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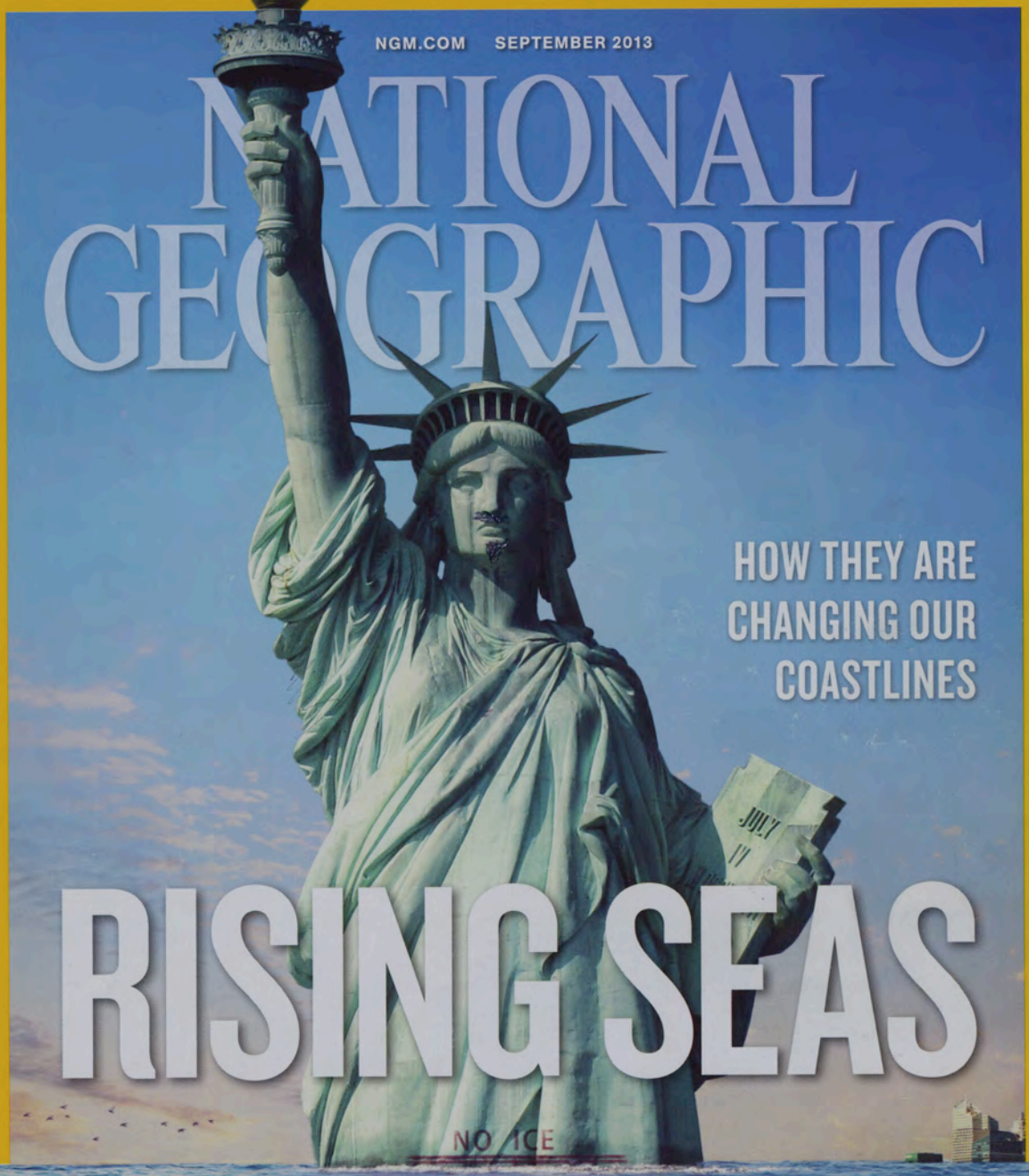
NGM.COM SEPTEMBER 2013

NATIONAL GEOGRAPHIC



HOW THEY ARE CHANGING OUR COASTLINES

RISING SEAS

Superstorm Sandy narrowed New Jersey's beaches by more than 30 feet on average. At Seaside Heights it swept away the pier under the roller coaster.

