Photo Gallery

Steinmetz Photography

George Steinmetz examines the potential impacts of rising seas.

Additional Gallery

The Damage Done

As the world warms, it may see more storms like Hurricane Sandy.

Graphic

Rising Seas

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Rising Seas

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?

By Tim Folger
Photographs by George Steinmetz

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

A Superstorm in 2100

What would happen to New York if the storm surge hurled at it by a storm like Sandy were riding on a sea that had risen five feet higher?

Chart

Rising Seas

Sea level didn't change much for nearly 2,000 years, but has been rising at an accelerated rate in the past few decades.

Map

Uneven Impacts

If sea level rises an average of three feet by 2100, the impacts will be felt the most in vulnerable coastal cities.

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.

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 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 of artificial reefs built from stone, rope, and wood pilings and seeded with oysters and other shellfish. The reefs would continue to grow as sea levels rose, helping to buffer storm waves—and the shellfish, being filter feeders, would also help clean the harbor. “Twenty-five percent of New York Harbor used to be oyster beds,” Orff says.

Orff estimates her “oystertecture” vision could be brought to life at relatively low cost. “It would be chump change compared with a conventional barrier. And it wouldn’t be money wasted: Even if another Sandy never happens, you’d have a cleaner, restored harbor in a more ecologically vibrant context and a healthier New York.”

In June, Mayor Michael Bloomberg outlined a $19.5 billion plan to defend New York City against rising seas. “Sandy was a temporary setback that can ultimately propel us forward,” he said. The mayor’s proposal calls for the construction of levees, local storm-surge barriers, sand dunes, oyster reefs, and more than 200 other measures. It goes far beyond anything planned by any other American city. But the mayor dismissed the idea of a harbor barrier. “A giant barrier across our harbor is neither practical nor affordable,” Bloomberg said. The plan notes that since a barrier would remain open most of the time, it would not protect the city from the inch-by-inch creep of sea-level rise.

Meanwhile, development in the city’s flood zones continues. Klaus Jacob, a geophysicist at Columbia University, says the entire New York metropolitan region urgently needs a master plan to ensure that future construction will at least not exacerbate the hazards from rising seas.

“The problem is we’re still building the city of the past,” says Jacob. “The people of the 1880s couldn’t build a city for the year 2000—of course not. And we cannot build a year-2100 city now. But we should not build a city now that we know will not function in 2100. There are opportunities to renew our infrastructure. It’s not all bad news. We just have to grasp those opportunities.”

Will New York grasp them after Bloomberg leaves office at the end of this year? And can a single storm change not just a city’s but a nation’s policy? It has happened before. The Netherlands had its own stormy reckoning 60 years ago, and it transformed the country.

The storm roared in from the North Sea on the night of January 31, 1953. Ria Geluk

was six years old at the time and living where she lives today, on the island of Schouwen Duiveland in the southern province of Zeeland. She remembers a neighbor knocking on the door of her parents' farmhouse in the middle of the night to tell them that the dike had failed. Later that day the whole family, along with several neighbors who had spent the night, climbed to the roof, where they huddled in blankets and heavy coats in the wind and rain. Geluk's grandparents lived just across the road, but water swept into the village with such force that they were trapped in their home. They died when it collapsed.

"Our house kept standing," says Geluk. "The next afternoon the tide came again. My father could see around us what was happening; he could see houses disappearing. You knew when a house disappeared, the people were killed. In the afternoon a fishing boat came to rescue us."

In 1997 Geluk helped found the Watersnoodmuseum—the "flood museum"—on Schouwen Duiveland. The museum is housed in four concrete caissons that engineers used to plug dikes in 1953. The disaster killed 1,836 in all, nearly half in Zeeland, including a baby born on the night of the storm.

Afterward the Dutch launched an ambitious program of dike and barrier construction called the Delta Works, which lasted more than four decades and cost more than six billion dollars. One crucial project was the five-mile-long Oosterscheldekering, or Eastern Scheldt barrier, completed 27 years ago to defend Zeeland from the sea. Geluk points to it as we stand on a bank of the Scheldt estuary near the museum, its enormous pylons just visible on the horizon. The final component of the Delta Works, a movable barrier protecting Rotterdam Harbor and some 1.5 million people, was finished in 1997.

Like other primary sea barriers in the Netherlands, it's built to withstand a 1-in-10,000-year storm—the strictest standard in the world. (The United States uses a 1-in-100 standard.) The Dutch government is now considering whether to upgrade the protection levels to bring them in line with sea-level-rise projections.

Such measures are a matter of national security for a country where 26 percent of the land lies below sea level. With more than 10,000 miles of dikes, the Netherlands is fortified to such an extent that hardly anyone thinks about the threat from the sea, largely because much of the protection is so well integrated into the landscape that it's nearly invisible.

On a bitingly cold February afternoon I spend a couple of hours walking around Rotterdam with Arnoud Molenaar, the manager of the city's Climate Proof program, which aims to make Rotterdam resistant to the sea levels expected by 2025. About 20 minutes into our walk we climb a sloping street next to a museum designed by the architect Rem Koolhaas. The presence of a hill in this flat city should have alerted me, but I'm surprised when Molenaar tells me that we're walking up the side of a dike. He gestures to some nearby pedestrians. "Most of the people around us don't realize this is a dike either," he says. The Westzeedijk shields the inner city from the Meuse River a few blocks to the south, but the broad, busy boulevard on top of it looks like any other Dutch thoroughfare, with flocks of cyclists wheeling along in dedicated lanes.

As we walk, Molenaar points out assorted subtle flood-control structures: an

underground parking garage designed to hold 10,000 cubic meters—more than 2.5 million gallons—of rainwater; a street flanked by two levels of sidewalks, with the lower one designed to store water, leaving the upper walkway dry. Late in the afternoon we arrive at Rotterdam's Floating Pavilion, a group of three connected, transparent domes on a platform in a harbor off the Meuse. The domes, about three stories tall, are made of a plastic that's a hundred times as light as glass.

Inside we have sweeping views of Rotterdam's skyline; hail clatters overhead as low clouds scud in from the North Sea. Though the domes are used for meetings and exhibitions, their main purpose is to demonstrate the wide potential of floating urban architecture. By 2040 the city anticipates that as many as 1,200 homes will float in the harbor. "We think these structures will be important not just for Rotterdam but for many cities around the world," says Bart Roeffen, the architect who designed the pavilion. The homes of 2040 will not necessarily be domes; Roeffen chose that shape for its structural integrity and its futuristic appeal. "To build on water is not new, but to develop floating communities on a large scale and in a harbor with tides—that is new," says Molenaar. "Instead of fighting against water, we want to live with it."

While visiting the Netherlands, I heard one joke repeatedly: "God may have built the world, but the Dutch built Holland." The country has been reclaiming land from the sea for nearly a thousand years—much of Zeeland was built that way. Sea-level rise does not yet panic the Dutch.

"We cannot retreat! Where could we go? Germany?" Jan Mulder has to shout over the wind—we're walking along a beach called Kijkduin as volleys of sleet exfoliate our faces. Mulder is a coastal morphologist with Deltares, a private coastal management firm. This morning he and Douwe Sikkema, a project manager with the province of South Holland, have brought me to see the latest in adaptive beach protection. It's called the *zandmotor*—the sand engine.

The seafloor offshore, they explain, is thick with hundreds of feet of sand deposited by rivers and retreating glaciers. North Sea waves and currents once distributed that sand along the coast. But as sea level has risen since the Ice Age, the waves no longer reach deep enough to stir up sand, and the currents have less sand to spread around. Instead the sea erodes the coast here.

The typical solution would be to dredge sand offshore and dump it directly on the eroding beaches—and then repeat the process year after year as the sand washes away. Mulder and his colleagues recommended that the provincial government try a different strategy: a single gargantuan dredging operation to create the sandy peninsula we're walking on—a hook-shaped stretch of beach the size of 250 football fields. If the scheme works, over the next 20 years the wind, waves, and tides will spread its sand 15 miles up and down the coast. The combination of wind, waves, tides, and sand is the zandmotor.

The project started only two years ago, but it seems to be working. Mulder shows me small dunes that have started to grow on a beach where there was once open water. "It's very flexible," he says. "If we see that sea-level rise increases, we can increase the amount of sand." Sikkema adds, "And it's much easier to adjust the amount of sand than to rebuild an entire system of dikes."

Later Mulder tells me about a memorial inscription affixed to the Eastern Scheldt barrier in Zeeland: "It says, '*Hier gaan over het tij, de maan, de wind, en wij*—Here the tide is ruled by the moon, the wind, and us.' " It reflects the confidence of a generation that took for granted, as we no longer can, a reasonably stable world. "We have to understand that we are not ruling the world," says Mulder. "We need to adapt."

