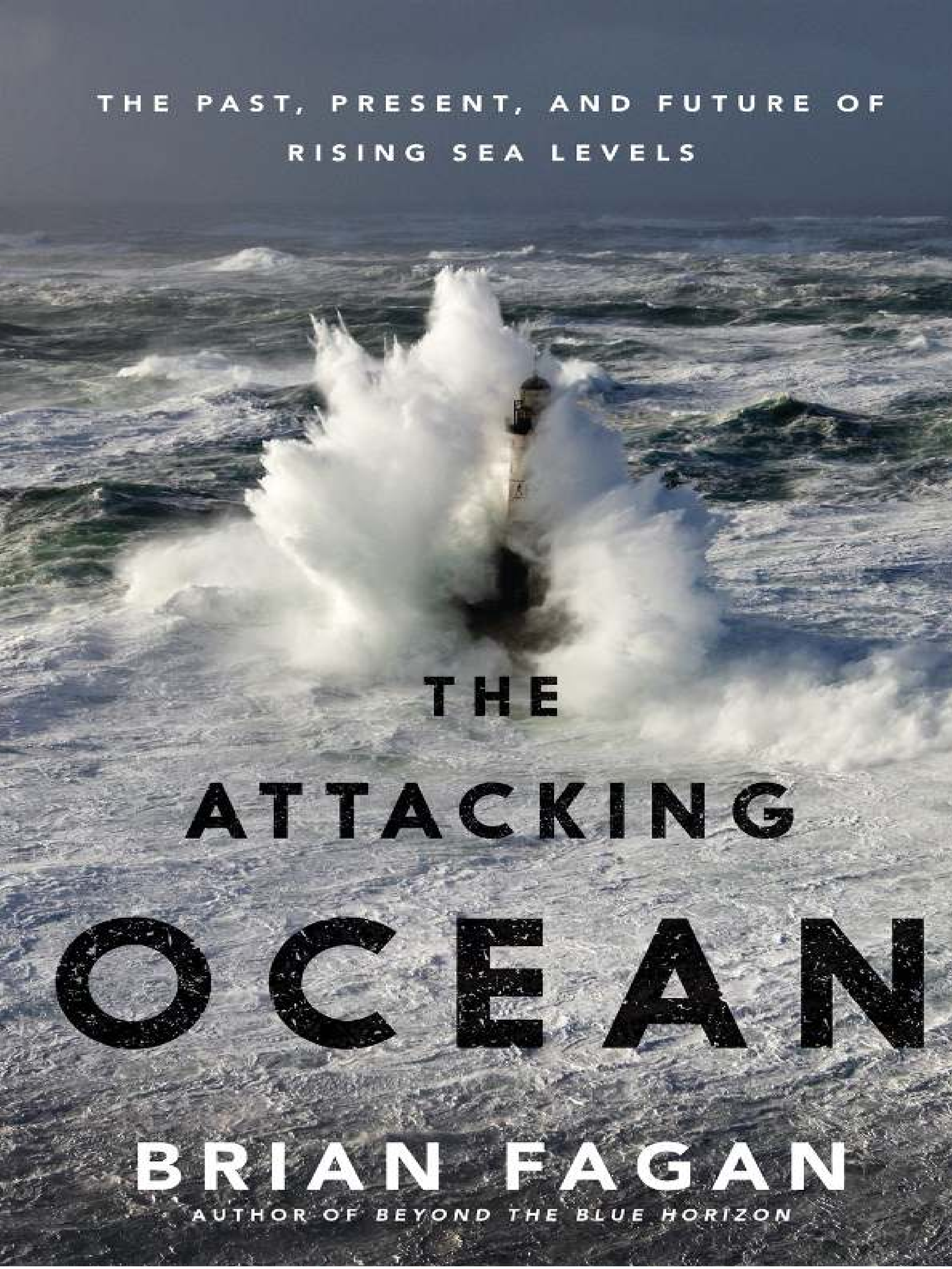
THE PAST, PRESENT, AND FUTURE OF
RISING SEA LEVELS
THE
ATTACKING
OCEAN
BRIAN FAGAN
AUTHOR OF BEYOND THE BLUE HORIZON

The Attacking Ocean

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RISING SEA LEVELS

Brian Fagan

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(For those who prefer to explore the narrative geographically)

Also by Brian Fagan

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

Preface

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

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

Think of walking on a sandy beach as the tide is rising. You start at low water as the flood begin As you walk, you play with the encroaching breakers in bare feet. But, as the hours pass, you fin yourself walking farther upslope, often on a much narrower beach. The rise is slow, inexorable, an sure. This is exactly what the gradual sea levels since the end of the Ice Age some fifteen thousan 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 unfoldin thousands of kilometers away.

