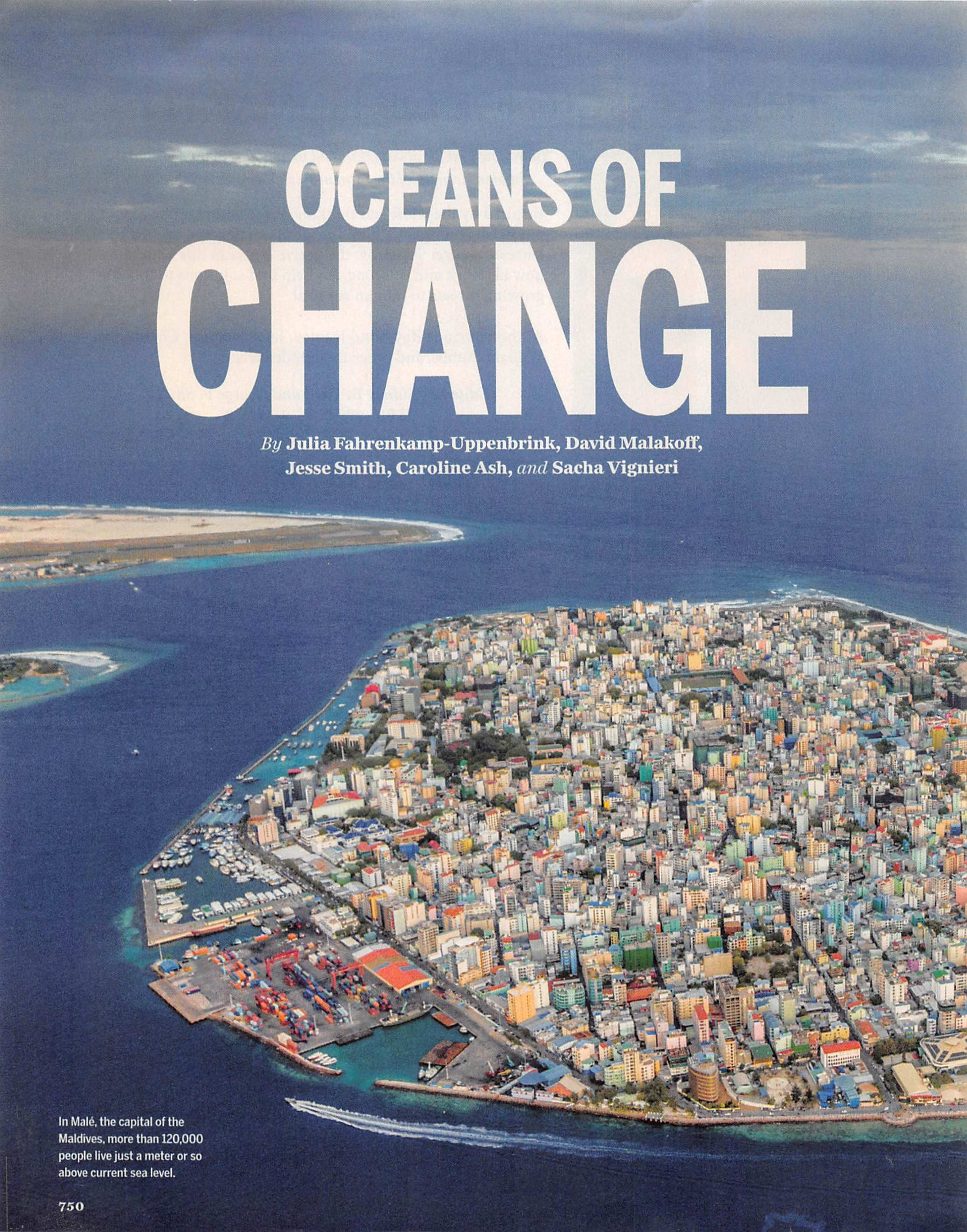
OCEANS OF CHANGE

By **Julia Fahrenkamp-Uppenbrink, David Malakoff, Jesse Smith, Caroline Ash,** *and* **Sacha Vignieri**



In Malé, the capital of the Maldives, more than 120,000 people live just a meter or so above current sea level.

The phrase "climate change" typically evokes thoughts of rising air temperatures or other atmospheric phenomena such as droughts and extreme storms. Much less often do we consider the parallel changes that are occurring in the oceans, despite their extent and importance.

Climate change in the oceans has many facets. One is a rise in sea levels. Scientists are learning about how previous warm periods altered sea levels, and what that past may tell us about the future. To help us cope, so-called green infrastructure, such as planted marshes or oyster reefs, may help protect low-lying shorelines. Climate change is also creating problems for fisheries; for example, commercially valuable stocks move in response to warming seas.