With the threats of climate change and sea-level rise looming over us all, cities around the world, from New York to Ho Chi Minh City, have turned to the Netherlands for guidance. One Dutch firm, Arcadis, has prepared a conceptual design for a storm-surge barrier in the Verrazano Narrows to protect New York City. The same company helped design a $1.1 billion, two-mile-long barrier that protected New Orleans from a 13.6-foot storm surge last summer, when Hurricane Isaac hit. The Lower Ninth Ward, which suffered so greatly during Hurricane Katrina, was unscathed.

"Isaac was a tremendous victory for New Orleans," Piet Dircke, an Arcadis executive, tells me one night over dinner in Rotterdam. "All the barriers were closed; all the levees held; all the pumps worked. You didn't hear about it? No, because nothing happened."

New Orleans may be safe for a few decades, but the long-term prospects for it and other low-lying cities look dire. Among the most vulnerable is Miami. "I cannot envision southeastern Florida having many people at the end of this century," says Hal Wanless, chairman of the department of geological sciences at the University of Miami. We're sitting in his basement office, looking at maps of Florida on his computer. At each click of the mouse, the years pass, the ocean rises, and the peninsula shrinks. Freshwater wetlands and mangrove swamps collapse—a death spiral that has already started on the southern tip of the peninsula. With seas four feet higher than they are today—a distinct possibility by 2100—about two-thirds of southeastern Florida is inundated. The Florida Keys have almost vanished. Miami is an island.

When I ask Wanless if barriers might save Miami, at least in the short term, he leaves his office for a moment. When he returns, he's holding a foot-long cylindrical limestone core. It looks like a tube of gray, petrified Swiss cheese. "Try to plug this up," he says. Miami and most of Florida sit atop a foundation of highly porous limestone. The limestone consists of the remains of countless marine creatures deposited more than 65 million years ago, when a warm, shallow sea covered what is now Florida—a past that may resemble the future here.

A barrier would be pointless, Wanless says, because water would just flow through the limestone beneath it. "No doubt there will be some dramatic engineering feats attempted," he says. "But the limestone is so porous that even massive pumping systems won't be able to keep the water out."

Sea-level rise has already begun to threaten Florida's freshwater supply. About a quarter of the state's 19 million residents depend on wells sunk into the enormous Biscayne aquifer. Salt water is now seeping into it from dozens of canals that were built to drain the Everglades. For decades the state has tried to control the saltwater influx by building dams and pumping stations on the drainage canals. These

"salinity-control structures" maintain a wall of fresh water behind them to block the underground intrusion of salt water. To offset the greater density of salt water, the freshwater level in the control structures is generally kept about two feet higher than the encroaching sea.

But the control structures also serve a second function: During the state's frequent rainstorms their gates must open to discharge the flood of fresh water to the sea."We have about 30 salinity-control structures in South Florida," says Jayantha Obeysekera, the chief hydrological modeler at the South Florida Water Management District. "At times now the water level in the sea is higher than the freshwater level in the canal." That both accelerates saltwater intrusion and prevents the discharge of flood waters. "The concern is that this will get worse with time as the sea-level rise accelerates," Obeysekera says.

Using fresh water to block the salt water will eventually become impractical, because the amount of fresh water needed would submerge ever larger areas behind the control structures, in effect flooding the state from the inside. "With 50 centimeters [about 20 inches] of sea-level rise, 80 percent of the salinity-control structures in Florida will no longer be functional," says Wanless. "We'll either have to drown communities to keep the freshwater head above sea level or have saltwater intrusion." When sea level rises two feet, he says, Florida's aquifers may be poisoned beyond recovery. Even now, during unusually high tides, seawater spouts from sewers in Miami Beach, Fort Lauderdale, and other cities, flooding streets.

In a state exposed to hurricanes as well as rising seas, people like John Van Leer, an oceanographer at the University of Miami, worry that one day they will no longer be able to insure—or sell—their houses. "If buyers can't insure it, they can't get a mortgage on it. And if they can't get a mortgage, you can only sell to cash buyers," Van Leer says. "What I'm looking for is a climate-change denier with a lot of money."

Unless we change course dramatically in the coming years, our carbon emissions will create a world utterly different in its very geography from the one in which our species evolved. "With business as usual, the concentration of carbon dioxide in the atmosphere will reach around a thousand parts per million by the end of the century," says Gavin Foster, a geochemist at the University of Southampton in England. Such concentrations, he says, haven't been seen on Earth since the early Eocene epoch, 50 million years ago, when the planet was completely ice free. According to the U.S. Geological Survey, sea level on an iceless Earth would be as much as 216 feet higher than it is today. It might take thousands of years and more than a thousand parts per million to create such a world—but if we burn all the fossil fuels, we will get there.

No matter how much we reduce our greenhouse gas emissions, Foster says, we're already locked in to at least several feet of sea-level rise, and perhaps several dozens of feet, as the planet slowly adjusts to the amount of carbon that's in the atmosphere already. A recent Dutch study predicted that the Netherlands could engineer solutions at a manageable cost to a rise of as much as five meters, or 16 feet. Poorer countries will struggle to adapt to much less. At different times in different places, engineering solutions will no longer suffice. Then the retreat from the coast will begin. In some places there will be no higher ground to retreat to.

By the next century, if not sooner, large numbers of people will have to abandon coastal areas in Florida and other parts of the world. Some researchers fear a flood tide of climate-change refugees. “From the Bahamas to Bangladesh and a major amount of Florida, we’ll all have to move, and we may have to move at the same time,” says Wanless. “We’re going to see civil unrest, war. You just wonder how—or if—civilization will function. How thin are the threads that hold it all together? We can’t comprehend this. We think Miami has always been here and will always be here. How do you get people to realize that Miami—or London—will not always be there?”

What will New York look like in 200 years? Klaus Jacob, the Columbia geophysicist, sees downtown Manhattan as a kind of Venice, subject to periodic flooding, perhaps with canals and yellow water cabs. Much of the city’s population, he says, will gather on high ground in the other boroughs. “High ground will become expensive, waterfront will become cheap,” he says. But among New Yorkers, as among the rest of us, the idea that the sea is going to rise—a lot—hasn’t really sunk in yet. Of the thousands of people in New York State whose homes were badly damaged or destroyed by Sandy’s surge, only 10 to 15 percent are expected to accept the state’s offer to buy them out at their homes’ pre-storm value. The rest plan to rebuild.

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

A SUPERSTORM IN 2100

What would happen to New York if the storm surge hurled at it by a storm like Sandy were riding on a sea that had risen five feet higher? That's the high end of the range in 2100 that the U.S. Army Corps of Engineers now recommends planning for. Sandy's surge flooded subway tunnels, knocked out the power grid in lower Manhattan for days, and damaged 218,000 cars in the region as a whole. If the city doesn't protect itself, a future flood will surge farther and deeper into its cavernous streets.

During Sandy, seawater gushed into the Ground Zero construction site. New federal maps include the site in a 100-year flood zone.

METHODOLOGY This estimated footprint of a Sandy-like storm surge in 2100 assumes high tide and a sea-level rise of five feet. It was produced using a National Weather Service storm-surge model called SLOSH and a U.S. Army Corps of Engineers procedure for translating the model's coarse output into a detailed inundation map. It doesn't consider future changes in coastal terrain that would affect a storm surge, such as erosion of beaches or sandbars.