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

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

Global sea levels stabilized about six thousand years ago except for local adjustments that cause often quite significant changes to low-lying places like the Nile delta. The curve of inexorably risir seas flattened out as urban civilizations developed in Egypt, Mesopotamia, and South Asi Imperceptible changes marked the centuries when Rome ruled the Western world and imperial Chir reached the height of its power. The Norse explored a North Atlantic identical to ours a thousand yea ago; Christopher Columbus and the mariners of the European Age of Discovery sailed over seas th had changed little from the time of the pharaohs. But another variable was now in play, that of th world's population, which climbed rapidly after 4000 B.C.E. By the time of Christ, at least tw hundred million people lived on earth. The number had reached a billion or so by the late eighteen century, when the Industrial Revolution was under way. The densest of these growing populatior lived in cities, many of them on river floodplains and low-lying coastal plains. With the rap expansion of maritime and river-based trade, more and more people settled in strategic coast locations that became important ports. Now the threat from the ocean increased dramatically, n because of rising sea levels, but from severe weather events like hurricanes and tropical cyclones wi their violent sea surges. Tsunamis generated by deep-sea earthquakes assumed much more menacir proportions once people had settled in crowded cities close to the shore. Human vulnerability to potentially climbing ocean has increased dramatically because there are now so many of us—toda 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 Revolutio Since then, the world has warmed significantly and the ocean is once again climbing inexorabl Without question, we humans have contributed to the accelerating warming of recent decades. The se level changes are cumulative and gradual; no one knows when they will end—and the ascent's end unlikely to come in any of our lifetimes. We live in a very different world from even that of 186 with tens of millions more people living in coastal cities or farming land only a few meters above se level. Even a rise of a meter or so will inundate thousands of hectares of rice paddies and maj international ports—this before one factors in the savage destruction wrought by sea surges tsunamis. Our sheer numbers and profound dependence on cargoes transported on the ocean hav raised our vulnerability to rising sea levels to a point at which we face agonizing and extreme expensive decisions about flood-control works, sea defenses, or relocation questions that humanity h never wrestled with before.

The Attacking Ocean tells a tale of the increasing complexity of the relationship between humar and the sea at their doorsteps, a complexity created not by the oceans, whose responses to temperatu ~~changes and severe storms have changed but little. What has changed is us, and the number of~~ us o earth.

LIKE MY OTHER BOOKS about ancient climate, *The Attacking Ocean* has many narratives an multiple story lines, for the tale covers fifteen millennia of human history, multiple continents, and great variety of societies—ancient and modern, simple and complex. There is a somewh chronological gradient in these pages, from earlier societies to later ones. Such an organization is logical way to explore the tangled history of sea level changes over the past fifteen thousand year since post–Ice Age warming began. Once the stage is set in chapter 1, which describes how sea leve rise and introduces the dangers of tsunamis and other extreme events, I've divided the story into thr parts. "Millennia of Dramatic Change" covers the rapid sea level changes between fifteen thousan years ago and 4000 B.C.E. and their impact on human societies. Chapters 2 to 4 take us from northe Europe to the Black Sea, the Nile valley, and Mesopotamia, through coastal landscapes change dramatically by fast-climbing sea levels. Chapter 2 brings out a persistent theme—that of th importance of marshes and wetlands to both hunters and subsistence farmers, for these borderlands a as dietary insurance when harvests fail or powerful storms attack low-lying coastlines. In chapter we explore the major environmental changes that resulted from climbing shorelines in the Dardanell Strait between Europe and Asia. We describe how rising sea levels caused the ponding of the Nil which led to the creation of the Nile delta, one of the breadbaskets for the Egyptian state. Chapter examines the complex relationship between the early Mesopotamians and a Persian Gulf that turne from a gorge-bisected desert into an arm of the Arabian Sea in a few thousand years, with momento 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 fir civilizations.

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

"Challenging Inundations" comprises the final five chapters, in which I describe some of th extraordinary challenges that confront us today. Again, the coverage is geographic, largely becau each area has its own distinctive issues. Chapter 11 describes the menacing difficulties that confro Bangladesh, where 168 million people live close to sea level with nowhere to go. Here, the long-ter problem of environmental refugees raises its head, a global problem that is currently on fe governments' agendas, although it should be. Chapter 12, "The Dilemma of Islands" raises not on the issue of environmental refugees, but also the difficulties of relocating entire villages and sma island nations. “The Crookedest River in the World” takes us back deep into the history of th ~~Mississippi and its peoples to a delta coast and modern cities threatened from both up-~~ ar downstream. This is a story of sea defenses erected in the face of extreme storms, unpredictable riv floods, and rising sea levels. The Low Countries face the same dilemma as Bangladesh, lands walle off in an ultimate expression of human determination to resist the attacking sea to the death. Th epilogue looks at the future and rising sea levels in the context of the United States, where millions people live in houses but a few meters above today’s sea level. Hurricane Sandy, which devastate much of New York and the New Jersey Shore in October 2012, provided a sobering reminder of ju how vulnerable we are to a future of more frequent extreme weather events and violent sea surges th can render tens of thousands homeless.