136

Large coastal cities now at risk from sea-level rise

40 MILLION

People at risk in those cities

$3 TRILLION

Value of assets at risk

As the planet warms,
the sea rises. Coastlines flood.
What will we protect?
What will we abandon?
How will we face the danger of

RISING SEAS

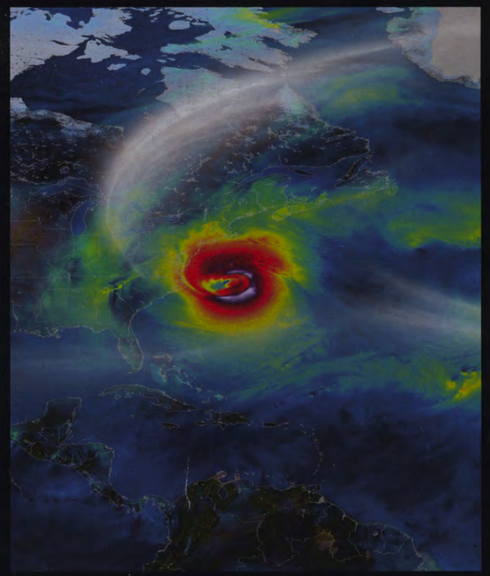
In Manhattan, Sandy's surging tide knocked out a Con Ed substation, darkening the city below Midtown. Private generators provided some light, including the blue glow of the new World Trade Center, whose base is three feet above sea level.

14 FEET
Height of Sandy's surge at Battery Park

43
Deaths in New York City

$19 BILLION
Damages in the city

IWAN BAAN, REPORTAGE BY GETTY IMAGES



THE DAMAGE DONE

By the time Sandy struck the Northeast, as a NASA computer model (above) had predicted four days earlier, it had killed 72 people in the Caribbean. It was no longer a hurricane—but it was a thousand miles wide, with 80-mile-an-hour winds that drove the sea onto the coast in lethal surges. The final death toll was 147. As the world warms, it may see more storms like Sandy. It will certainly see higher seas.

BROOKLYN, NEW YORK

PATH STATION, HOBOKEN, NEW JERSEY

HE, NORTH CAROLINA

STATEN ISLAND, NEW YORK

BREEZY POINT, QUEENS, NEW YORK

UNION BEACH, NEW JERSEY

RAWAY PARK, QUEENS, NEW YORK

HOBOKEN, NEW JERSEY

MANTOLOKING, NEW JERSEY

SABANA PERDIDA, DOMINICAN REPUBLIC

LONG BEACH, NEW YORK

STATEN ISLAND, NEW YORK

STATEN ISLAND, NEW YORK

LEFT: WILLIAM PUTNAM, NASA GODDARD SPACE FLIGHT CENTER. ABOVE (FROM TOP, LEFT TO RIGHT): KIRSTEN LUCE, NEW YORK TIMES/REDUX; PORT AUTHORITY OF NEW YORK & NEW JERSEY, AFP PHOTO; JB NICHOLAS, SPLASH NEWS/CORBIS; KEN CEDENO, CORBIS; CHARLES SYKES, AP IMAGES; GEORGE STEINMETZ; RICARDO ROJAS, REUTERS; ANDREW BURTON, GETTY IMAGES

ABOVE (FROM TOP, LEFT TO RIGHT): STEVE EARLEY, *VIRGINIAN-PILOT*; MICHAEL KIRBY SMITH, NEW YORK TIMES/REDUX; KEN CEDENO, CORBIS; CHANG W. LEE, NEW YORK TIMES/REDUX; JOHN MINCHILLO, AP IMAGES

BY TIM FOLGER
PHOTOGRAPHS BY GEORGE STEINMETZ

An orange line sprayed on this condemned house—and on Robb Braidwood of the Chesapeake, Virginia, Office of Emergency Management—marks the typical flood height in the neighborhood. "It doesn't take a major storm," says Braidwood. "Heavy rain and the right wind during a high tide will do it."

MARK THIESSEN, NGM STAFF

BY THE TIME HURRICANE SANDY VEERED TOWARD THE NORTHEAST

coast of the United States last October 29, it had mauled several countries in the Caribbean and left dozens dead. Faced with the largest storm ever spawned over the Atlantic, New York and other cities ordered mandatory evacuations of low-lying areas. Not everyone complied. Those who chose to ride out Sandy got a preview of the future, in which a warmer world will lead to inexorably rising seas.