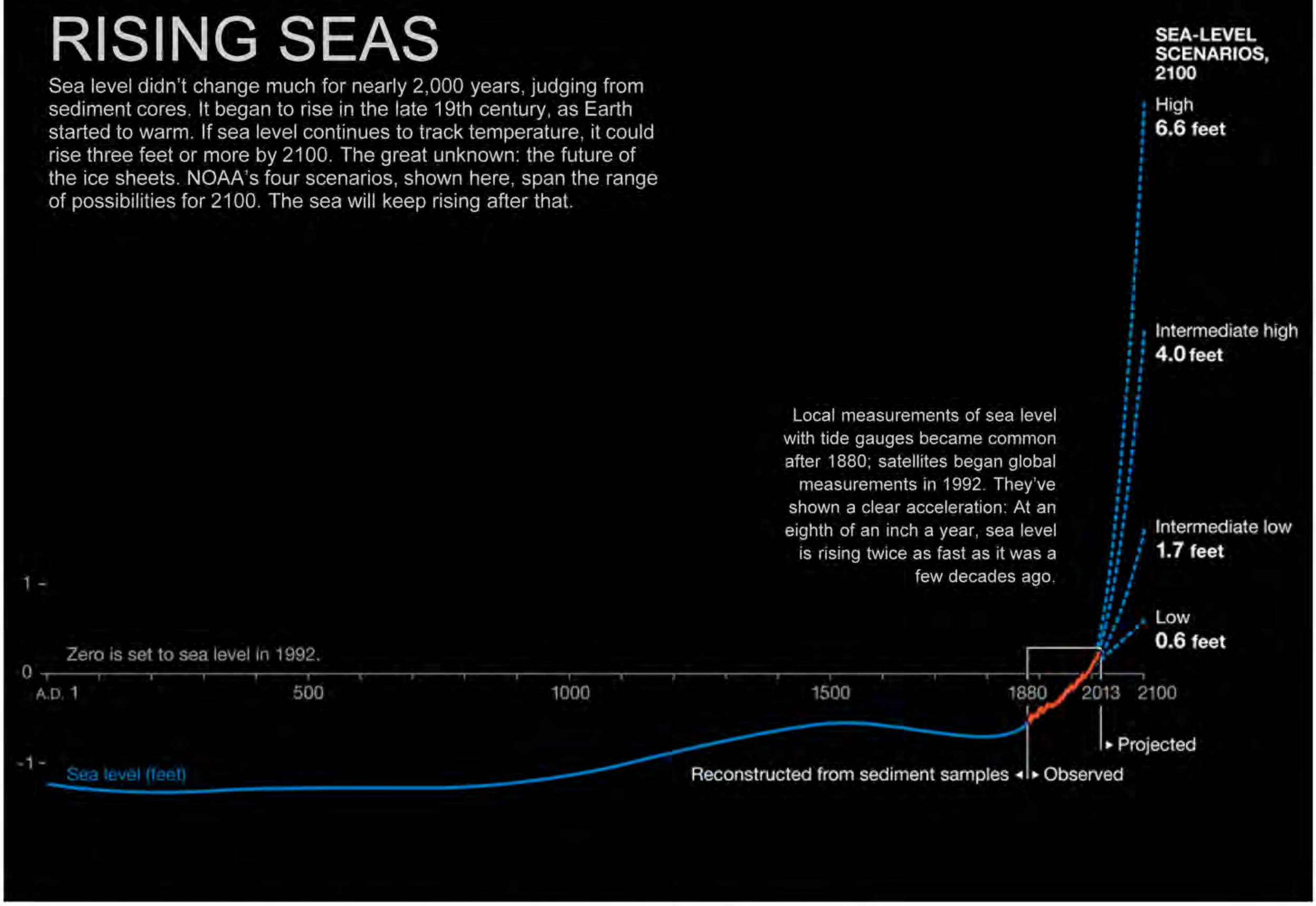
MANHATTAN MODEL PROVIDED BY PICTOMETRY (2009, 2012)

RYAN MORRIS, MATTHEW TWOMBLY, AND MAGGIE SMITH, NGM STAFF. ART: IXTRACT GMBH, BERLIN. SOURCES: NOAA; U.S. ARMY CORPS OF ENGINEERS; NEW YORK CITY DEPARTMENT OF CITY PLANNING; NEW YORK CITY OFFICE OF EMERGENCY MANAGEMENT; USGS; NATIONAL HURRICANE CENTER; NATIONAL WEATHER SERVICE; STEVENS INSTITUTE OF TECHNOLOGY (DIGITAL ELEVATION MODEL); RENAISSANCE COMPUTING INSTITUTE, UNIVERSITY OF NORTH CAROLINA AT CHAPEL HILL; FEMA (2012 STORM-SURGE EXTENT)

RISING SEAS

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.



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

RISING SEAS

UNEVEN IMPACTS

If sea level rises an average of around three feet by 2100, winds, currents, and melting ice sheets will distribute the rise unevenly. Certain coastal cities will be especially vulnerable.

SEA-LEVEL RISE (by 2100)
0 +4 ft
Sea-level drop

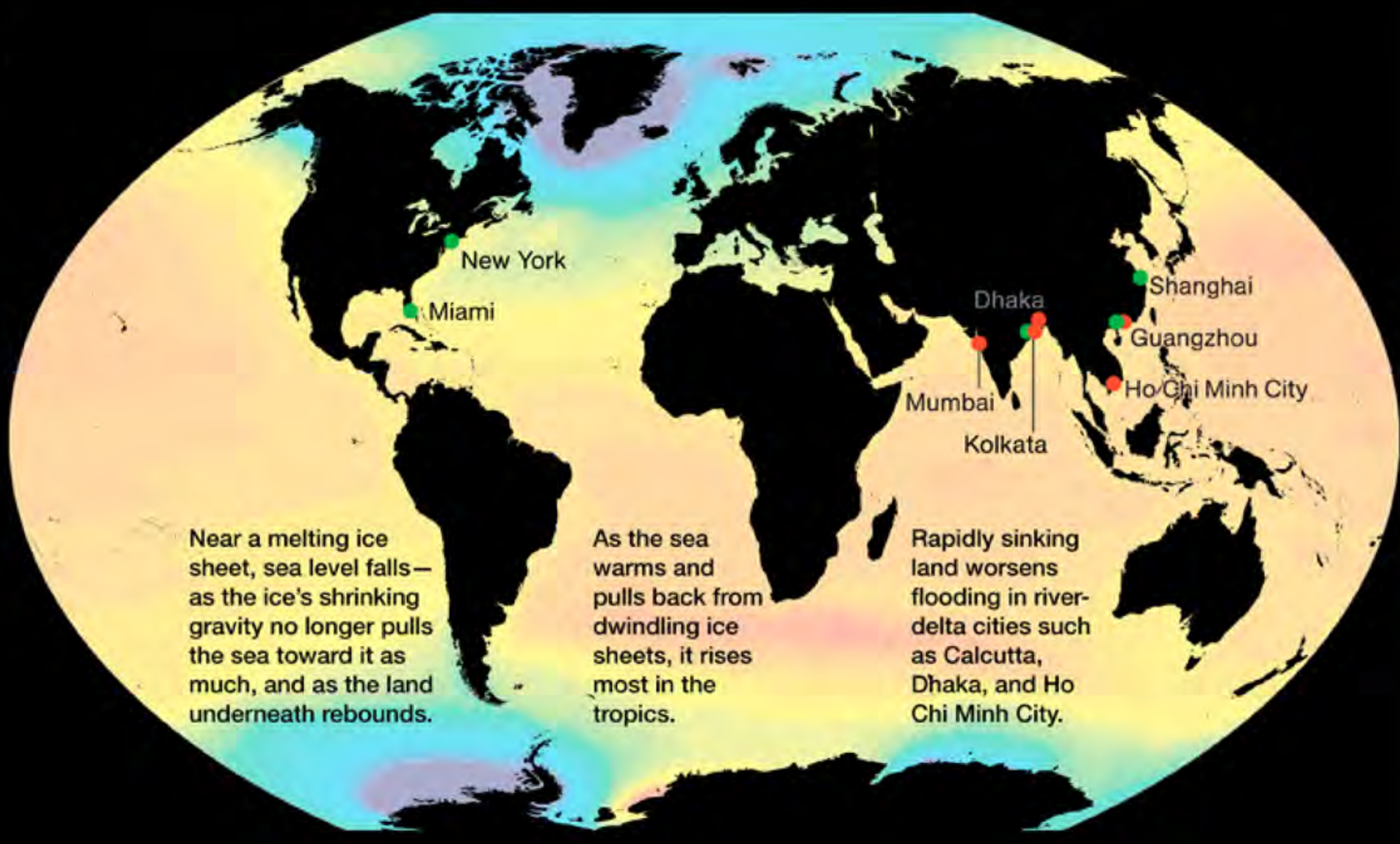
TOP CITIES MOST AT RISK FROM RISING SEAS (by 2070)

BY EXPOSED ASSETS

1. Miami — *$3.5 trillion*
2. Guangzhou — *3.4*
3. New York — *2.1*
4. Kolkata (Calcutta) — *2.0*
5. Shanghai — *1.8*

BY EXPOSED POPULATION

1. Kolkata (Calcutta) — *14.0 million*
2. Mumbai (Bombay) — *11.4*
3. Dhaka — *11.1*
4. Guangzhou — *10.3*
5. Ho Chi Minh City — *9.2*

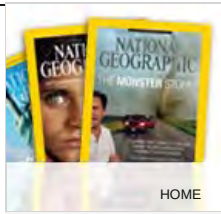


Near a melting ice sheet, sea level falls—as the ice's shrinking gravity no longer pulls the sea toward it as much, and as the land underneath rebounds.

As the sea warms and pulls back from dwindling ice sheets, it rises most in the tropics.

Rapidly sinking land worsens flooding in river-delta cities such as Calcutta, Dhaka, and Ho Chi Minh City.