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

1

Minus One Hundred Twenty-Two Meters and Climbing

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

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

The scale of destruction was mind-boggling. Sandy brought torrential downpours, heavy snowfa and exceptionally high winds to an area of the eastern United States larger than Europe. Over o hundred people died in the affected states, forty of them in New York City. The storm cut o electricity for days for over 4.8 million customers in 15 states and the District of Columbia, 1,514,14 of them in New York alone. Most destructive of all, a powerful, record-breaking 4.26-meter sea surg swept into New York Harbor on the evening of October 29. The rising waters inundated street tunnels, and subways in Lower Manhattan, Staten Island, and elsewhere. Fires caused by electric explosions and downed power wires destroyed homes and businesses, over one hundred residences the Breezy Point area of Queens alone. Even the Ground Zero construction site was floode Fortunately, the authorities had advance warning. In advance of the storm, all public transit system were shut down, ferry services were suspended, and airports closed until it was safe to fly. All maj bridges and tunnels into the city were closed. The New York Stock Exchange shut down for two day 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 almo 150 years, people from hot, crowded cities have flocked to the Shore to lie on its beaches, famili often going to the same place for generations. They eat ice cream and pizza, play in arcades once use by their grandparents, drink in bars, and go to church. The Shore could be a seedy place, fraught wi racial tensions, and sometimes crime and violence, but there was always something for everybody, b they a wealthy resident of a mansion, a contestant in a Miss America pageant, a reality TV actor, skinny-dipper, or a musician. Bruce Springsteen grew up along the Shore and his second albu featured the song “4th of July, Asbury Park (Sandy),” an ode to a girl of that name and the Shor “Sandy, the aurora is rising behind us; the pier lights our carnival life forever,” he sang. The wor have taken on new meaning since the hurricane came.

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

As the waters of destruction receded, they left $50 billion of damage behind them, and a soberi reminder of the hazards millions of people face along the densely populated eastern coast of th United States. Like Hurricanes Katrina in 2005 and Irene in 2011, Sandy showed us in no uncerta terms that a higher incidence of extreme weather events with their attendant sea surges threaten lo lying communities along much of the East Coast—from Rhode Island and Delaware to the Chesapea and parts of Washington, DC, and far south along the Carolina coasts and into Florida, which escape the full brunt of Sandy’s fury. There, high winds and waves washed sand onto coastal roads and the was some coastal flooding, a warning of what would certainly occur should a major hurricane com 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 en of the Ice Age some fifteen thousand years ago. Slowly, inexorably, the ascent continues in a warmin world. Today the ocean laps at millions of people’s doorsteps—crouched, ready to wreak catastroph destruction with storm-generated sea surges and floods. We face a future that we are not prepared t handle, and it’s questionable just how much most of us think about it. This makes the lessons o Katrina, Irene, and Sandy, and other recent storms important to heed. Part of our understanding of th threat must come from an appreciation of the complex relationship between humanity and the risin ocean, which is why this book begins on a low land bridge between Siberia and Alaska fiftee thousand years ago …

BETWEEN SIBERIA AND Alaska, late summer, fifteen thousand years ago. A pitiless north win fills ~~the air with fine dust that masks the pale-blue sky. Patches of snow lie in the shallow river~~ valley that dissect the featureless landscape. A tiny group of humans trudge down the valley close to water edge, the wind at their backs, the men's eyes constantly on the move, searching for predators. The can hear the roar of the ocean in the shallow bay, where wind squalls whip waves into a white frenz A few days earlier, the women had trapped some arctic ptarmigan with willow snares, but the fe remaining birds hanging at their belts are barely enough for another meal. A dark shadow loom 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 youn beast is weakening rapidly after days in the muddy swamp. Nothing is to be gained by going in for th kill at the moment, so the band pitches camp a short distance away and lights a large fire to keep awa predators. A gray, bitterly cold dawn reveals the helpless mammoth barely clinging to life, mired u to its stomach. A young man leaps onto the beast's hairy back and drives his stone-tipped spea between its shoulder blades, deep into the heart. He jumps off to one side, landing in the mud. Th hunters watch the mammoth's death throes and thrust more spears into their helpless prey. Soo everyone moves in to skin the flanks and dismember the exposed parts. A short distance away, wolve 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 the ceaseless wind, while the women and children cook meat over the fire. Around them, the dus filled gloom never lifts, the wind blows, and the roar of the ocean never leaves their consciousnes 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 prolonged deep freeze. The bitter cold of a long glacial cycle had peaked about seven thousand yea earlier, the most recent of a more than 750,000-year seesaw of lengthy cold and shorter inter-glaci 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 moder shorelines. The seas were beginning to rise fast, as a rapid thaw began and glacial meltwater flowe into northern oceans. Soon one would need a skin boat to cross from Siberia to Alaska and th 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 wi breathtaking rapidity by geological standards, between about fifteen thousand years ago and 600 B.C.E. Most of the ascent resulted from powerful meltwater pulses that emptied enormous quantiti of freshwater from ice sheets on land into northern waters and around Antarctica. This was not, o course, the first time that such a dramatic rise had transformed an ice-bound world, but there was a important difference fifteen millennia ago. For the first time, significant numbers of human being 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 heigh small numbers of Southeast Asians had already ventured into open tropical waters to what are no Australia and New Guinea. Well before twenty thousand years ago, people were living on the island of the Bismarck Strait in the southwestern Pacific.[2] These voyages took place long before melting ic 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 lon ~~term climate change and have done so since the Industrial Revolution, when fossil fuels like~~ co came into widespread use. It's hard for us to imagine just how different the world was twenty-or thousand years ago. Much of it lay under thick ice. Two huge ice sheets covered virtually all of Nor America, from the Atlantic to the Pacific. The Cordilleran ice sheet, centered on the Rockies ar western coastal ranges, mantled 2.5 million square kilometers. The enormous Laurentide ice she lapped the Cordilleran in the west and covered over 13 million square kilometers of what is no Canada. It was nearly 3,353 meters thick over Hudson Bay. Its southern extremities covered the Gre Lakes and penetrated deep into today's United States. The Greenland ice sheet was 30 percent larg 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 ov an area of 6.6 million square kilometers, may even have reached Spitsbergen, and flowed over muc of the north German Plain. A smaller ice sheet covered about 340,000 square kilometers and reache halfway down the British Isles. Glaciers descended close to sea level in the Southern Alps. In Siber and Northeast Asia, ice extended over at least ten times the area of the British ice sheet. Extensive ic sheets mantled the Himalayas.