Brandon d'Leo, a 43-year-old sculptor and surfer, lives on the Rockaway Peninsula, a narrow, densely populated, 11-mile-long sandy strip that juts from the western end of Long Island. Like many of his neighbors, d'Leo had remained at home through Hurricane Irene the year before. "When they told us the tidal surge from this storm would be worse, I wasn't afraid," he says. That would soon change.

D'Leo rents a second-floor apartment in a three-story house across the street from the beach on the peninsula's southern shore. At about 3:30 in the afternoon he went outside. Waves were crashing against the five-and-a-half-mile-long boardwalk. "Water had already begun to breach the boardwalk," he says. "I thought, Wow, we still have four and a half hours until high tide. In ten minutes the water probably came ten feet closer to the street."

Back in his apartment, d'Leo and a neighbor, Davina Grincevicius, watched the sea as wind-driven rain pelted the sliding glass door of his living room. His landlord, fearing the house might flood, had shut off the electricity. As darkness fell, Grincevicius saw something alarming. "I think the boardwalk just moved," she said. Within minutes another surge of water lifted the boardwalk again. It began to snap apart.

Three large sections of the boardwalk smashed against two pine trees in front of d'Leo's apartment.

The street had become a four-foot-deep river, as wave after wave poured water onto the peninsula. Cars began to float in the churning water, their wailing alarms adding to the cacophony of wind, rushing water, and cracking wood. A bobbing red Mini Cooper, its headlights flashing, became wedged against one of the pine trees in the front yard. To the west the sky lit up with what looked like fireworks—electrical transformers were exploding in Breezy Point, a neighborhood near the tip of the peninsula. More than one hundred homes there burned to the ground that night.

The trees in the front yard saved d'Leo's house, and maybe the lives of everyone inside—d'Leo, Grincevicius, and two elderly women who lived in an apartment downstairs. "There was no option to get out," d'Leo says. "I have six surfboards in my apartment, and I was thinking, if anything comes through the wall, I'll try to get everyone on those boards and try to get up the block. But if we'd had to get in that water, it wouldn't have been good."

After a fitful night's sleep d'Leo went outside shortly before sunrise. The water had receded, but thigh-deep pools still filled parts of some streets. "Everything was covered with sand," he says. "It looked like another planet."