RYAN MORRIS, NGM STAFF. SOURCES: FELIX LANDERER, NASA/JPL; M.PERETTE ET AL, 2013; ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT



The Damage Done

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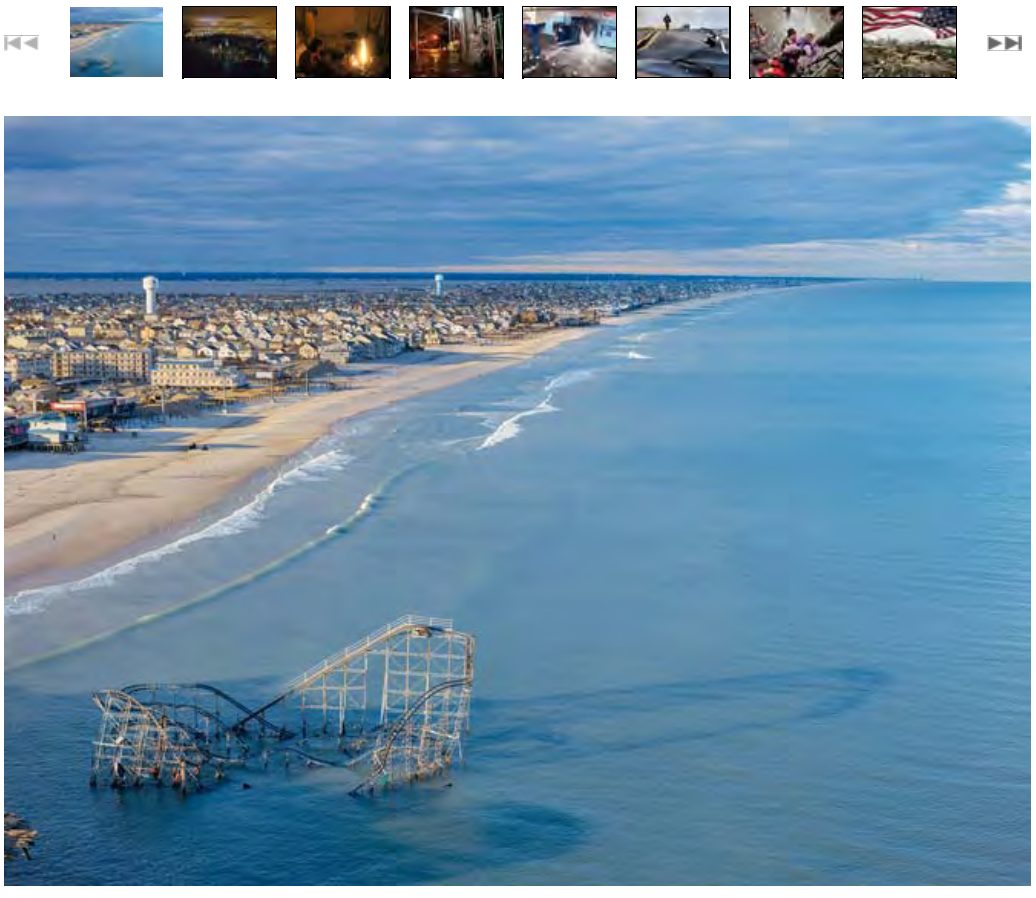
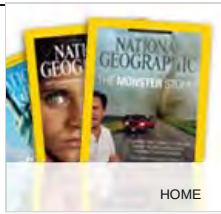


Photograph by Stephen Wilkes

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.



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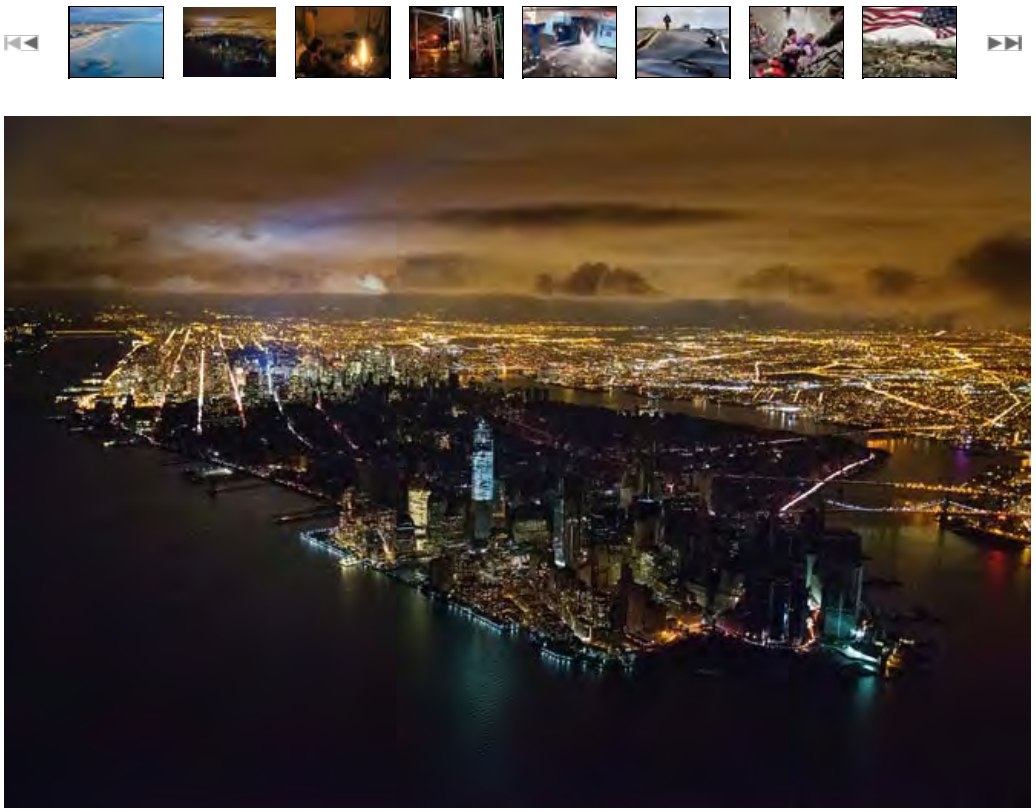
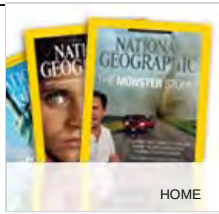


Photograph by Iwan Baan, Reportage by Getty Images

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.



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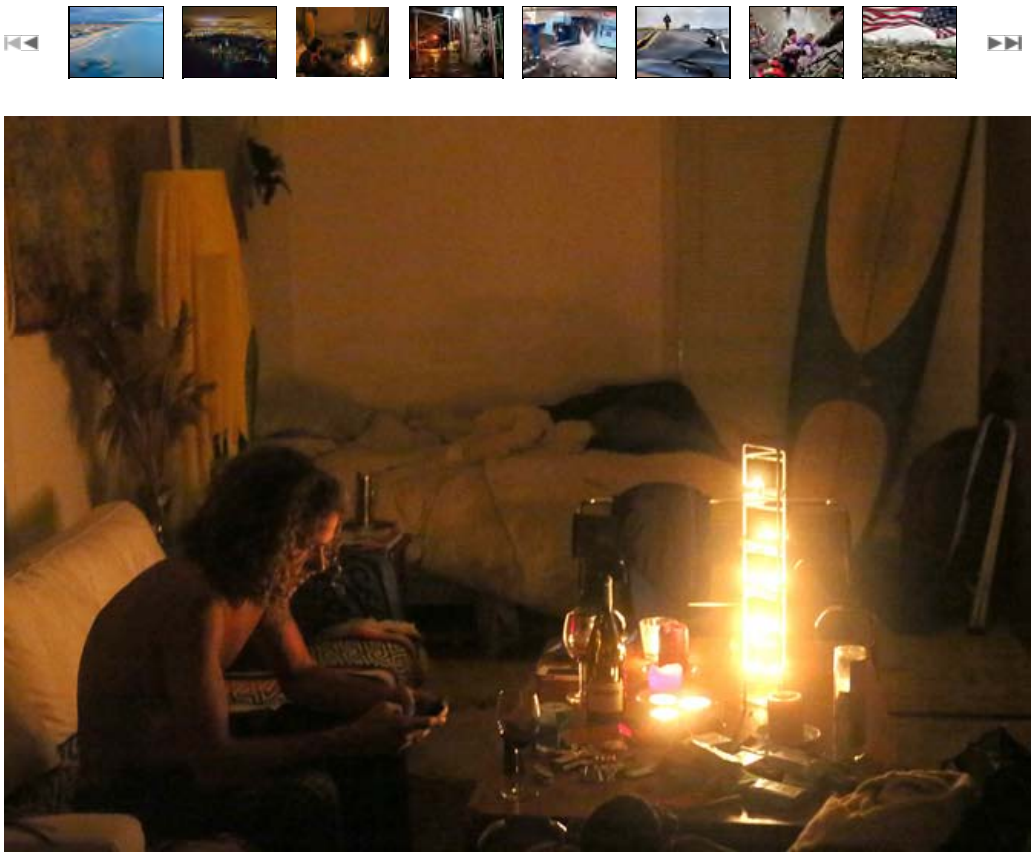
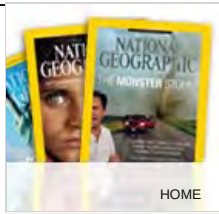


Photograph by Davina Grincevicius

After a long day of organizing relief efforts, Brandon d'Leo, a surfer and sculptor, rests in his candlelit apartment in the Rockaway Beach neighborhood of Queens, New York. Like many of his neighbors, d'Leo lost electricity for a few days—and heat and hot water for more than two months—after Sandy pounded the community.