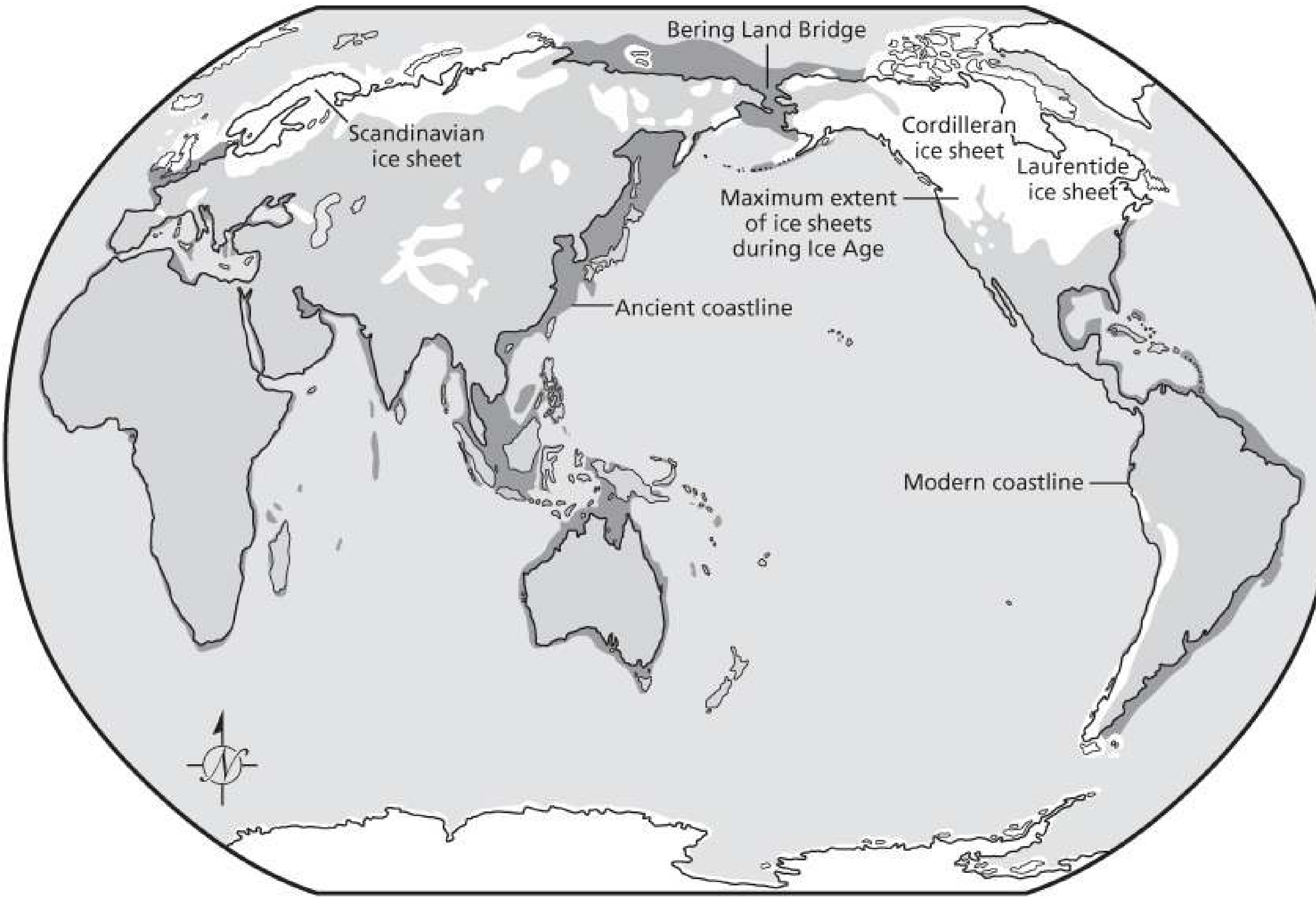

Figure 1.1 *Map showing approximate extent of ice sheets and lower sea levels during the late Ice Age.*

The Antarctic ice sheet was about 10 percent larger; seasonal sea ice extended eight hundre kilometers out from the continent. There were important ice sheets on the Andes Mountains, in Sou 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 percen on ~~Antarctica, and 5 percent on Greenland. Today, 86 percent of the world's continental ice~~ is o Antarctica, 11.5 percent on Greenland.