Climate change has caused ocean temperatures to rise, a trend that will continue in the coming centuries even if fossil fuel emissions are curtailed. The uptake of carbon dioxide also makes the oceans more acidic, affecting the ability of organisms to create and maintain calcium-based shells and skeletons. Warm-water corals are particularly susceptible to these effects and may not survive the century unless carbon emissions are greatly reduced. Climate change impacts in the deep ocean are less visible, but the longevity and slow pace of life in the deep makes that ecosystem uniquely sensitive to environmental variability. Marine vertebrates at every depth are being affected, as are humans. Even if international negotiations like those kicking off soon in Paris succeed, we will be coping with the impacts of ocean climate change for centuries.

INSIDE

PHOTO: GEORGE STEINMETZ

GHOSTS OF OCEANS PAST

Ancient reefs and beaches can reveal how high and fast seas rose in the past—and perhaps what the future holds

By **Warren Cornwall**

Studies of fossil coral reefs exposed at an amusement park in Mexico suggest a rapid rise in sea level some 120,000 years ago, during a warm spell in Earth's history.

PHOTO: © KEN GARRETT

Andrea Dutton's hunt for ancient coral reefs has taken her from white sand beaches along the Indian Ocean to wave-beaten cliffs beside the Caribbean. But the geologist's strangest field trip may have come last year, when she spent days at a Mexican amusement park carved from the seaside jungle of the Yucatán Peninsula.

Dutton was not there for the water rides and wild animal exhibits. She had made the trek from her lab at the University of Florida in Gainesville to sample the rocks that the park's builders had cut and exposed: the remains of coral reefs more than 100,000 years old. Dutton was stunned by the star and staghorn corals preserved in the outcrops—including a mosaic of fossils in the walls of an underground room next to a jaguar pen. "It was the most amazing exposure to a reef of that period that I have ever seen, or ever will," she recalls.

Dutton seeks out ancient reefs to understand what's in store for Earth's coastlines. She's one of a small cadre of scientists scouring the planet for evidence of how high the oceans rose when polar ice melted during previous global warming spells. The jaguar pen's fossil reefs, for instance, are providing insight into one past episode of sea level rise, driven by the decline of ice sheets in Greenland and Antarctica more than 125,000 years ago.

Accurately measuring ancient sea levels has proven to be difficult work. But by marrying gritty fieldwork with computer models, Dutton and others are showing with increasing certainty that the sea was many meters higher at times when the past climate was only slightly warmer than today. The results are providing important—and sobering—evidence for how high the seas might climb in the future.

"There are a lot of things I'm uncertain about as a scientist," says Dutton, one of the leaders of PALSEA2, an international effort by scientists to nail down the details of ancient sea levels. "But we're certain sea level is going to keep rising" with the extra heat already added to the climate in recent decades. "And not just a little bit. We've got a long way to go."

TO REACH THAT CONCLUSION, sea level researchers have focused on three periods when fossil and chemical evidence indicates that slight wobbles in Earth's orbit, sometimes abetted by elevated levels of atmospheric carbon dioxide (CO_2), triggered global temperatures that were as warm or warmer than today. Some 3 million years ago, global temperatures were 1 to 2 degrees above modern levels and CO_2 levels were about the same as today's 400 parts per million (ppm). In more recent episodes, some 125,000 and 400,000 years ago, the world was close to today's temperatures, but CO_2 levels were likely far lower, at about 250 to 300 ppm (see graphic, p. 755).

In the early 2000s, when Dutton first began trying to gauge past sea levels during

Geologist Andrea Dutton examines fossil corals, such as these reefs in Florida, as part of her studies of past sea levels.

these periods, some scientists still simply measured how high an ancient shoreline—a beach turned to sandstone, for example, or rocks holding fossils of corals or mollusks—sits above today's sea level. They would date the outcrop, and announce how high the ocean's surface once stood.

The results were sometimes a mess. For instance, when scientists sought to determine what the sea level was 400,000 years ago, shorelines at some sites suggested it was as much as 9 meters higher than today's. But on several islands—Bermuda and the Bahamas—the evidence suggested a difference of as much as 21 meters. The sea could only have risen that high if much of East Antarctica's ice sheet, the world's biggest single mass of ice, had melted. Some scientists doubted that scenario, arguing that the high-standing beaches and corals were a fluke, perhaps created by a giant ancient tsunami.

In fact, a dizzying number of things can cloud efforts to use the past as a crystal ball. The chemical makeup of fossil coral changes over time, making it tricky to calculate its age. There's uncertainty about the depths at which corals grew, complicating efforts to estimate past sea level from an ancient reef's current height above the sea. Ice sheets can be so massive that their sheer gravity drags the ocean's water closer to them; when ice sheets are at their maximum, nearby seas are unusually high, whereas other places are below average, potentially skewing estimates of sea level around the globe. And heavy ice sheets can dimple the crust under them, while nearby land bulges upward. As Jerry Mitrovica, a geophysicist at Harvard University, puts it, Earth "is dynamic, it's evolving. And that's what distorts this lens."

