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After the storm:
How clues from past hurricanes help prepare us for our future

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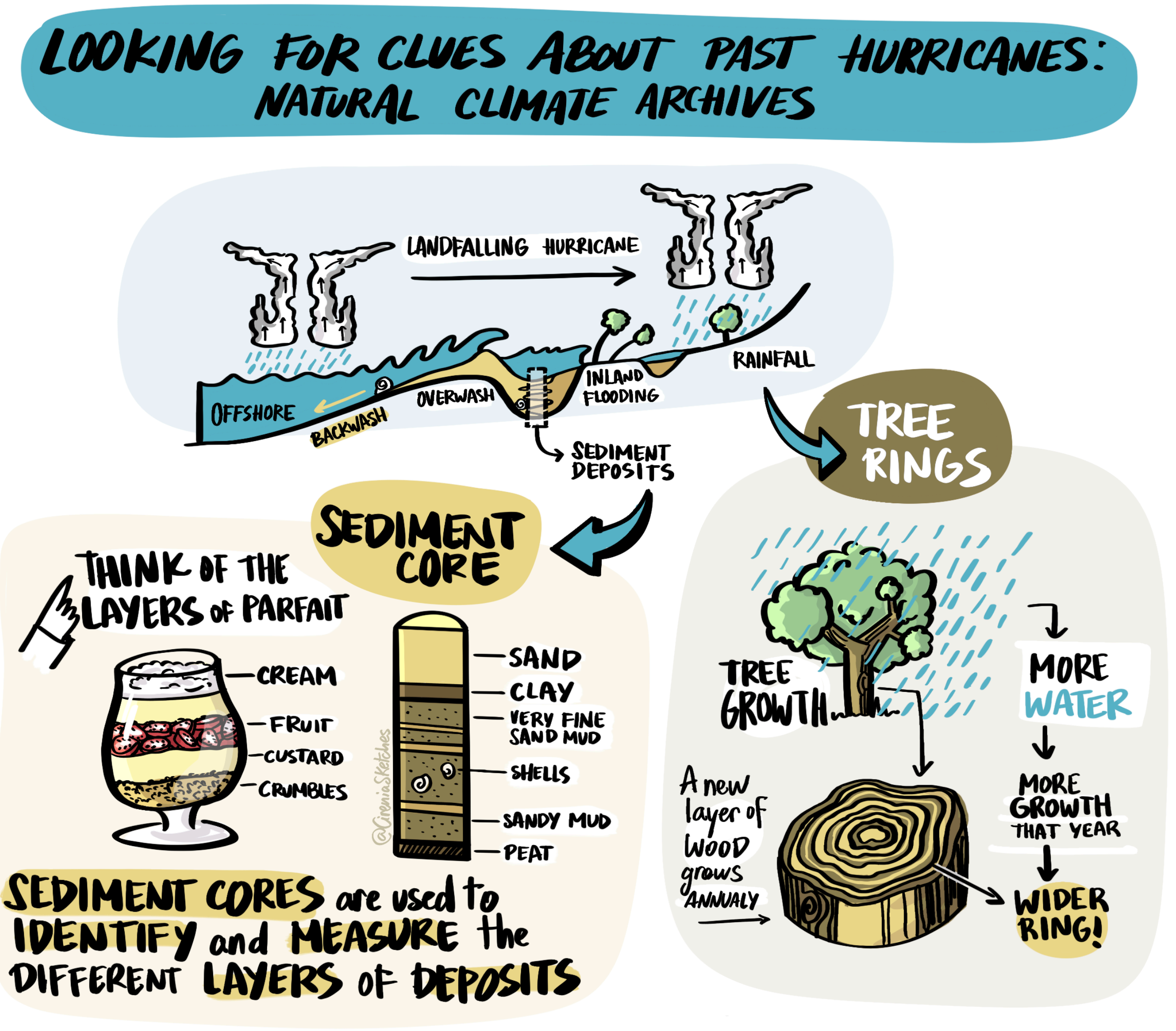
If you were asked to think of devastating tropical cyclones (TCs), a few names likely come to mind: Mitch (1998), Katrina (2005), Haiyan (2013), Harvey (2017), Maria (2017), Dorian (2019), Goni (2020), Ian (2022), and the list continues. While the list seems to be densely populated by the names of infamous storms, the reality is that high-impact events are rare.