There was so much water locked up in glacial ice sheets and sucked out of the oceans that glob sea levels were up to 122 meters below those of today. These much lower sea levels changed the shap of entire continents. Perhaps most significant historically was the bitterly cold and low-lying Berin Land Bridge that linked Siberia and Alaska, a natural highway that brought the first humans to th Americas. Dry land joined islands in Southeast Alaska and the Pacific Northwest of North Americ Much farther south, San Francisco's Golden Gate channel was a narrow tidal gorge with fast-movin rapids. Continental shelves extended some distance off the Southern California coast, leaving b 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 th north and brought them much closer to the Chinese and Korean mainland. In China, major rivers lik the Huang He in the north and the Yangtze in the south flowed through incised, narrow valleys rathe than broad floodplains. Rolling plains stretched far into the distance off Southeast Asia. Only sho stretches of open water separated the mainland from Australia and New Guinea, which were a sing landmass, now covered by the shallow Arafura Sea.

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

Had one looked down from a satellite at Europe and the Mediterranean eighteen thousand yea ago, one would have surveyed unfamiliar landscapes. Continental shelves extended far into the Bay Biscay. You could walk from Britain to France, had you possessed a canoe to carry you across a enormous estuary that carried the waters of the Rhine, Seine, and Thames Rivers of today. Th southern North Sea was a land of shallow lakes and marshes. The Mediterranean was far smaller, i narrow entrance at the Strait of Gibraltar scoured by fast-running currents. The northern Aegean Se ended in a high barrier that isolated what is now the Black Sea from the ocean. The Euxine Lak formed by glacial and freshwater runoff from the north, lay behind the natural berm. On the other sid 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 f different from those of today. The Nile flowed through a twisting, narrow gorge, where the annu flood for the most part remained close to the river channel rather than spilling over a wide floodpla as it did until the building of the Aswan Dam. In the Americas, the St. Lawrence River did not exist; was under the Laurentide ice sheet. The Mississippi and Amazon Rivers cut far below their moder 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 a entirely different place in less than ten thousand years. Within this brief time frame, the world's se 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 cau the world's sea levels to rise and fall? Isostatic changes result from local upward and downward shif 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. Subsidenc in ~~river deltas, changes in glaciers, even sediment compaction—anything that adds to or subtrac~~ from the weight of the earth's crust—all can cause isostatic sea level rises, such as are common places like Shanghai.[3]