In the last few years, Maureen Raymo, a marine geologist at Columbia University's Lamont-Doherty Earth Observatory in Palisades, New York, has learned just how maddening these complications can be. In 2009, she teamed with scientists from four other universities to figure out how high seas rose during the Pliocene, some 3 million years ago. That's an era scientists are particularly interested in, because CO_2 in the atmosphere then mirrored modern levels. Initially, Raymo expected to gather precise elevation measurements along hundreds of kilometers of ancient shorelines on several continents, adjust for the weight of past glaciers, and then emerge with a fairly precise estimate of sea level.

"That did not happen," Raymo recalls. The measurements were "all over the place."

That's when she learned the importance of one more factor, called dynamic topography. The geologic drama of Earth's tectonic plates is usually associated with earthquakes and fault lines. But massive sections of the planet's crust can also slowly tilt back and forth, rocking like rafts on the ocean. In the United States, for instance, the southern part of the eastern seaboard has been gradually rising relative to the northern part. Ancient shorelines in the southern region may have been uplifted by as much as 60 meters over the past 3 million years, according to one estimate.

For Raymo, that dynamic lift made one of her main research targets—a 900-kilometer-long ancient shoreline running from Georgia to Virginia—nearly unusable. Don't believe "anyone who tells you they know the Pliocene sea level to within 10 meters," she says.

FOR PERIODS more recent than the Pliocene, however, answers are coming into focus with the help of sophisticated computer modeling. In 2012, for example, Raymo and Mitrovica argued that astonishing high-end numbers for sea level rise 400,000 years ago, from Bermuda and the Bahamas, were largely an illusion created by the weight of ice from an earlier ice age. Bermuda and the Bahamas sat on a spot that had bulged upward during the ice age and sank afterward, they concluded. After adjusting for the effect, they pegged sea level at 6 to 13 meters above today's. Since then, observations in South Africa have pointed to an even narrower range of 8 to 11.5 meters, according to a 2014 study in the *Journal of Climate*.

Along with computer models, studies done in places far from the influence of ice sheets have helped to sharpen the view of the past. Dutton, for example, headed to the Seychelles islands, 1500 kilometers off Africa's eastern coast in the Indian Ocean, to survey shorelines from 125,000 years ago. Besides being geologically quiet, the islands have ancient corals that grew vertically up the sides of rocky outcrops, providing a relatively easy-to-read yardstick of changing sea levels. (Then there are the palm trees and the silky soft beaches. "You have to choose your profession very carefully," Dutton jokes.)

Other researchers are trying to directly measure the major contributor to past sea level rise: losses of polar ice. This month, a team led by John Stone, a geologist at the University of Washington, Seattle, is scouting a place to drill into the bedrock beneath ice sheets in West Antarctica's Pirrit Hills. Their goal is to find radioactive isotopes generated by the rock's exposure to cosmic rays. The presence of the isotopes would indicate that the ice had once vanished there, exposing the bedrock. And because the isotopes decay into other elements at a predictable rate, the researchers hope to use them as a clock that shows when the ice melted. "I really do think we're going to end up knowing something significant once we get these cores," Stone says.

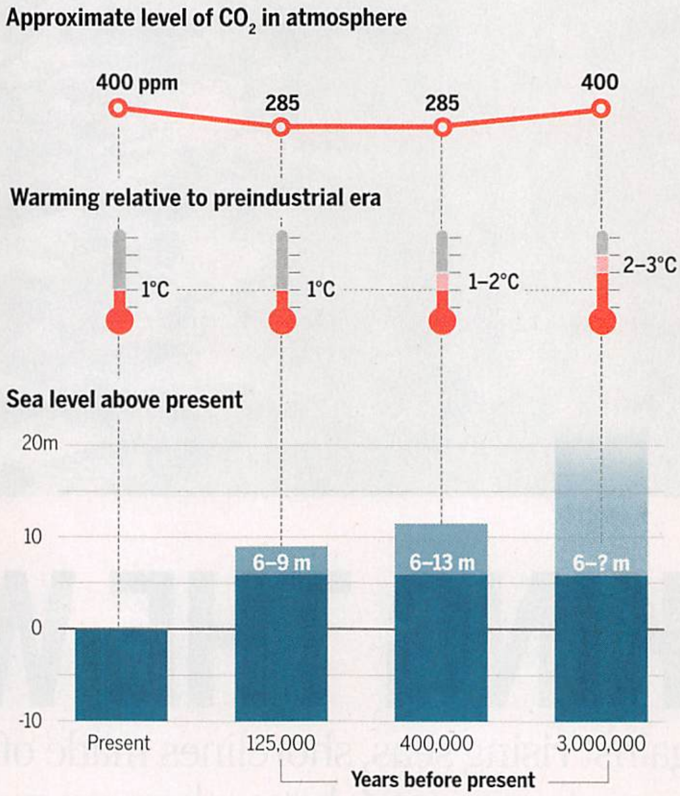
ALREADY, the sea level findings indicate that it may not take much more warming to melt large parts of major ice sheets. Current forecasts suggest a bump of up to 4.8°C by 2100 could lift sea levels by as much as a meter—exposing many coastal communities to serious threats from erosion and flooding. But clues from multiple past warm periods indicate that over time, ice sheets are sensitive to even smaller temperature increases, Dutton says. She was lead author of a study in *Science* this year that noted modern temperatures are close to those 125,000 years ago, when the sea level likely was 6 to 9 meters above today's.