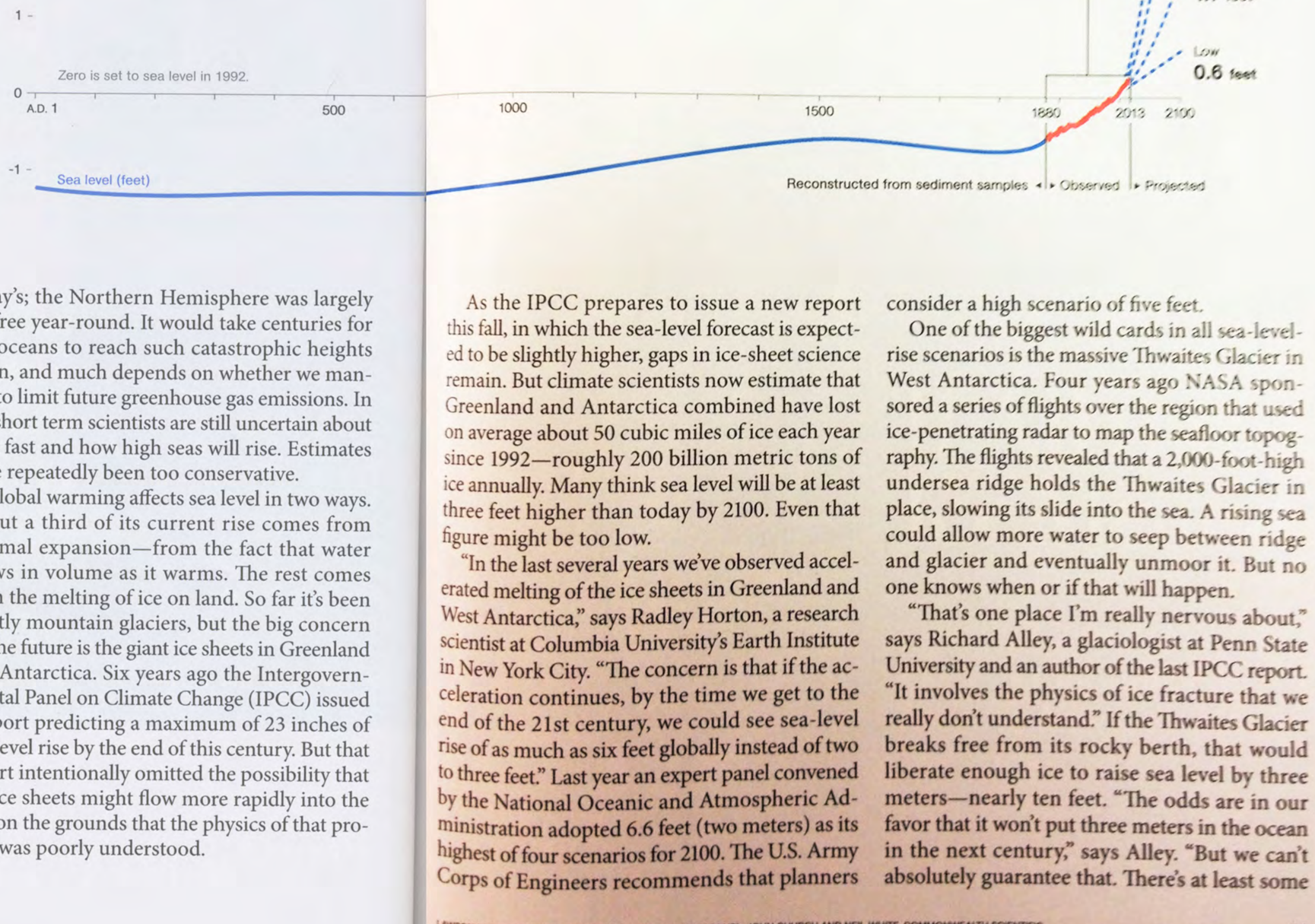
A PROFOUNDLY ALTERED PLANET is what our fossil-fuel-driven civilization is creating, a planet where Sandy-scale flooding will become more common and more destructive for the world's coastal cities. By releasing carbon dioxide and other heat-trapping gases into the atmosphere, we have warmed the Earth by more than a full degree Fahrenheit over the past century and raised sea level by about eight inches. Even if we stopped burning all fossil fuels tomorrow, the existing greenhouse gases would continue to warm the Earth for centuries. We have irreversibly committed future generations to a hotter world and rising seas.

In May the concentration of carbon dioxide in the atmosphere reached 400 parts per million, the highest since three million years ago. Sea levels then may have been as much as 65 feet above today's; the Northern Hemisphere was largely ice free year-round. It would take centuries for the oceans to reach such catastrophic heights again, and much depends on whether we manage to limit future greenhouse gas emissions. In the short term scientists are still uncertain about how fast and how high seas will rise. Estimates have repeatedly been too conservative.

Global warming affects sea level in two ways. About a third of its current rise comes from thermal expansion—from the fact that water grows in volume as it warms. The rest comes from the melting of ice on land. So far it's been mostly mountain glaciers, but the big concern for the future is the giant ice sheets in Greenland and Antarctica. Six years ago the Intergovernmental Panel on Climate Change (IPCC) issued a report predicting a maximum of 23 inches of sea-level rise by the end of this century. But that report intentionally omitted the possibility that the ice sheets might flow more rapidly into the sea, on the grounds that the physics of that process was poorly understood.

Rising Seas

Sea level didn't change much for nearly 2,000 years, judging from sediment cores. It began to rise in the late 19th century, as Earth started to warm. If sea level continues to track temperature, it could rise three feet or more by 2100. The great unknown: the future of the ice sheets. NOAA's four scenarios, shown here, span the range of possibilities for 2100. The sea will keep rising after that.



As the IPCC prepares to issue a new report this fall, in which the sea-level forecast is expected to be slightly higher, gaps in ice-sheet science remain. But climate scientists now estimate that Greenland and Antarctica combined have lost on average about 50 cubic miles of ice each year since 1992—roughly 200 billion metric tons of ice annually. Many think sea level will be at least three feet higher than today by 2100. Even that figure might be too low.