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

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

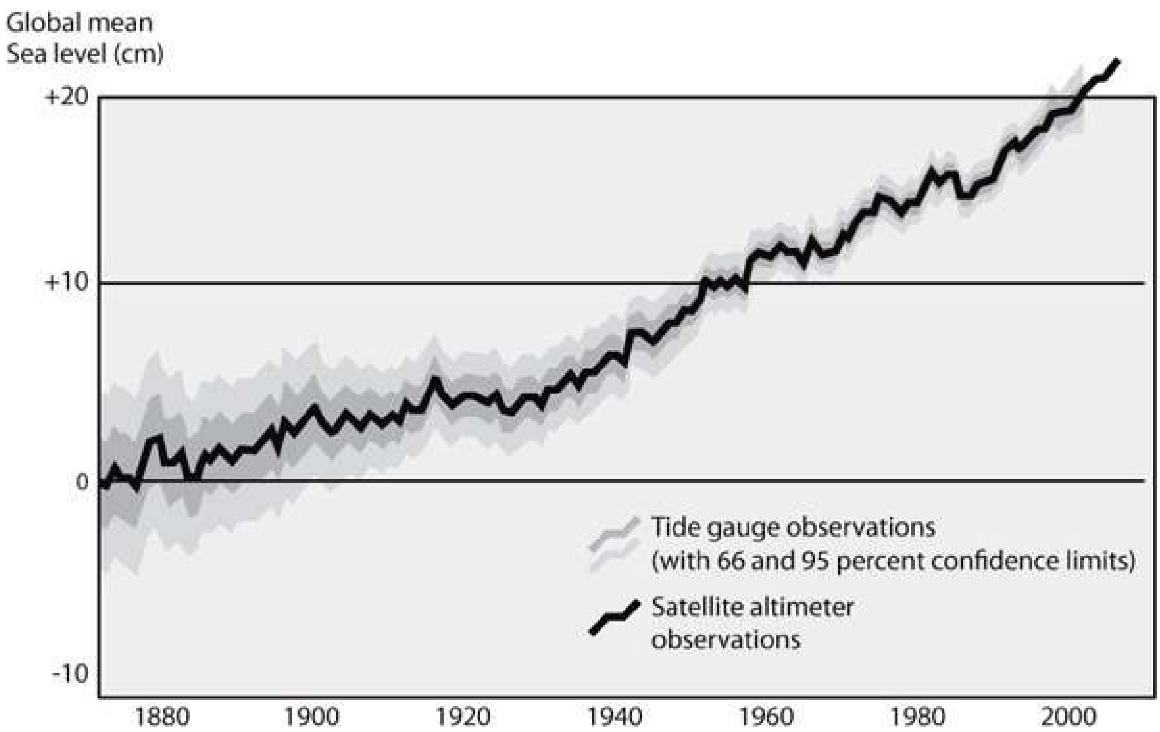

Figure 1.2 *A global average of tide gauge data from 1870 to 2000. The new satellite altimeter data is superimposed from 1990. Da from both sources is very similar, chronicling a more rapid sea level rise since 1990. Courtesy: NASA.*

Glaciers retreat most rapidly when they end in water. The Mendenhall Glacier near Juneau ha retreated five kilometers since 1760 and a kilometer since 2000. Muir Glacier in Glacier Bay h receded ten kilometers since 1941, the Columbia Glacier in Prince William Sound by thirteen sinc 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 completel ~~global sea levels would rise by seven meters. Recent estimates using a variety of high-technolog~~ measurements and satellite data place the annual loss of Greenland ice at about 96 cubic kilometers 1996, and almost three times that, at 290 cubic kilometers a year, in 2006. Most of this acceleration occurring in the southernmost glaciers, but the melting is gradually moving northward. Were th entire Greenland ice sheet to melt, which has happened in the remote past, what is now a froze continent would become an archipelago of islands surrounding a central sea—until crust 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 covere with ice. Until about 2000, the amount of Antarctic ice was slowly increasing. But recent satelli measurements show that the ice sheets are now losing mass. The East Antarctic ice sheet lies abov sea level and is relatively stable. If it were to melt, the resulting sea level rise would be in the order fifty meters. Much of the West Antarctic ice sheet is aground on the seabed, where changing ocea temperatures affect the stability of its foundations. When these decay, the upper parts of the ice she can detach and move seaward. Such melting occurred at the end of the last Ice Age and may we occur again in the near future. Should the entire West Antarctic ice sheet melt, world sea levels woul rise by about five meters. If the sheet were to vanish within twelve hundred years, the ocean wou climb about thirty to fifty centimeters per century. A five-hundred-year meltdown would cause se 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 establish whether changes in ice sheets are mere decadal events, part of normal fluctuations, something that portends much more dramatic changes in the future. Many experts believe that a tw meter rise by 2100 should be the basis for future planning. Geoscientists Orrin Pilkey and Rob Youn believe that “coastal management and planning should be carried out assuming that the ice she disintegration will continue and accelerate. This is a cautious and conservative approach.”[5] Pilkey an Young are sober voices in what often becomes a morass of alarmism and sensationalist headline 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 factor are involved that it’s hard to provide anything more than a general portrait of global sea level chang over the past fifteen thousand years—and even then the experts disagree. Here’s a generalize 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. Enormou volumes of meltwater cascaded into northern waters, much of it in dramatic accelerations in sea lev rise (often called “pulses”) recorded in Caribbean corals and other sources. There were at least fo major pulses, the first about 19,000 years ago, when the sea rose between ten and fifteen meters with a mere five centuries. Another major meltwater release, most likely from North American ice sheet came between 14,600 and 13,600 years ago. This time the sea level rose between sixteen and twent four meters. These major sea level rises came before the onset of a 1,300-year cold snap, the so-calle Younger Dryas of 10,800 to 9500 B.C.E. (named by geologists after a polar flower), when sea lev rise slowed, only to resume sharply with another meltwater pulse between 9500 and 9000 B.C.E. 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 crust adjustments as a result of melting ice sheets. Many islands and coastal areas far from glaciated are experienced sea levels several meters higher than they are today. The earth’s crust responded locall to changes in ice coverage and water loading by siphoning water away from equatorial ocean basi into ~~depressed areas close to vanished ice sheets. At the same time, the weight of increased amoun~~ 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-nineteen century C.E.