The more extreme the storm, the rarer it is. The current instrumental record extends to the 1850s in the North Atlantic, and while that may seem like a long time, the devastation wrought by these storms shows that our benchmark for the worst-case scenario is severely underestimated.

To illustrate this, look at Camille (1969) and Katrina (2005), which struck the same area in Mississippi, separated by only 36 years. If you ask anyone from the area, Camille was the storm that left a painful legacy. The storm surge was catastrophic, and Camille was used as the standard with which to compare subsequent storms for years. However, in 2005, Katrina—a storm that was less intense than Camille at landfall—produced a storm surge that far exceeded that of Camille. This storm scarred the coast and set a new standard for tropical cyclone extremes. This illustrates the point that even in two “extreme” events that share similar categories and locations of impact, no two storms are created equally, and we must do a better job of understanding the drivers of TCs if we want a chance to mitigate their impact.

To this end, the instrumental record has been invaluable in understanding these storms, especially with respect to the internal dynamics of a TC. Unfortunately, these data alone are not enough to fully capture that range of variability exhibited by these systems. This is particularly concerning as we continue experiencing the historically unprecedented ongoing warming trend,



which models indicate will lead to more intense TCs. In the face of climate change, how can we understand TCs and their associated hazards despite a relatively short (and sometime fragmented) instrumental record? The answer is that the best way to look forward is by looking back to extend our records in time using paleoclimate proxies to reconstruct paleohurricanes. This subdiscipline of paleoclimatology, where we use natural climate archives (i.e. proxies) to reconstruct past storm events, is called paleotempestology.

When a TC roars ashore, it brings with it an onslaught of water by both sea and sky. Water is the leading cause of fatalities in a storm, and directly on the coast storm surge is the primary threat. Waves of water rush forward, pummeling the shore as the sea claims everything in its way, a problem only exacerbated by sea-level rise. From the sky comes torrents of rainfall, which brings the effects of a TC inland and can lead to a host of cascading hazards: areal flooding, landslides, sediment and contaminant laden waters, nutrient overloading, eutrophication and even outbreaks of disease. Modeled data indicate that TC rainfall intensity will continue increasing as a consequence of warming. Despite the danger these two hazards (TC surge and precipitation) pose to people, they are the key to understanding prehistoric hurricanes.

TCs are architects of the coast, using storm surge to transport sand, according to the storm's beachside blueprints. If you have ever seen aerial photographs or videos of the beach following a TC, you may have noticed areas where sand has spilled behind the beach, forming a splay of sand that breaches into the vegetated, marshy, or lagoonal area behind. As the storm approaches, the sand is picked up and transported inland by increased wave energy as the ocean churns. The larger the storm surge, the greater the capacity for sand movement as it washes up and over the shoreline, and moves inland. When the wave energy subsides, that sand is deposited inland, essentially leaving a geologic fingerprint of the storm. If we are lucky, the sand transported by the surge will be deposited in a coastal lake, lagoon, estuary or marsh, where it will be buried by the fine-grained background sedimentation of the relatively quiescent environment. Think of it like a parfait: the yogurt or custard acts as the primary feature of the dish (background sediment like mud) with crumbled coarse bits of fruit or granola in different, defined layers interspersed throughout (sand deposits). We can then take a sediment core to identify and measure the different layers, similar to the way you can identify the layering of the parfait when it is in a glass. The observations that we obtain from these sediment deposits provide important information regarding the frequency of TCs. Moreover, if the sediment core contains a deposit from a modern TC, like Camille or Katrina, we can use that storm as a metric with which to compare previous events. By analyzing both the sediment from the paleohurricane and the modern storm, we can estimate storm surge height that would be required to deposit both layers of sediment, which can then help us understand how intense TCs were in the past. We can then use this information to assess the pre-industrial and pre-anthropogenic influence of TCs along our coastal zone to truly assess how storm intensity is increasing with warming temperatures and overall climate change. This information is critical for understanding the frequency and intensity of future storms and how we can prepare for such events.