"In the last several years we've observed accelerated melting of the ice sheets in Greenland and West Antarctica," says Radley Horton, a research scientist at Columbia University's Earth Institute in New York City. "The concern is that if the acceleration continues, by the time we get to the end of the 21st century, we could see sea-level rise of as much as six feet globally instead of two to three feet." Last year an expert panel convened by the National Oceanic and Atmospheric Administration adopted 6.6 feet (two meters) as its highest of four scenarios for 2100. The U.S. Army Corps of Engineers recommends that planners consider a high scenario of five feet.

One of the biggest wild cards in all sea-level-rise scenarios is the massive Thwaites Glacier in West Antarctica. Four years ago NASA sponsored a series of flights over the region that used ice-penetrating radar to map the seafloor topography. The flights revealed that a 2,000-foot-high undersea ridge holds the Thwaites Glacier in place, slowing its slide into the sea. A rising sea could allow more water to seep between ridge and glacier and eventually unmoor it. But no one knows when or if that will happen.

"That's one place I'm really nervous about," says Richard Alley, a glaciologist at Penn State University and an author of the last IPCC report. "It involves the physics of ice fracture that we really don't understand." If the Thwaites Glacier breaks free from its rocky berth, that would liberate enough ice to raise sea level by three meters—nearly ten feet. "The odds are in our favor that it won't put three meters in the ocean in the next century," says Alley. "But we can't absolutely guarantee that. There's at least some

LAWSON PARKER, NGM STAFF. SOURCES: JOSH WILLIS, NASA/JPL; JOHN CHURCH AND NEIL WHITE, COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION; ANDREW KEMP ET AL., 2011; R. STEVEN NEREM ET AL., 2010; NOAA

Contributors to Rising Sea Levels

Locally, sea level can rise because the land is sinking. Globally, it rises because the total volume of seawater is increasing. Global warming drives that in two basic ways: by warming the ocean and by melting ice on land, which adds more water. Since 1900 global sea level has risen about eight inches. It's now rising at about an eighth of an inch a year—and accelerating.

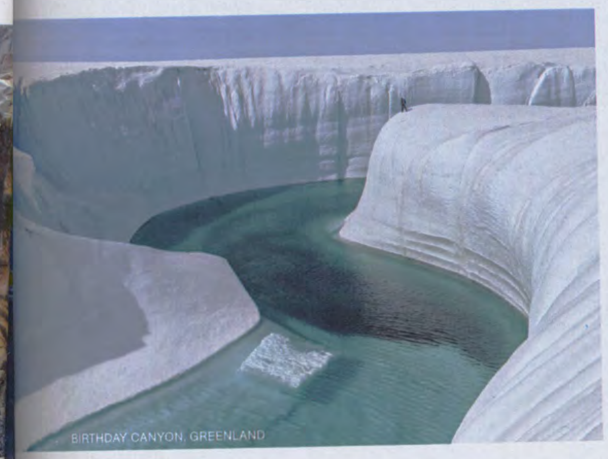
TAHUMMING GLACIER, BRITISH COLUMBIA

Thermal expansion

As seawater warms, its volume increases. This thermal expansion accounts for around a third of the current sea-level rise.

Glaciers and ice caps

Melting mountain glaciers contribute another third. By 2100 they'll probably add a few inches to sea level—but not feet. They don't contain that much ice.



BIRTHDAY CANYON, GREENLAND

Greenland ice sheet

It's a small contributor now, but its surface has started melting in summer—a worrisome sign. The ice sheet contains enough water to raise sea level nearly 25 feet.

PINE ISLAND GLACIER, WEST ANTARCTICA

Antarctica, East and West

East Antarctica seems fairly stable. But parts of West Antarctica's ice sheet are being undermined by a warming ocean. Its future, like Greenland's, is very uncertain.

chance that something very nasty will happen."

Even in the absence of something very nasty, coastal cities face a twofold threat: Inexorably rising oceans will gradually inundate low-lying areas, and higher seas will extend the ruinous reach of storm surges. The threat will never go away; it will only worsen. By the end of the century a hundred-year storm surge like Sandy's might occur every decade or less. Using a conservative prediction of a half meter (20 inches) of sea-level rise, the Organisation for Economic Co-operation and Development estimates that by 2070, 150 million people in the world's large port cities will be at risk from coastal flooding, along with $35 trillion worth of property—an amount that will equal 9 percent of the global GDP. How will they cope?