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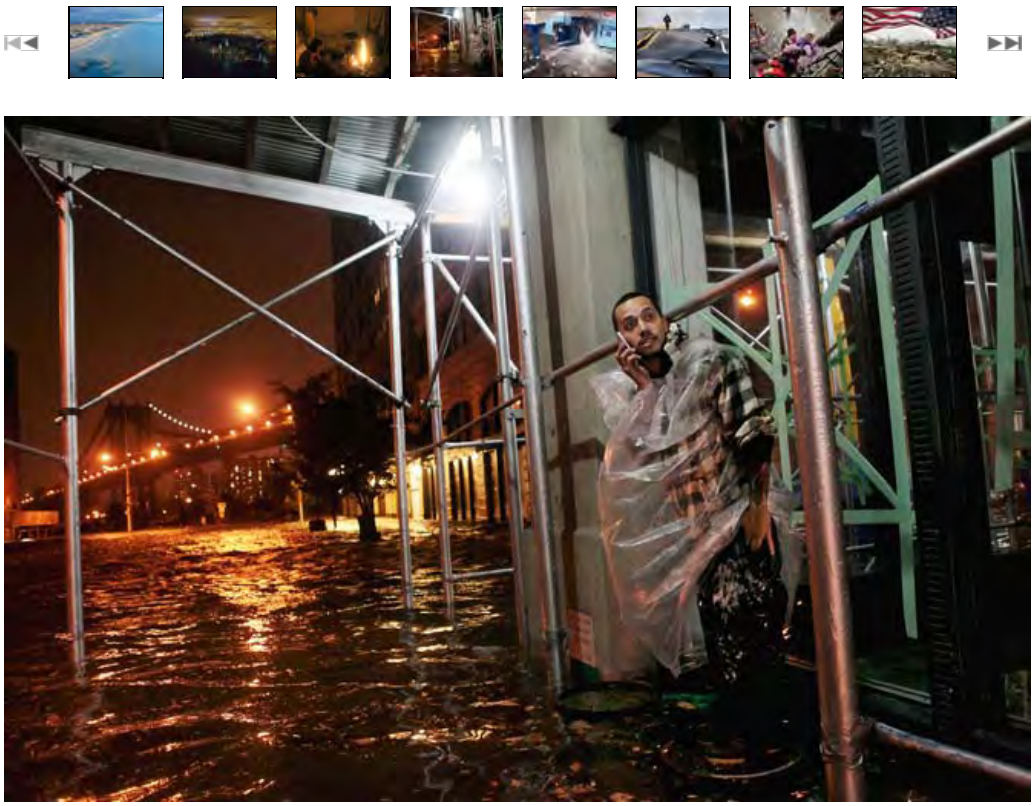
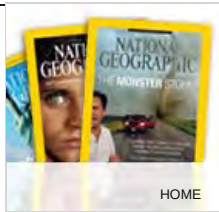


BROOKLYN, NEW YORK

Photograph by Kirsten Luce, New York Times/Redux



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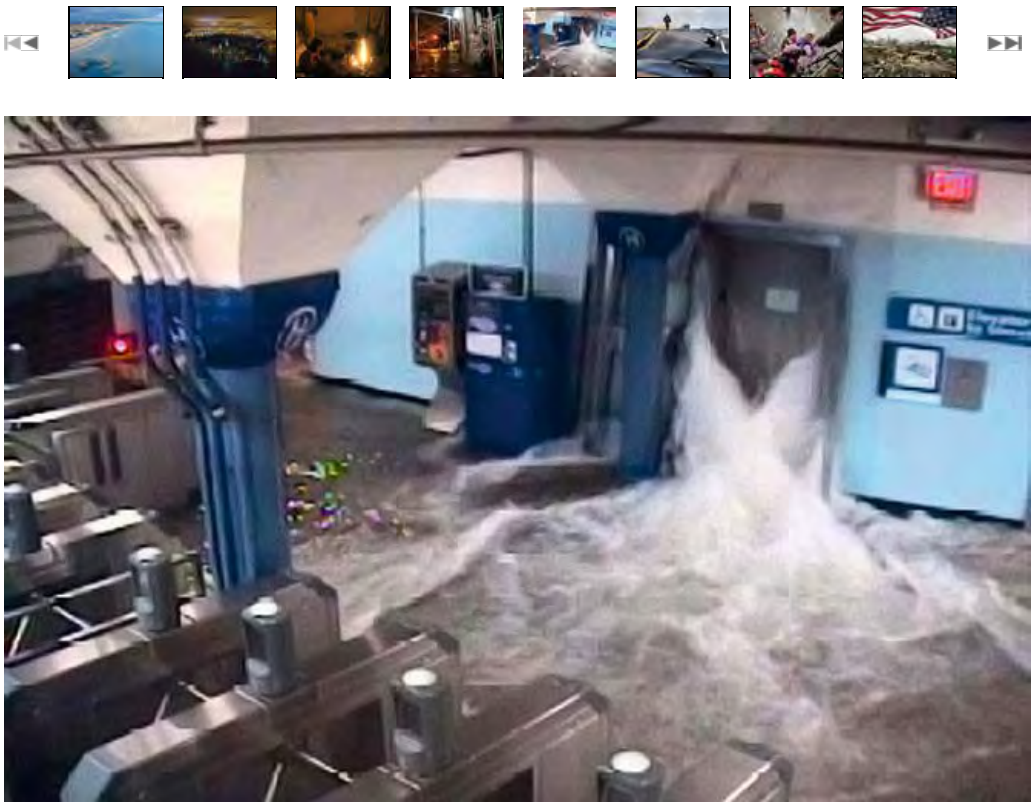

PATH STATION, HOBOKEN, NEW JERSEY

Photograph by Port Authority of New York & New Jersey, AFP Photo

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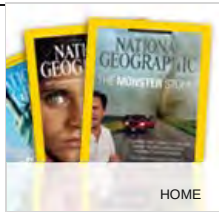

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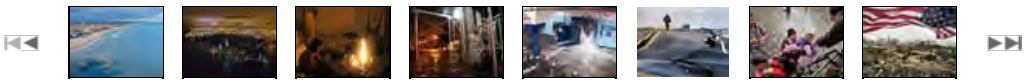
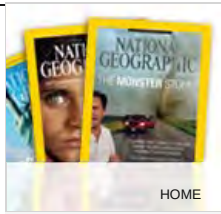


RODANTHE, NORTH CAROLINA

Photograph by Steve Earley, Virginian-Pilot



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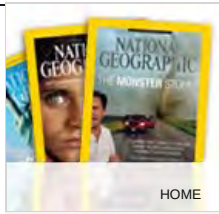
STATEN ISLAND, NEW YORK

Photograph by Michael Kirby Smith, New York Times/Redux



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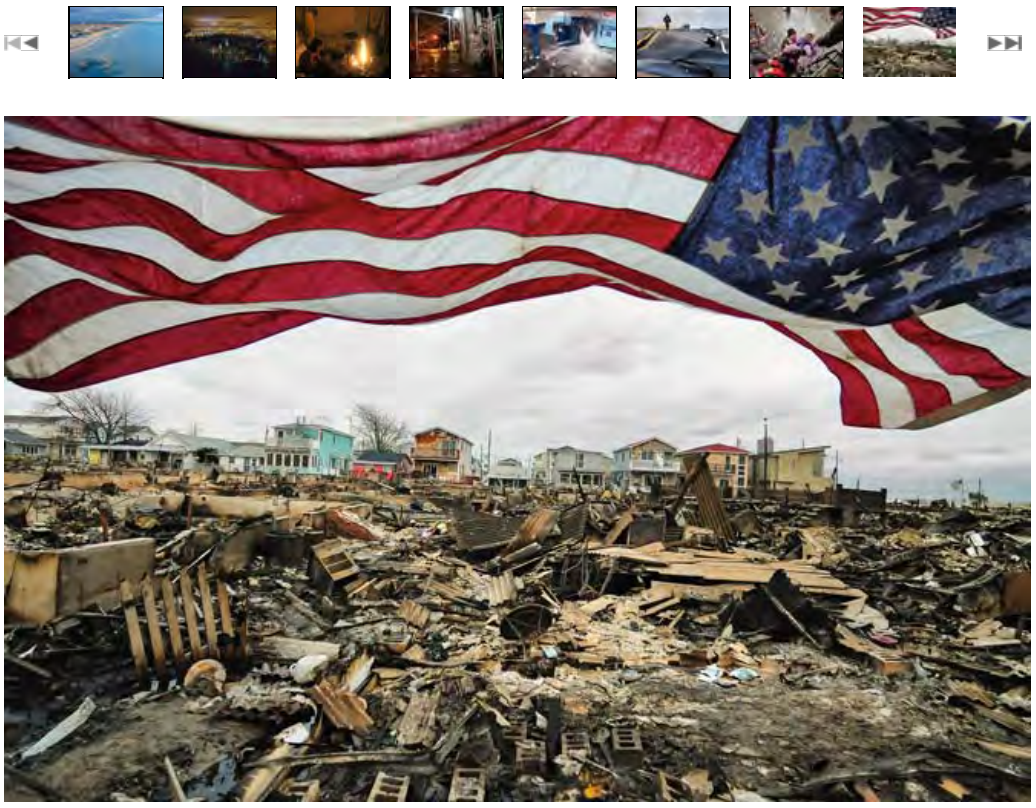
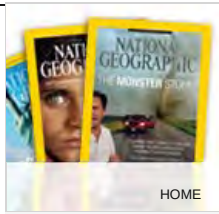