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

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

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

The survivors fled to open ground, away from tottering buildings and raging fires. Many headed f the open banks of the Tagus River, where they stood in shock, convinced that the Day of Judgment ha ~~come. They loudly begged for divine mercy. Priests moved through the crowds urging them to~~ repe for their sins in the face of God’s wrath. How else could such a catastrophe have descended on the 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 Popul Description, *published in 1887. Author’s collection.*

Ninety minutes after the earthquake, the crowds at water’s edge saw the Tagus rock and roll. Shi at anchor offshore gyrated wildly. Then “there appeared at some distance a large body of water, risi as it were like a mountain; it came foaming and roaring, and rushed towards the shore with su impetuosity, that we all immediately ran for our lives.”[9] The roaring came from a huge tsunami wav said to have been at least twelve meters high, which swept up the river and surged ashore as spectato fled. The three thousand or so people standing on a new stone wharf in hopes of finding a bo drowned when the quay tipped over. The wall of water rushed as far as 2.4 kilometers inlan inundating buildings, overthrowing bridges, and dashing thousands of helpless onlookers again buildings and walls. Then the wave receded precipitously, carrying hundreds more victims to the deaths and uncovering areas of the riverbed that were normally twelve meters underwater. Oceangoi ships lay helplessly aground. The surviving onlookers moved to the bank, gasping at the sight of fi flapping helplessly. Ten minutes later a second even more violent fifteen-meter wave advanced up t estuary and also cascaded ashore, promptly followed by a third, both traveling “like a torrent, th against the wind and tide.”[10] The waves moved so fast that galloping horses could barely escape then

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

Tsunamis are unpredictable events generated by invisible earth movements, such as earthquak caused by the collision of tectonic plates far below the sea surface. The word “tsunami” itself is Japanese term meaning “harbor wave,” which dates back at least four centuries and is said to ha been coined by fishermen when they returned to devastated harbors after not even having notic tsunami waves in deep water. Great tsunamis result from extensive displacements of the seaflo perhaps over hundreds of kilometers, over distances longer than the depth of the water. The wav ~~generated by these enormous earthquakes are extremely long and travel great distances at speeds~~ up 640 kilometers an hour.[11] They are far more damaging than smaller scale tsunamis caused by mo local events such as a underwater landslide. In such cases, big waves may result, but they soo dissipate. Large tsunami waves are immensely powerful and quite different from the convention breakers beloved by surfers. They are solid walls of water that sweep everything before them and ru 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 larg tsunamis have struck the coasts of Spain, Portugal, and Morocco over the past twelve thousand year at intervals of about fifteen hundred years. In 6100 B.C.E., the Storegga underwater landsli displaced vast amounts of seawater off western Norway and caused a tsunami as far away as t Orkney Islands off northern Scotland.[12] Then there is what one might call the mother of all historic natural disasters, the great eruption and resulting tsunami that blew much of Santorini Island in t Aegean into space in about 1627 B.C.E. An entire town, now known as Akrotiri, vanished under cloud of ash and pumice.[13] The inhabitants must have had some warning, for no skeletons lie amo its ash-smothered dwellings, which stand up to three stories high. Wine jars, storage pots, the remai of a bed, and bright friezes are all that remains of a once-vibrant community. On the walls, fisherman returns home with his catch; two boys exchange fisticuffs. Fast ships with serried oarsm 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 inhabitan grabbing their possessions, driving bleating goats into boats, and rowing hastily away as lumps pumice drop into the seething water. Then a sudden explosion and oblivion, and a once-prosperou town was forgotten until Greek archaeologist Spyridon Marinatos unearthed some of its houses a alleyways in 1967. The scale of the explosion boggles the mind. What had once been one isla measuring about nine by six kilometers became four small ones. Ash from the eruption fell over large area, some of it on Crete, 177 kilometers to the south, at the time the center of Mino civilization with its far-flung trade networks, extensive olive groves, and wealthy palaces. A tsuna after the eruption lashed the Cretan shoreline with huge waves, which must have caused considera damage and disrupted mercantile activity over a vast area. Many experts believe the surging oce permanently weakened Minoan civilization.

When visiting the deep Santorini crater, one's mind turns to Plato's account of the lost continent Atlantis immortalized by the Greek philosopher with his tale of kings "of great and marvelous powe overthrown by "portentous earthquakes and floods."[14] Despite enduring searches by the obsesse Atlantis is almost certainly a figment of classical imagination and never existed, perhaps a fo memory of the Santorini cataclysm or some other tsunami. The Greek historian Thucydides witness an earthquake at Orobiae in the Euboian Gulf off eastern Greece in 429 B.C.E. He recorded how t sea, "retiring from the then line of coast, returned in a huge wave and invaded a great part of the tow and retreated leaving some of it still under water, so what was once land is now sea; such of t 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 a tsunami that hit Shimoda, south of Tokyo in Japan on December 1, 1854, brought small waves to Sa Diego and San Francisco. When the island of Krakatoa in Southeast Asia blew up in 1883, a tsuna with fifteen-meter waves destroyed 165 villages along the Java and Sumatra coasts.[16] Thirty-fi thousand people perished along the Sunda Strait coastline alone. As the Lisbon disaster, the Indi 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. Th hazard is far greater today than it was in 1755, when Lisbon had 200,000 inhabitants, and the large city ~~in the world, Beijing, about a million. Today, tens of millions of us are crowded in cities~~ ar 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, torrenti rainfall, and long-enduring droughts, to mention only a few. However, the most dangerous ar hurricanes and tropical cyclones, which generate not only powerful winds and sheets of rain, but als violent sea surges. The infamous Hurricane Katrina, which devastated New Orleans in 2005, alerted u forcibly to the dangers of exceptional storms along low coasts besieged by subsidence and rising se levels. As we describe in chapter 13, much of the damage and loss of life came not from the hurrican force winds and rain, but from the sea surge and high tides that followed on the storm. Raging wate swept ashore and carried away entire parishes and massive artificial levees that protected low-lyin parts of New Orleans.

