowds spilled into the streets. Most of the foreigners in the cosmopolitan city stayed at home. As the hymns and prayers were at their height, a loud rumbling and trembling from deep beneath the earth drowned out the sounds of worship, for all the world like distant peals of thunder or the wheels of a passing heavy carriage. Then came the shaking, so violent that houses collapsed in seconds. Towers and spires swayed uncontrollably; church bells pealed in a terrible cacophony, then tumbled to the ground. Entire congregations met their deaths under collapsing roofs and church walls. Huge chunks of masonry and jagged rubble filled alleyways and streets, burying helpless, screaming victims. Dense clouds of dust obscured the blue sky of what had been a lovely sunny day. Within minutes, Lisbon was a rubble field, ravaged by fires started by church candles and scattered hearths.

The survivors fled to open ground, away from tottering buildings and raging fires. Many headed for

the open banks of the Tagus River, where they stood in shock, convinced that the Day of Judgment had come. They loudly begged for divine mercy. Priests moved through the crowds urging them to repent for their sins in the face of God's wrath. How else could such a catastrophe have descended on them on the holiest of days? There were, at the time, no plausible scientific explanations.



Figure 1.3 *The Lisbon earthquake and tsunami as depicted in Georg Ludwig Hartwig's Volcanoes and Earthquakes: A Popular Description, published in 1887. Author's collection.*

Ninety minutes after the earthquake, the crowds at water's edge saw the Tagus rock and roll. Ships at anchor offshore gyrated wildly. Then "there appeared at some distance a large body of water, rising as it were like a mountain; it came foaming and roaring, and rushed towards the shore with such impetuosity, that we all immediately ran for our lives."⁹ The roaring came from a huge tsunami wave said to have been at least twelve meters high, which swept up the river and surged ashore as spectators fled. The three thousand or so people standing on a new stone wharf in hopes of finding a boat were drowned when the quay tipped over. The wall of water rushed as far as 2.4 kilometers inland, inundating buildings, overthrowing bridges, and dashing thousands of helpless onlookers against buildings and walls. Then the wave receded precipitously, carrying hundreds more victims to their deaths and uncovering areas of the riverbed that were normally twelve meters underwater. Ocean-going ships lay helplessly aground. The surviving onlookers moved to the bank, gasping at the sight of fish flapping helplessly. Ten minutes later a second even more violent fifteen-meter wave advanced up the estuary and also cascaded ashore, promptly followed by a third, both traveling "like a torrent, though against the wind and tide."¹⁰ The waves moved so fast that galloping horses could barely escape them.

As many as twenty thousand to sixty thousand people died in the Lisbon earthquake and tsunami. Entire cities in southern Portugal and Spain fell victim to the waves. Tsunami waves swept ashore as far away as Morocco and the island of Madeira (520 kilometers) west of Africa in the Atlantic. Nine hours later, 3.6-meter breakers flooded lowlands on Caribbean islands. Northern Europe felt the effects of the tsunami, the first global natural disaster that prompted the first serious research into such events.

Tsunamis are unpredictable events generated by invisible earth movements, such as earthquakes caused by the collision of tectonic plates far below the sea surface. The word "tsunami" itself is a Japanese term meaning "harbor wave," which dates back at least four centuries and is said to have been coined by fishermen when they returned to devastated harbors after not even having noticed tsunami waves in deep water. Great tsunamis result from extensive displacements of the seafloor

perhaps over hundreds of kilometers, over distances longer than the depth of the water. The waves generated by these enormous earthquakes are extremely long and travel great distances at speeds up to 640 kilometers an hour.¹¹ They are far more damaging than smaller scale tsunamis caused by more local events such as an underwater landslide. In such cases, big waves may result, but they soon dissipate. Large tsunami waves are immensely powerful and quite different from the conventional breakers beloved by surfers. They are solid walls of water that sweep everything before them and rush ashore until friction or gravity cause them to slow and recede.

The Lisbon tsunami of 1755 was not unprecedented. We know, for example, that at least eight large tsunamis have struck the coasts of Spain, Portugal, and Morocco over the past twelve thousand years at intervals of about fifteen hundred years. In 6100 B.C.E., the Storegga underwater landslide displaced vast amounts of seawater off western Norway and caused a tsunami as far away as the Orkney Islands off northern Scotland.¹² Then there is what one might call the mother of all historical natural disasters, the great eruption and resulting tsunami that blew much of Santorini Island in the Aegean into space in about 1627 B.C.E. An entire town, now known as Akrotiri, vanished under a cloud of ash and pumice.¹³ The inhabitants must have had some warning, for no skeletons lie among its ash-smothered dwellings, which stand up to three stories high. Wine jars, storage pots, the remains of a bed, and bright friezes are all that remains of a once-vibrant community. On the walls, a fisherman returns home with his catch; two boys exchange fisticuffs. Fast ships with serried oarsmen pass by a town amid a pod of dolphins.