"DURING THE LAST ICE AGE there was a mile or two of ice above us right here," says Malcolm Bowman, as we pull into his driveway in Stony Brook, New York, on Long Island's north shore. "When the ice retreated, it left a heap of sand, which is Long Island. All these rounded stones you see—look there," he says, pointing to some large boulders scattered among the trees near his home. "They're glacial boulders."

Bowman, a physical oceanographer at the State University of New York at Stony Brook, has been trying for years to persuade anyone who will listen that New York City needs a harbor-spanning storm-surge barrier. Compared with some other leading ports, New York is essentially defenseless in the face of hurricanes and floods. London, Rotterdam, St. Petersburg, New Orleans, and Shanghai have all built levees and storm barriers in the past few decades. New York paid a high price for its vulnerability last October. Sandy left 43 dead in the city, of whom 35 drowned; it cost the city some $19 billion. And it was all unnecessary, says Bowman.

"If a system of properly designed storm-surge barriers had been built—and strengthened with sand dunes at both ends along the low-lying coastal areas—there would have been no flooding damage from Sandy," he says.

Bowman envisions two barriers: one at Throgs Neck, to keep surges from Long Island Sound out of the East River, and a second one spanning the harbor south of the city. Gates would accommodate ships and tides, closing only during storms, much like existing structures in the Netherlands and elsewhere. The southern barrier alone, stretching five miles between Sandy Hook, New Jersey, and the Rockaway Peninsula, might cost $10 billion to $15 billion, Bowman estimates. He pictures a six-lane toll highway on top that would provide a bypass route around the city and a light-rail line connecting the Newark and John F. Kennedy Airports.

"It could be an asset to the region," says Bowman. "Eventually the city will have to face up to this, because the problem is going to get worse. It might take five years of study and another ten years to get the political will to do it. By then there might have been another disaster. We need to start planning immediately. Otherwise we're mortgaging the future and leaving the next generation to cope as best it can."

Another way to safeguard New York might be to revive a bit of its past. In the 16th-floor loft of her landscape architectural firm in lower Manhattan, Kate Orff pulls out a map of New York Harbor in the 19th century. The present-day harbor shimmers outside her window, calm and unthreatening on an unseasonably mild morning three months to the day after Sandy hit.

"Here's an archipelago that protected Red Hook," Orff says, pointing on the map to a small cluster of islands off the Brooklyn shore. "There was another chain of shoals that connected Sandy Hook to Coney Island."

The islands and shallows vanished long ago, demolished by harbor-dredging and landfill projects that added new real estate to a burgeoning city. Orff would re-create some of them, particularly the Sandy Hook–Coney Island chain, and connect them with sluice gates that would close during a storm, forming an eco-engineered barrier that would cross the same waters as Bowman's more conventional one. Behind it, throughout the harbor, would be dozens

Tim Folger wrote about tsunamis for the February 2012 issue. George Steinmetz has photographed 28 stories for the magazine, the last one on Libya.

If All the Ice Melted

How the ultimate sea-level catastrophe would reshape our world

There are more than five million cubic miles of ice on Earth, and no one really knows how long it would take to melt it all. Probably more than 5,000 years, some scientists say. But if we burn all the coal, oil, and gas, adding some five trillion more tons of carbon to the atmosphere, we'll very likely create an ice-free planet. It would be a hot planet, with an average temperature of perhaps 80 degrees Fahrenheit instead of the current 58. Large swaths of it might become too hot for humans; deserts would doubtless expand. The maps here don't show such changes. They show the world as it is now, with only one difference: All the ice on land has melted and drained into the sea, raising it 216 feet.

GREENLAND AND THE ARCTIC OCEAN
In a few decades the Arctic Ocean may be ice free in summer. The ice sheet that covers nearly all of Greenland is up to two miles thick and will last far longer. But it's still at risk. It shrank or vanished during earlier interglacial periods, when Earth was only a few degrees warmer than it is today. Since 1992 it has lost more than 140 billion metric tons of ice a year on average.