BREEZY POINT, QUEENS, NEW YORK

Photograph by JB Nicholas, Splash News/Corbis



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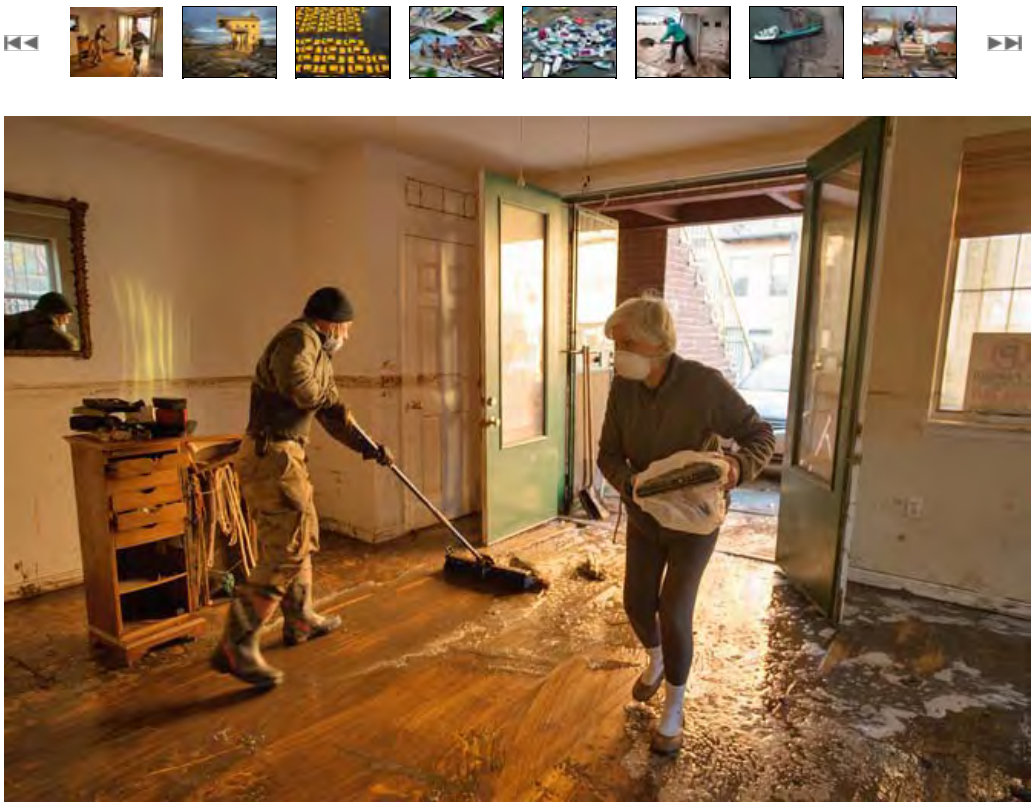
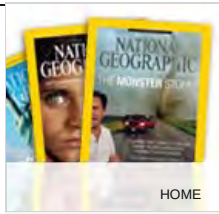


ROCKAWAY PARK, QUEENS, NEW YORK

Photograph by Ken Cedeno, Corbis



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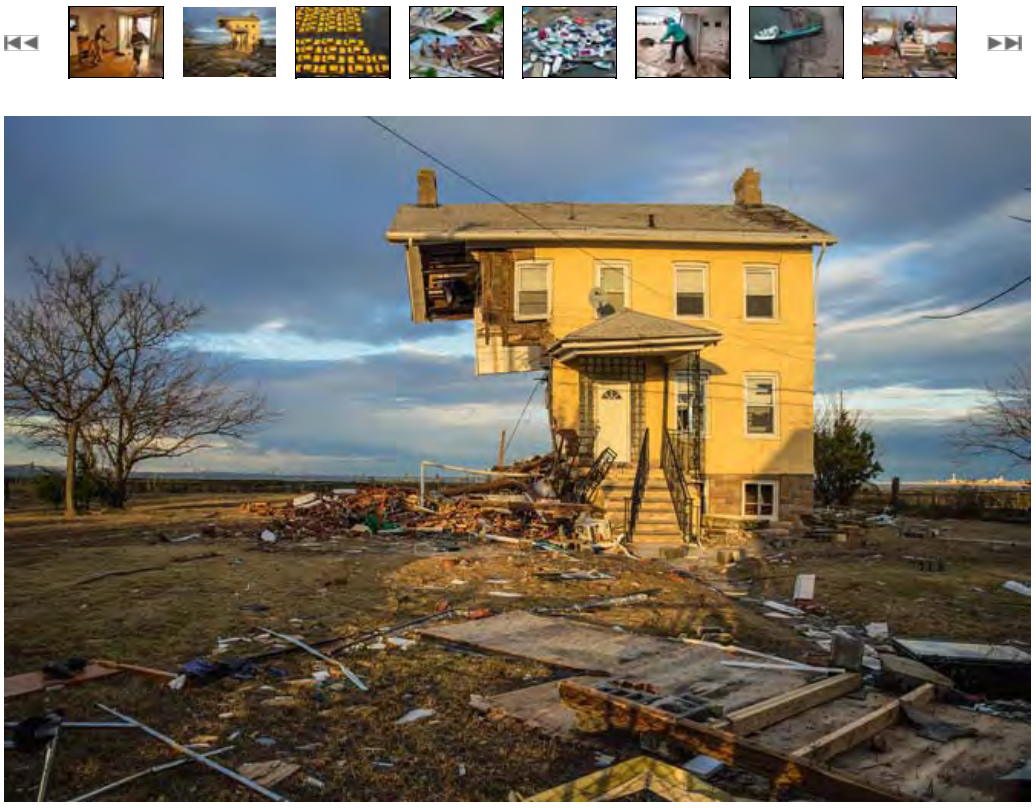
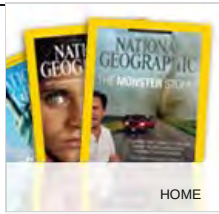


UNION BEACH, NEW JERSEY

Photograph by Ken Cedeno, Corbis



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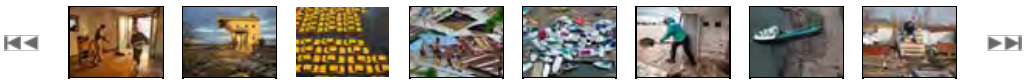
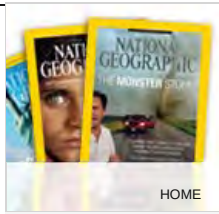


HOBOKEN, NEW JERSEY

Photograph by Charles Sykes, AP Images



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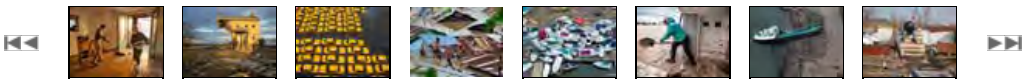
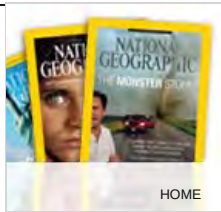


SABANA PERDIDA, DOMINICAN REPUBLIC

Photograph by Ricardo Rojas, Reuters



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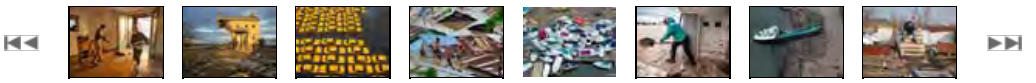

MANTOLOKING, NEW JERSEY

Photograph by George Steinmetz

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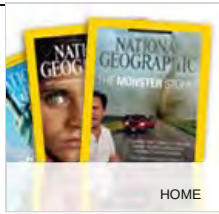

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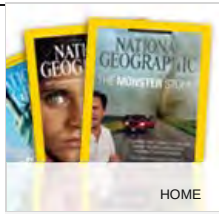
LONG BEACH, NEW YORK