A visit to Akrotiri is a stroll through a moment frozen in time. One can imagine the inhabitants grabbing their possessions, driving bleating goats into boats, and rowing hastily away as lumps of pumice drop into the seething water. Then a sudden explosion and oblivion, and a once-prosperous town was forgotten until Greek archaeologist Spyridon Marinatos unearthed some of its houses and alleyways in 1967. The scale of the explosion boggles the mind. What had once been one island measuring about nine by six kilometers became four small ones. Ash from the eruption fell over a large area, some of it on Crete, 177 kilometers to the south, at the time the center of Minoan civilization with its far-flung trade networks, extensive olive groves, and wealthy palaces. A tsunami after the eruption lashed the Cretan shoreline with huge waves, which must have caused considerable damage and disrupted mercantile activity over a vast area. Many experts believe the surging ocean permanently weakened Minoan civilization.

When visiting the deep Santorini crater, one's mind turns to Plato's account of the lost continent of Atlantis immortalized by the Greek philosopher with his tale of kings "of great and marvelous power" overthrown by "portentous earthquakes and floods."¹⁴ Despite enduring searches by the obsessed, Atlantis is almost certainly a figment of classical imagination and never existed, perhaps a fond memory of the Santorini cataclysm or some other tsunami. The Greek historian Thucydides witnessed an earthquake at Orobiae in the Euboian Gulf off eastern Greece in 429 B.C.E. He recorded how the sea, "retiring from the then line of coast, returned in a huge wave and invaded a great part of the town and retreated leaving some of it still under water, so what was once land is now sea; such of the inhabitants perishing as could not run up to the higher ground in time."¹⁵

Really major tsunamis like the Lisbon event have global consequences. The earthquake and tsunami that hit Shimoda, south of Tokyo in Japan on December 1, 1854, brought small waves to San Diego and San Francisco. When the island of Krakatoa in Southeast Asia blew up in 1883, a tsunami with fifteen-meter waves destroyed 165 villages along the Java and Sumatra coasts.¹⁶ Thirty-five thousand people perished along the Sunda Strait coastline alone. As the Lisbon disaster, the Indian Ocean tsunami of 2008, and the Japanese earthquake and tsunami of 2011 remind us (see [chapter 10](#)), great tsunamis ravage low-lying shores and raze entire communities with devastating force. The

hazard is far greater today than it was in 1755, when Lisbon had 200,000 inhabitants, and the largest city in the world, Beijing, about a million. Today, tens of millions of us are crowded in cities and towns a few meters above sea level. Lisbon alone has 547,000 inhabitants—and rising.

EXTREME WEATHER EVENTS come in many forms—blanketing snowstorms, tornadoes, torrential rainfall, and long-enduring droughts, to mention only a few. However, the most dangerous are hurricanes and tropical cyclones, which generate not only powerful winds and sheets of rain, but also violent sea surges. The infamous Hurricane Katrina, which devastated New Orleans in 2005, alerted us forcibly to the dangers of exceptional storms along low coasts besieged by subsidence and rising sea levels. As we describe in [chapter 13](#), much of the damage and loss of life came not from the hurricane's force winds and rain, but from the sea surge and high tides that followed on the storm. Raging waters swept ashore and carried away entire parishes and massive artificial levees that protected low-lying parts of New Orleans.

Hurricanes like Katrina generate sea surges by the wind blowing directly toward shore and pushing water up onto the land. This is what devastated the Mississippi delta in 2005 and Galveston, Texas, in September 1900, when a hurricane-generated surge flooded the city streets to a depth of at least six meters, destroying thirty-five hundred buildings and killing over six thousand people. Since the Galveston disaster, improved early warning systems, seawalls, and stronger buildings have reduced casualties in better-developed parts of the world, but rising urban populations and the complex and expensive logistics of warning, evacuation, and recovery make it increasingly difficult to avoid truly catastrophic human and material destruction.

Tropical cyclones are a major hazard in many parts of the world, notably in the western Pacific and the Bay of Bengal. Low-lying Bangladesh is basically a huge river delta at the head of the bay, where tropical cyclones breed, cover large areas, and move northward into the funnel created by the coast on either side of the ocean.

We are already reaping a whirlwind of vicious assaults by an ocean that once lay 122 meters below today's threatened shorelines. Billions of people are at risk from an attacking sea. Our future will be challenging, even before one factor in the ever-present threat of earthquakes and tsunamis. As history shows us, our vulnerability to an encroaching and often aggressive ocean has increased exponentially especially since the rapid population growth of the Industrial Revolution. While as recently as eight thousand years ago, only a few tens of thousands of people lived at risk from rising waters—and they could adapt readily by upping stakes and moving—today millions of us live in imminent danger from the attacking ocean and from the savage weather events that await in a warmer future.

Millennia of Dramatic Change

There is one knows not what sweet mystery about this sea, whose gently awful stirrings seem to speak of some hidden soul beneath.

—Herman Melville, 1851

The nine millennia between fifteen thousand and six thousand years ago saw complex human adjustments to rising seas, but also witnessed major shifts in people's day-to-day lives. Ancient human societies living by seacoasts and lakes focused heavily on fishing, sea mammal hunting, and fowling. Many groups lived in such food-rich environments like northern Europe, Southeast Asia, and parts of the South African coastline, dwelling at the same locations for generations. In many parts of the world, large Ice Age animals became extinct. People turned to smaller game and to plant foods for much of their diet as the climate changed the world around them.

