Correction

INNER WORKINGS

Correction for “Inner Workings: Exploring ancient storms in marshes, corals, and caves,” by Danielle Venton, which appeared in issue 12, March 22, 2016, of *Proc Natl Acad Sci USA* (113:3125–3126; 10.1073/pnas.1600798113).

The editors note that ref. 5 appeared incorrectly. The complete corrected reference appears below.

5. Frappier AB, et al. (2014) Two millennia of tropical cyclone-induced mud layers in a northern Yucatán stalagmite: Multiple overlapping climatic hazards during the Maya Terminal Classic “megadroughts.” *Geophys Res Lett* 41(14):5148–5157.

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CORRECTION

Exploring ancient storms in marshes, corals, and caves

Danielle Venton, *Science Writer*

Storms have changed the course of history. In 1274, Kublai Khan, seeking to expand the Mongol Empire, led a fleet of 900 ships and sailed for Japan. After initial victories, the fleet met fierce resistance from Japanese samurai clans. As the Mongols retreated, a strong typhoon hit. Most of the Mongol ships sank and most of the Mongol soldiers drowned along with them. The Japanese samurai attributed the storm to divine forces, dubbing it "Kamikaze" or the divine wind.

Seven years later, Khan tried again, sending more than 4,000 ships carrying 140,000 men. Once more the fleet was destroyed by a great Kamikaze and the Mongols never attempted invading again. But for these storms, the history of the Far East could have been drastically different (1–3).

For many years it was unknown if these accounts had been exaggerated, or even fabricated entirely, as typhoons are extremely rare and unlikely to occur in November, when the invasions reportedly took place. However, in a coastal lake near the site of the Mongol invasions, researchers have found evidence that the Kamikaze typhoons did indeed strike as recorded (1, 2).

Researchers who study ancient storms gather data from many places, whether trawling the historical records, exploring caves, or searching for storm traces in stalagmites. Although the field is relatively young, the study of ancient storms—or "paleotempestology," as it has been coined by Massachusetts Institute of Technology meteorology professor, Kerry Emanuel—has matured and expanded its reach. Researchers are finding increasingly inventive and accurate ways to build timelines of where and when severe storms have occurred. Among those with a keen interest in their findings are those in the insurance industry, looking to better calculate storm risk, and climatologists seeking to understand the effects of climate change.

Surge in Storm Interest

Not long after Hurricane Andrew ravaged the Bahamas, Louisiana, and South Florida in August of 1992, a group of reinsurers (those who ensure the insurance companies) came together and realized they had a research need. "They realized that they basically got burned in Andrew," says Jeff Donnelly, of Woods Hole Oceanographic Institution. "They didn't have good information about the risks of these extreme events that could hit very populated areas. They were looking for other sources of data." Companies reached out to researchers such as Donnelly, asking for estimates of how frequently catastrophic storms hit certain regions. The first few years of Donnelly's work studying the Earth's stormy past was funded by industry.

A graduate student rappels down into a cave in Yucatan, Mexico that can only be reached via a deep hand-dug well shaft. The researchers were looking for stalagmites sensitive to stable isotope records of past hurricanes and climate variability. Image courtesy of Amy Benoit Frappier.

This work helped Donnelly found the field of paleotempestology. As a young researcher at Brown University, he studied sea level rise by examining cores in coastal salt marshes. Donnelly and his colleagues routinely found evidence of past storms: layers of coarse sand among the fine organic sediments. "It was always in the back of my head that was useful information," he says, "but [it] wasn't what we were pursuing at the time."

Donnelly and other researchers date sediment by using signposts: evidence of drastic changes in the landscape that can be tied to human activity. In New England the transition from forestland to grassland following European settlement (1600–1700) can be identified from pollen deposits. Heavy metals showed up via Industrial Revolution pollution, signaling the mid- to late-1800s. Radioactive particles made an appearance in the year 1954 and increased to a peak in 1963, right before the nuclear test ban treaty.

After several years of data-gathering for industry, Donnelly's interests began to morph. "It soon became

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very clear that there was a lot of variability in these long-term records, the statistics of [where storms made] landfall were quite variable," he says. "There were things like climate change going on, so it got more complicated from their perspective, but from a scientific perspective it got much more interesting."