Photograph by Andrew Burton, Getty Images



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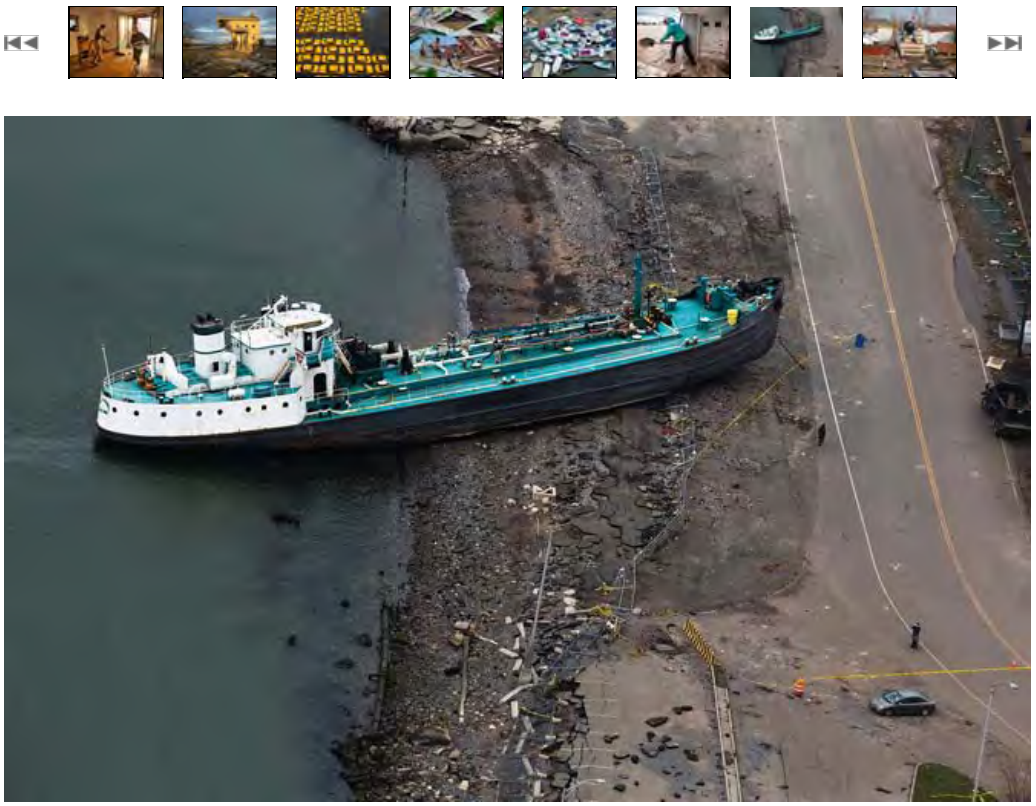
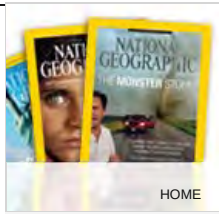


STATEN ISLAND, NEW YORK

Photograph by John Minchillo, AP Images



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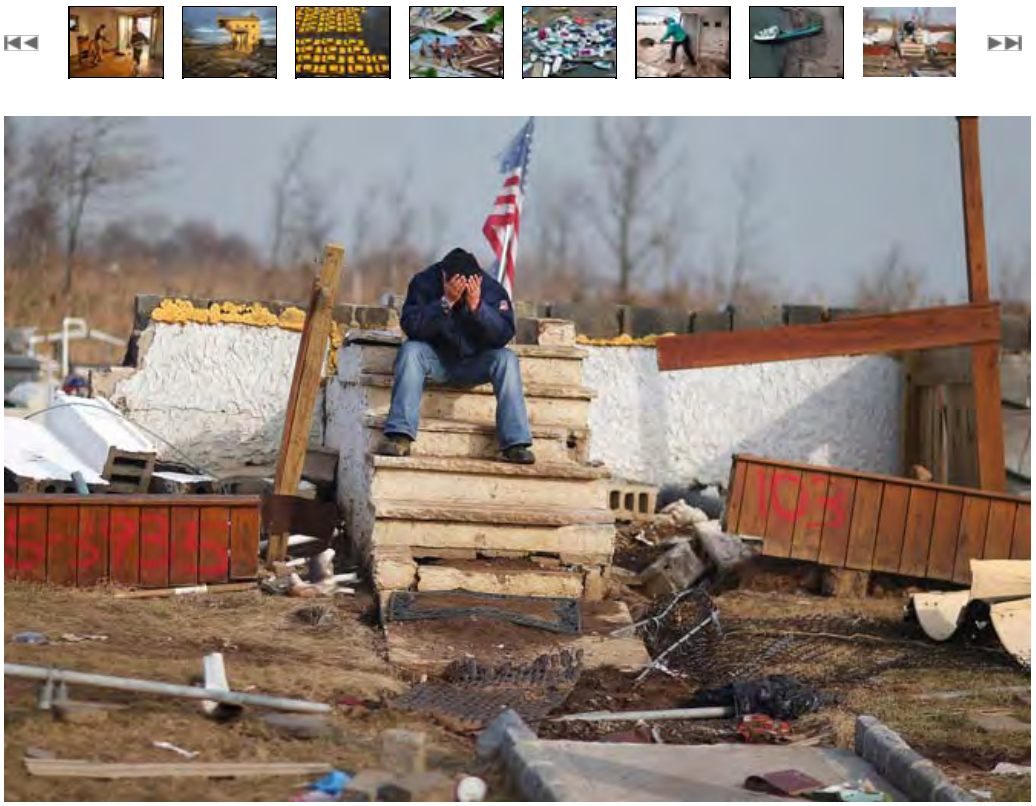

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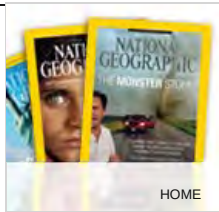
Photograph by Chang W. Lee, New York Times/Redux



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Photograph by Mark Thiessen, NGM Staff

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.”

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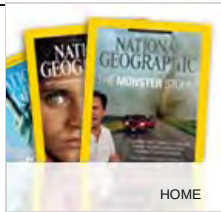
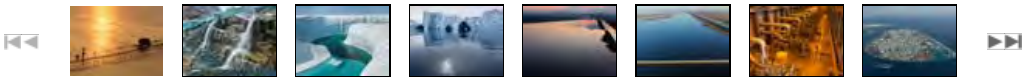


Why the Seas Rise

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.



MANILA, PHILIPPINES

Photograph by George Steinmetz

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

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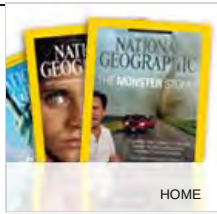

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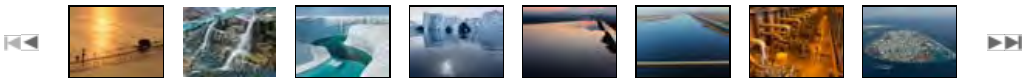
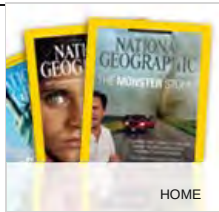


TAHUMMING GLACIER, BRITISH COLUMBIA

Photograph by James Balog, Extreme Ice Survey

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.



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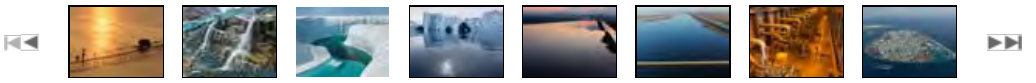
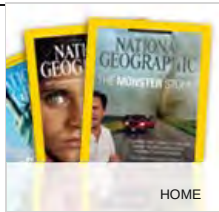


BIRTHDAY CANYON, GREENLAND

Photograph by James Balog, Extreme Ice Survey

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.



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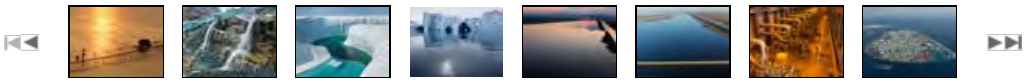
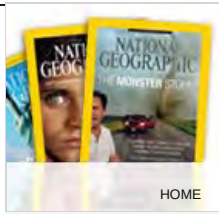


PINE ISLAND GLACIER, WEST ANTARCTICA

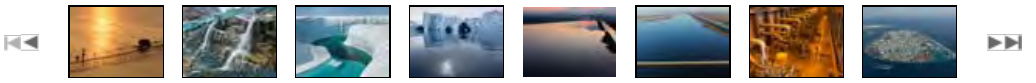
Photograph by Maria Stenzel

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.



Why the Seas Rise

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.



Photograph by George Steinmetz

These cypress trees in a marsh east of New Orleans probably succumbed to salty water seeping in from the Gulf of Mexico even before Hurricane Katrina hit in 2005. But when Katrina's storm surge breached a nearby levee, it dealt a devastating blow to the rest of the marsh.