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

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

We are already reaping a whirlwind of vicious assaults by an ocean that once lay 122 meters belo today's threatened shorelines. Billions of people are at risk from an attacking sea. Our future will b challenging, even before one factors in the ever-present threat of earthquakes and tsunamis. As histor shows us, our vulnerability to an encroaching and often aggressive ocean has increased exponentiall especially since the rapid population growth of the Industrial Revolution. While as recently as eig thousand years ago, only a few tens of thousands of people lived at risk from rising waters—and the could adapt readily by upping stakes and moving—today millions of us live in imminent danger fro 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 huma adjustments to rising seas, but also witnessed major shifts in people's day-to-day lives. Ancie human societies living by seacoasts and lakes focused heavily on fishing, sea mammal hunting, ar fowling. Many groups lived in such food-rich environments like northern Europe, Southeast Asia, ar parts of the South African coastline, dwelling at the same locations for generations. In many parts the world, large Ice Age animals became extinct. People turned to smaller game and to plant foods f 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 thousands of years, gigantic ice sheets had covered much of the north. Fifteen thousand years ago, t English Channel was little more than a large estuary. During the rapid warming that occurred after t glacial maximum, the sparse hunter-gatherer societies of northern Europe had to contend wi staggering environmental changes. High-tech science has revealed a sunken Ice Age landscape und the waters of the southern North Sea. Here, low-lying coastlines changed significantly from o 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 orde Eight thousand years ago, after the thousand-year Younger Dryas cold snap, perhaps as few as tw thousand to three thousand people called northern Europe their home, most of them in the Lo Countries and in the now-submerged lowlands of the southern North Sea.[1] Population densiti increased reasonably rapidly as warming resumed, to conceivably as many as twenty thousand, if o adds central and northern Scandinavia to the equation. Even the largest communities, situated ne bountiful fisheries and lush wetlands, would not have supported more than a few dozen peopl probably significantly fewer. People were so thin on the ground at first that moving in the face encroaching seawater or shifting camp to higher ground was a routine practiced with effortle 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 dramat ravages of an encroaching ocean, which may have had life-changing effects on European societies the day. Here, farming villages and fertile agricultural land vanished under rapidly rising seawate perhaps within a few weeks or months. From the threshold of the now-flooded Euxine, our journe takes us to the Nile delta, then to Mesopotamia, the Land Between the Rivers. Both areas witnesse major environmental changes that affected hunters and subsistence farmers, and then growing citi and nascent civilizations. As we will see in later chapters, the same low-lying environments are still magnet of human settlement in the twenty-first century.

2

Doggerland

The North sea is Shallow, vicious, and unrelenting in its sudden weather shifts. Steep waves assau you on every side even in moderate winds. The fogs are dense and notorious; thick haze is a way life. I once sailed from Den Helder in the northern Netherlands bound for the Dover Strait. We had s in port for four days waiting out persistent southwesterly gales. At last they moderated and the wi shifted to the northwest. Full sail and a departure on top of the tide: We had smooth seas and 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 w reefed down and running at full speed before a forty-knot gale. Even with the storm blowing fro astern, the seas were violent and cooking hot soup in the galley was an acrobatic exercise. Six hou later, having dodged a supertanker anchored off Rotterdam, we were becalmed once more. Yet th weather forecast spoke of southerly winds of thirty-five knots or so, moderate to rough seas, a squally showers. Fortunately the southerly winds veered to the northwest and we sailed on before lon

“REMEMBER THAT THIS was once dry land,” one of the crew remarked as we once slatted back a forth on the Dogger Bank and he gulped coffee laced with spray. “Hard to believe, isn’t it?” I was th only archaeologist aboard and I must confess that I’d forgotten that we were sailing over a seabed th 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 southe 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 they trawled for bottom fish on the once-marshy seabed. But this time a peat block emitted unfamiliar sound when hit with a shovel. The skipper broke it open. Out fell a beautifully preserv antler harpoon. Intrigued, the skipper brought the find back to port. The unexpected artifact found way to the British Museum, which identified it as a hunting weapon used commonly some eig thousand years ago. But the staff didn’t want it, because they already possessed three found on d land. Eventually, the *Colinda*’s find ended up in the Norwich Castle Museum in East Anglia. O February 29, 1932, the members of the Prehistoric Society of East Anglia admired the harpoon, whic was identical to such weapons found along the shores of the Baltic in Denmark on the other side of t North Sea. But how had it traveled so far from land? Had some hunter in a canoe dropped it while on deep-sea fishing expedition or while crossing to the Continent? Or had people crossed from th continent to Britain at a time when a low-lying plain joined northwestern Europe to the higher grou of southern England?[1]

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