Much of his work still has to do with hazard assessment, although these days his work is more likely to be funded by governmental agencies. One recent paper (4) used sea level records, storm frequency datasets, and storm surge models to evaluate how flooding risk has changed for New York City. Before 1800, floods of two and a half meters occurred about once every 500 years. That has now fallen to roughly 25 years, suggesting that officials must plan for such emergencies.

Uncovering this kind of information is what keeps Donnelly in the field. "This is a very societally relevant problem," he says. "We've got a huge amount of coastal population growth over the past century or so. We've put a lot of people and their belongings in harm's way." One likely aim, he notes, is predicting the impacts of extreme tropical cyclones in the wake of rising sea levels. "The answer is going to matter to quite a few people," he says.

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—Jeff Donnelly

Data Gathering Innovations

Although the field's roots lie in the scouring sediment layers, there are now many ways for paleotempestologists to gather data. A researcher might core one of the marine caverns known as "blue holes" off the coast of the Bahamas or search for phytoplankton (rather than sand) in core samples. Radiotopic studies are also becoming more widespread; tropical cyclones, for example, drop radiotopically distinctive oxygen species in a predictable pattern. The heavier oxygen-18 species tend to fall out first. The lighter isotopes can be detected in tree rings, coral deposits, or karst landscapes, the uneven landscapes carved out in rocks, such as limestone and gypsum.

Amy Frappier, of Skidmore College in New York, does much of her work studying caves in the Yucatan Peninsula. In addition to using stable isotopes to track hurricane rainfall, Frappier and her team also look for evidence of flooding in the profile of stalagmites. "Many of these low-lying caves have a water table that goes up and down seasonally, but when a hurricane comes by it dumps so much rain that it can flood it to the top," she explains. These caves can remain flooded for days or weeks after a large storm passes. "As the water drains slowly, it's like dirty water in a bathtub draining out; it leaves a film of mud over all the surfaces below the water."

For the stalagmites that are still growing, after a storm a little bit of that mud can become trapped inside. "If we take a stalagmite back to the lab and we slice it open with a rock saw we can see that most of the time we're getting these annual layers of calcite that are usually clear white," Frappier says. "But some years when there's a big hurricane, we get a mud layer." By spending many hours in the laboratory counting mud layers, she and her students have detected about 260 mud layers set down between A.D. 400 and 2007 (5, 6).

Already the work of paleotempestologists is helping climatologists refine models to predict how storms are likely to behave in the future. Some models have shown that storms will be both more frequent and more intense (7); some only suggest they'll be more intense. Regardless, modern hurricanes will surely leave a variety of signals for the paleotempestologists of the future.

1 Woodruff JD, Donnelly JP, Okusu A (2009) Exploring typhoon variability over the mid-to-late Holocene: evidence of extreme coastal flooding from Kamikoshiki, Japan. *Quat Sci Rev* 28(17-18):1774–1785.
2 Woodruff JD, Kanamaru K, Kundu S, Cook TL (2014) Depositional evidence for the Kamikaze typhoons and links to changes in typhoon climatology. *Geology* 3(1):91–94.
3 Emanuel KA (2005) *Divine Wind: The History and Science of Hurricanes* (Oxford University Press, Oxford).
4 Reed AJ, et al. (2015) Increased threat of tropical cyclones and coastal flooding to New York City during the anthropogenic era. *Proc Natl Acad Sci USA* 112(41):12610–12615.
5 Munksgaard NC, et al. (2015) Stable isotope anatomy of tropical cyclone Ita, North-Eastern Australia, April 2014. *PLoS One* 10(3): e0119728.
6 Baldini L, et al. (2015) North Atlantic tropical cyclone track migration since 1550 A.D. revealed using a Belizean stalagmite. *EGU General Assembly 2015*. Available at adsabs.harvard.edu/abs/2015EGUGA..1711828B. Accessed January 26, 2016.
7 Emanuel KA (2013) Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proc Natl Acad Sci USA* 110(30):12219–12224.