Nowhere were the environmental changes more profound than in northern Europe. For tens of thousands of years, gigantic ice sheets had covered much of the north. Fifteen thousand years ago, the English Channel was little more than a large estuary. During the rapid warming that occurred after the glacial maximum, the sparse hunter-gatherer societies of northern Europe had to contend with staggering environmental changes. High-tech science has revealed a sunken Ice Age landscape under the waters of the southern North Sea. Here, low-lying coastlines changed significantly from one generation to the next as the sea attacked the land.

No one knows how many people lived in northern Europe, so intelligent guesstimates are in order. Eight thousand years ago, after the thousand-year Younger Dryas cold snap, perhaps as few as two thousand to three thousand people called northern Europe their home, most of them in the Low Countries and in the now-submerged lowlands of the southern North Sea.¹ Population density increased reasonably rapidly as warming resumed, to conceivably as many as twenty thousand, if one adds central and northern Scandinavia to the equation. Even the largest communities, situated near bountiful fisheries and lush wetlands, would not have supported more than a few dozen people, probably significantly fewer. People were so thin on the ground at first that moving in the face of encroaching seawater or shifting camp to higher ground was a routine practiced with effortless familiarity in a little-known sunken North Sea world known to scientists as Doggerland.

From Doggerland, we travel to the Euxine Lake, now the Black Sea, to witness the dramatic ravages of an encroaching ocean, which may have had life-changing effects on European societies of the day. Here, farming villages and fertile agricultural land vanished under rapidly rising seawater, perhaps within a few weeks or months. From the threshold of the now-flooded Euxine, our journey takes us to the Nile delta, then to Mesopotamia, the Land Between the Rivers. Both areas witnessed major environmental changes that affected hunters and subsistence farmers, and then growing cities and nascent civilizations. As we will see in later chapters, the same low-lying environments are still a magnet of human settlement in the twenty-first century.

Doggerland

The North sea is Shallow, vicious, and unrelenting in its sudden weather shifts. Steep waves assault you on every side even in moderate winds. The fogs are dense and notorious; thick haze is a way of life. I once sailed from Den Helder in the northern Netherlands bound for the Dover Strait. We had sailed in port for four days waiting out persistent southwesterly gales. At last they moderated and the wind shifted to the northwest. Full sail and a departure on top of the tide: We had smooth seas and a pleasant, favorable breeze. The idyll lasted for fifty kilometers. Our barometer tumbled four tenths as many hours, but we were clear of off-lying dangers and kept going. By midafternoon, we were well reefed down and running at full speed before a forty-knot gale. Even with the storm blowing from the east, the seas were violent and cooking hot soup in the galley was an acrobatic exercise. Six hours later, having dodged a supertanker anchored off Rotterdam, we were becalmed once more. Yet the weather forecast spoke of southerly winds of thirty-five knots or so, moderate to rough seas, and squally showers. Fortunately the southerly winds veered to the northwest and we sailed on before long.

“REMEMBER THAT THIS was once dry land,” one of the crew remarked as we once slatted back and forth on the Dogger Bank and he gulped coffee laced with spray. “Hard to believe, isn’t it?” I was the only archaeologist aboard and I must confess that I’d forgotten that we were sailing over a seabed that had been dry, albeit marshy, land only eight thousand years ago.

In 1931, a British trawler, the *Colinda*, was working the Leman and Ower Banks in the southern North Sea. The trawler men cursed when their net brought up lumps of peat, known as “moorlog” from a depth of eighteen meters. Their nets routinely tore on waterlogged wood and mud lumps as they trawled for bottom fish on the once-marshy seabed. But this time a peat block emitted an unfamiliar sound when hit with a shovel. The skipper broke it open. Out fell a beautifully preserved antler harpoon. Intrigued, the skipper brought the find back to port. The unexpected artifact found its way to the British Museum, which identified it as a hunting weapon used commonly some eight thousand years ago. But the staff didn’t want it, because they already possessed three found on dry land. Eventually, the *Colinda*’s find ended up in the Norwich Castle Museum in East Anglia. On February 29, 1932, the members of the Prehistoric Society of East Anglia admired the harpoon, which was identical to such weapons found along the shores of the Baltic in Denmark on the other side of the North Sea. But how had it traveled so far from land? Had some hunter in a canoe dropped it while on a deep-sea fishing expedition or while crossing to the Continent? Or had people crossed from the continent to Britain at a time when a low-lying plain joined northwestern Europe to the higher ground of southern England?¹

The *Colinda*’s harpoon was by no means the first discovery to be dredged from the North Sea bed. Throughout the nineteenth century, oyster dredgers working the shallow waters off eastern England brought up the bones of extinct animals in their nets. As fishing technology improved and the trawlers moved into deeper water, finds from the Dogger Bank proliferated.² This famous shoal lies about one hundred kilometers off the English coast, rising about forty-five meters above the seabed and forming

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