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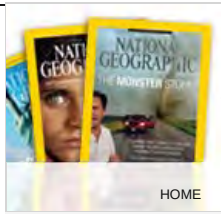

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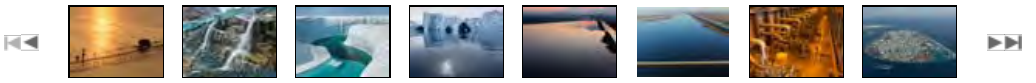
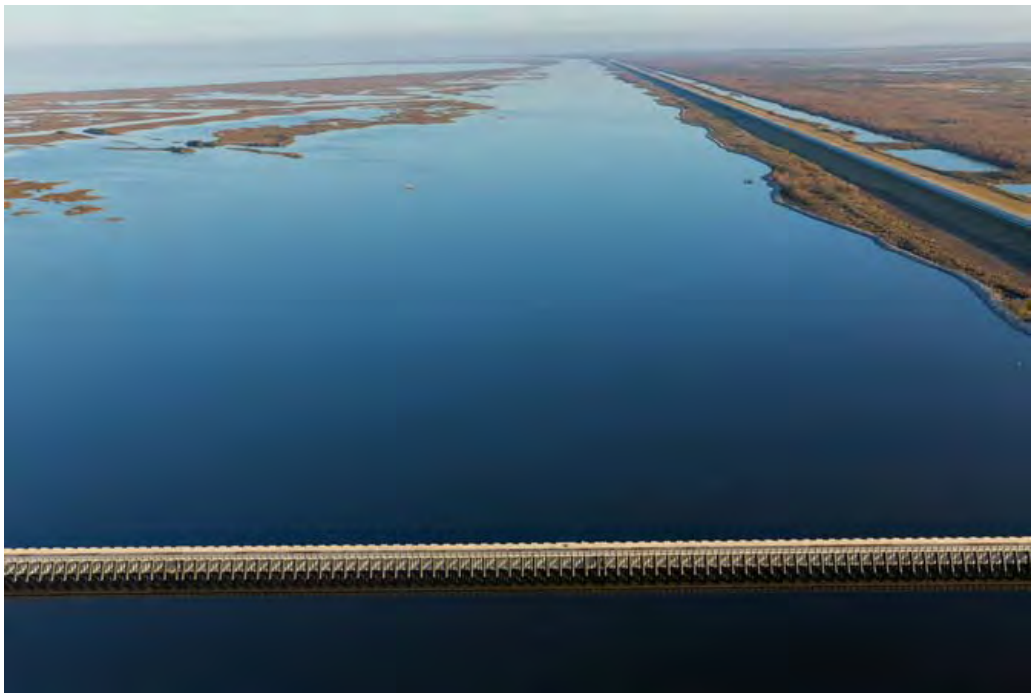
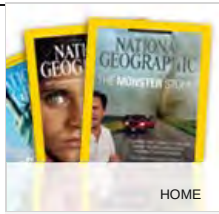




Photograph by George Steinmetz

This abandoned channel, known as MRGO, was once a shortcut for ships to the Gulf of Mexico. During Katrina it became a shortcut to New Orleans for the storm surge. Along with an intersecting channel, the Gulf Intracoastal Waterway, it funneled floodwater into the eastern parts of the city. A new 1.8-mile-long flood barrier now cuts across both channels.



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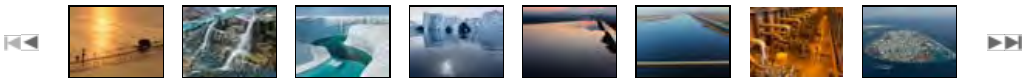

Photograph by George Steinmetz

The 11 diesel pumps housed in another new storm-surge barrier, this one south of New Orleans, can discharge 150,000 gallons of floodwater per second. In operation since 2011, the barrier helped protect the city's suburbs from Hurricane Isaac's storm surge last year.

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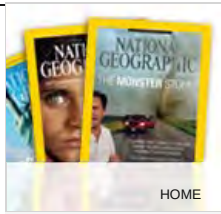

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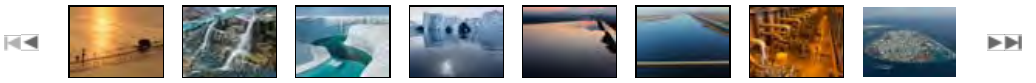
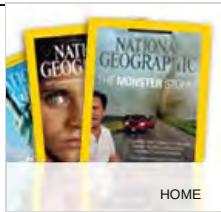


Photograph by George Steinmetz

A seawall now protects Maale, capital of the Maldives, an Indian Ocean archipelago that is the lowest, flattest country on Earth. By 2100 rising seas may force Maldivians to abandon their home. More than 100,000 live



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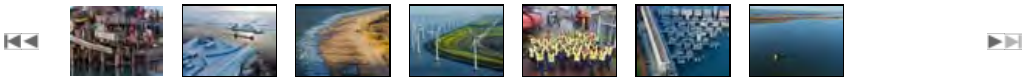
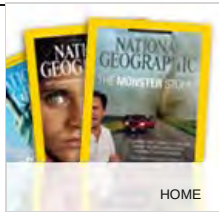


Photograph by George Steinmetz

Dangerously exposed to the next typhoon, squatter families crowd waterfront shanties in Manila, the Philippines. Global sea-level rise is amplified there by rapidly subsiding land.



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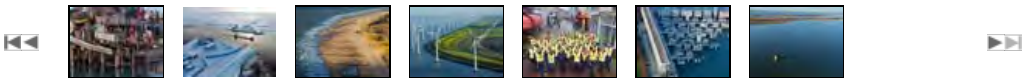
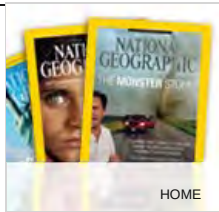


Photograph by George Steinmetz

Two curved steel gates, each more than 350 feet long, can swing shut to protect St. Petersburg, Russia, from Baltic Sea storms, which have flooded it repeatedly over the past three centuries. Completed in 2011, the gates



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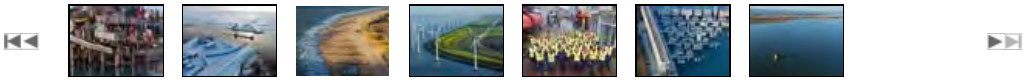

WALCHEREN ISLAND, THE NETHERLANDS

Photograph by George Steinmetz

For nearly a thousand years the Dutch have been reclaiming land from the sea—and occasionally losing some. A catastrophic flood that killed more than 1,800 people in 1953 spurred the country to develop the world's most elaborate and sophisticated system of dikes and other defenses. The most critical structures are built to withstand a 1-in-10,000-year storm. Here, rows of pilings along a Dutch beach trap sand and help build up the

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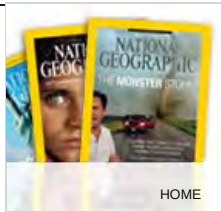

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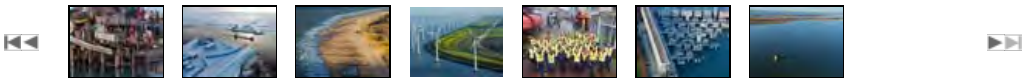

FLEVOLAND

Photograph by George Steinmetz

Flanked by windmills, this dike protects farmland that is almost entirely below sea level. Dikes and continuous pumping keep more than a quarter of the country from reverting to swamp or open water.

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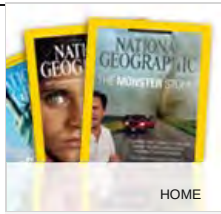

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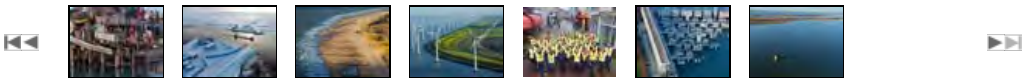

KAMPEN, OVERIJSSEL

Photograph by George Steinmetz

The control of dikes—and the power to levy taxes to maintain them—rests with community water boards that predate the existence of the Netherlands as a nation. These volunteers are trained to contain a breach within three hours.

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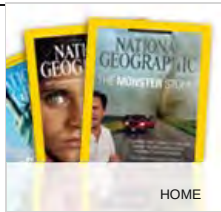

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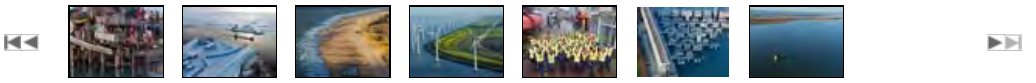

IJBURG, AMSTERDAM

Photograph by George Steinmetz

Small docks and communal walkways link the floating houses built on a lake in east Amsterdam. Secured by sliding collars to steel pilings, the houses can rise and fall during floods and storms.

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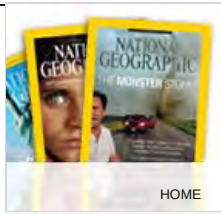

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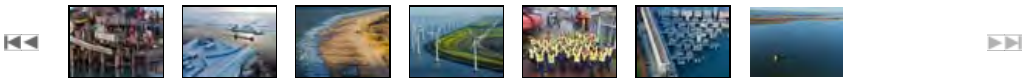

Photograph by George Steinmetz

An abandoned house still stands on Tiengemeten Island in South Holland, where the government intentionally broke the dikes to create a rare slice of wilderness in a country shaped by humans.