The effects of a TC, however, are not restricted to the coast. Farther inland, rainfall from TCs can bring a host of other hazards, especially flooding. While the risks associated with TC rainfall will continue to increase in response to warming, it remains a critical part of regional hydroclimates and is an important water source for ecosystems. Unlike storm surge, which reworks sediment and makes a deposit, identifying the signature left by rainfall is much more subtle. TCs are an important source of water for trees, especially in areas where the soil properties allow water to drain quickly. The large volume of water produced over a period of 2–3 days raises the water table, which trees are then able to readily access and grow. As trees produce a ring every year, thereby providing an absolute date, it is possible to reconstruct the amount of TC rainfall for a year by measuring the width of a ring. Just like people, trees need water to live. More water means more growth, i.e. wider rings, so scientists studying tree rings, or dendrochronologists, can see past hurricanes by looking for thicker rings. Essentially, tree rings can act as a weather station that can exclusively capture TCs. Measuring ring width is just one way to reconstruct TCs using trees; the presence of unusual growths in the ring, like false rings, and the chemical signals in the wood has also been shown to indicate the occurrence of a TC in the past. Because we can correlate different trees in the study area expanding through different age ranges, like different pieces of a puzzle, this technique can be incredibly useful for understanding the larger picture of regional storm patterns. Presently, longleaf pine and baldcypress have been important species for TC reconstructions, though other tree species are under examination for their use as paleohurricane archives.

These two environmental indicators, or proxies, have have been invaluable for extending the storm record and understanding TCs and their response to climate change. However, there are several important caveats that must be addressed if we want to have a full understanding of the TC climate. Both sediment cores and tree rings have their strengths and weaknesses that make it difficult to connect them with one another. Two particular issues come to mind: First, there is an issue of temporal resolution. Tree rings produce a ring every year, and depending on the species, it is possible to sample at seasonal timescales. Conversely, sediment cores typically have a much coarser resolution, with annually resolved records being rare. Further, tree-ring records are shorter than sediment records, largely due to logging practices and the low preservation potential for fallen trees. While some of this can be resolved by relying on wood samples from historical structures, it remains difficult to reach the same record length as sediment cores. Second, the proxies are responding to different components of a TC, which have different thresholds at which they are recorded. For example, a particularly intense storm may be required to create an overwash deposit, whereas a tree will generally respond to TC rainfall regardless of storm intensity. Conversely, it is typically easier to identify individual events in sediment records, whereas trees may amalgamate multiple TCs into a single ring.

While challenging, with an appropriate understanding of what each proxy archive is recording (e.g. TC precipitation in trees vs. TC surge from storms) and statistical rigor, modeled reconstructions of past TCs using both sediments and trees has remained an area of active research in paleotempestology and shows promise in the development of more well-rounded records of TC frequency and intensity through time. Furthermore, with new records coming out every year, we are another step closer to better understanding how TCs change with the climate system. Of course, this work is meaningless if we do not use our results to help shape policies and develop infrastructure designed to create resilient communities and address social and environmental justice issues in the face of climate change. **So, while paleotempestology provides a critical role in looking to the past to contextualize present storms, we must integrate this work into the larger context of working with coastal managers, engineers, policy makers, social and environmental advocates, and most importantly, coastal communities, to build an equitable, sustainable future for our coastlines in the midst of a rapidly changing world.**