ALL THE WATER IN THE WORLD
in cubic miles

269	Living organisms
2,752	Swamp water
3,095	Atmosphere
3,959	Soil moisture
42,829	Lakes and rivers
71,970	Ground ice and permafrost
5,614,000	Groundwater
5,773,000	Ice sheets, glaciers, and permanent snow
321,000,000	Oceans, seas, and bays

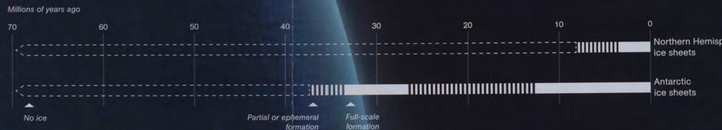
Vancouver
Seattle
Portland
San Francisco
Los Angeles
San Diego
Pine Bluff
Houston
New Orleans
Tallahassee
Jacksonville
Orlando
Tampa
Miami
Charleston
Norfolk
Baltimore
Washington, D.C.
Philadelphia
New York
Boston
Montréal
Halifax
Havana
Cancún
Veracruz
Port-au-Prince

WEST ANTARCTICA
Like the Greenland ice sheet, the West Antarctic one was apparently much smaller during earlier warm periods. It's vulnerable because most of it sits on bedrock that's below sea level. The warming ocean is melting the floating ice shelves that buttress it and could eventually melt the ice sheet itself from below, causing it to collapse. Since 1992 it has averaged a net loss of 65 billion metric tons of ice a year.

EAST ANTARCTICA
The East Antarctic ice sheet is so large—it contains four-fifths of all the ice on Earth—that it might seem unmeltable. It survived earlier warm periods intact. Lately it seems to be thickening slightly—because of global warming. The warmer atmosphere holds more water vapor, which falls as snow on East Antarctica. But even this behemoth is unlikely to survive a return to an Eocene climate.

A HISTORY OF ICE
The last time Earth was free of ice was more than 34 million years ago, in the Eocene epoch. Alligators swam in Arctic swamps. But the planet slowly cooled as carbon dioxide rained from the air and was locked up in seafloor sediments. Continental ice sheets formed first in Antarctica, but over the past few million years they've repeatedly surged across northern continents too. We're living in a warm interglacial period—20,000 years ago Chicago, New York, and London were buried under ice.

Spin and explore an ice-free globe on our digital editions.



NATIONAL GEOGRAPHIC

JASON TREAT AND MATTHEW TWOMBLY, NGM STAFF. ART: KEES VEENENBOS. SOURCES: PHILIPPE HUYBRECHTS, VRIJE UNIVERSITEIT BRUSSEL; RICHARD B. WILLIAMS, JR., WOODS HOLE OCEANOGRAPHIC CENTER; JAMES C. ZACHOS, UNIVERSITY OF CALIFORNIA, SANTA CRUZ; NOAA; ETOPO1 (BEDROCK), 1 ARC-MINUTE GLOBAL RELIEF MODEL.

The World at High Water

…if unchecked warming melts all the ice, raising seas 216 feet

Europe and the Mediterranean

London? A memory. Venice? Reclaimed by the Adriatic Sea. Thousands of years from now, in this catastrophic scenario, the Netherlands will have long since surrendered to the sea, and most of Denmark will be gone too. In Egypt, Alexandria and Cairo will be swamped by the intruding Mediterranean, whose expanding waters will also have swelled the Black and Caspian Seas.

South America

The Amazon Basin in the north and the Paraguay River Basin in the south would become Atlantic inlets, wiping out Buenos Aires, coastal Uruguay, and most of Paraguay. Mountainous stretches would survive along the Caribbean coast and in Central America.

Asia

Land now inhabited by 600 million Chinese would flood, as would all of Bangladesh, population 160 million, and much of coastal India. The inundation of the Mekong Delta would leave Cambodia's Cardamom Mountains stranded as an island.

Australia

Predominantly desert, the continent would gain a new inland sea—but it would lose much of the narrow coastal strip where four out of five Australians now live.

Africa

Compared with other continents, Africa would lose less of its land to the ultimate sea-level catastrophe, but Earth's rising heat might make much of it uninhabitable. The snows of Kilimanjaro won't survive the 21st century.