"That suggests ... we've warmed [our climate] so rapidly that the ice sheets are out of equilibrium. And they're playing catch-up," she says.

For societies today, though, the biggest question may not be how high the sea ultimately rose during past warmings, but how quickly it happened. In particular, researchers would like to know answers to two questions: Did Antarctic ice melt in sudden surges and, if so, exactly what climate conditions unleashed such an event?

Looking back

Studies of past periods when Earth was as warm as today, or warmer, suggest that even a few degrees rise can produce a major increase in sea level.



"The biggest question everyone has is, 'How quickly is the West Antarctic Ice Sheet going to collapse?'" Dutton says.

She thinks the fossil reefs in the Yucatán amusement park could help provide answers. A 2009 study of the coral's growth patterns made headlines after it concluded that, some 121,000 years ago, the sea rose as much as 3 meters in less than a century. The surge appears to have drowned one reef, setting the stage for the growth of a second, higher reef, says Paul Blanchon, the study's lead author and a geologist at the National Autonomous University of Mexico's Institute of Marine Sciences & Limnology in Puerto Morelos.

Dutton has doubts about that scenario. She thinks it's possible the estimates were thrown off because the land was sinking as North American glaciers receded.

To get a clearer picture of how fast sea level rose, she would like to return to the Yucatán, as well as to reefs in Australia and Florida. She hopes to drill meters-long reef cores recording past changes in sea levels that can be dated, much as tree rings record past weather. A core where all the coral is close to the same age could indicate that water rose quickly at that time, forcing the coral to grow rapidly upward. A single core with corals spanning thousands of years would indicate a gradual change.

But given the difficulties associated with analyzing fossil corals, don't expect them to produce fine-grained estimates, such as how fast seas rose over a decade or even a century, warns Peter Clark, a geologist at Oregon State University, Corvallis. "We can talk about meters per thousand years, but I don't think we can get it any finer than that," says Clark, one of the two top authors of the Intergovernmental Panel on Climate Change's most recent assessment of sea level science.

Dutton hopes further work in the Yucatán could also help resolve another issue: whether seas rose quickly some 120,000 years ago, after roughly 13,000 years of warmth, as Blanchon has suggested, or soon after the warming began, as she believes. Because the climate varied even during the warm period, knowing the timing could help scientists better decipher what conditions triggered an ice sheet collapse, Dutton says. And understanding those conditions could, in turn, offer clues to the future of today's West Antarctic Ice Sheet, which is already showing signs of an accelerating retreat. "That's why this question—did it happen in the beginning or the end—[is a] first order question now," she says.

Answering it could require studying many more ancient shores, now perched high above seas that are, once again, on the move. ■

Warren Cornwall is a freelance writer in Bellingham, Washington.

GRAPHIC: A. CUADRA/*SCIENCE*

BREAKING THE WAVES

As a defense against rising seas, shorelines made of marsh grasses and oyster reefs may work better than concrete armor

By **Gabriel Popkin** *Photography by* **Dylan Ray**

When Hurricane Irene hit North Carolina's coast in 2011, waves 2 meters high began pounding the shore. Two properties on Pine Knoll Shores, a community on one of the state's many barrier islands, provided a study in contrasts. One homeowner had installed a concrete bulkhead to protect his yard from the sea. But the churning waves overtopped and ultimately toppled the wall, washing away tons of sediment and leaving a denuded mud flat.

Less than 200 meters away, another owner had installed a "living shoreline"—a planted carpet of marsh grass that gently sloped into the water, held in place by a rock sill placed a few meters offshore. The onrushing water bent the marsh grasses almost flat, but their flexing stalks dampened the waves and their deep roots held the soil. After the hurricane passed, the grasses sprang back; the property weathered the storm largely intact.

The contrast highlights how defenses in-