CLIMATE TALES

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CURRENT AND FUTURE climate change necessarily preoccupies much of our attention. But human perception of climatic variation is imperfect and unreliable. Extreme events such as summer heat waves, abnormally cold winters, and major storms loom large in our memories. Our perception and recall of slow environmental change are less precise. As individuals, we have a limited capacity to perceive the one degree Celsius of global warming that has taken place over the last century, nor can we appreciate the significance of this change for global climate and ecosystems. Limitations in our perspective help explain our inertia when it comes to mitigating and adapting to a shifting climate. To understand the potential impacts of ongoing environmental change, and to imagine our potential future, we must turn to the physical, nonhuman memories of past climates. Written in the oceans, land, and ice sheets of our planet, these archives bear silent witness to the massive environmental changes that have occurred on Earth over geological time.

Earth's climate is shaped by complex interactions among the atmosphere, oceans, land, and ice, which are governed by the fundamental laws of physics and chemistry. These components of the climate system operate on vastly different time scales. For instance, gases, liquids, and solids have different viscosities, meaning that air, water masses, and glaciers move at different rates. Molecules in the atmosphere can be transported over thousands of kilometres in the span of days, whereas an ice sheet will creep forward only a few metres per year. Chemical processes likewise occur at different rates. The reaction time of aerosol formation can be less than seconds, whereas the chemical weathering of silicate rocks and the dissolution of deep-sea minerals, both critical to the uptake of atmospheric carbon dioxide, stretch out over millennia. These different physical and chemical processes occur simultaneously, leading to a complex system in which long-term and short-term events can be recorded at the same time. We can look to the geological past to see evidence of massive glaciations that occurred over tens of thousands of years. We can also see evidence of shorter-term climatic events associated with the eruption of a volcano and the release of ash plumes into the stratosphere. Much as in our own human memory, these long- and short-term memory traces can interact with one another in complex and sometimes surprising ways. Consider, for example, short-term variations in weather. A specific weather event at a particular location will not be "remembered" explicitly by the climate system for more than a few weeks. Owing to atmospheric turbulence and mixing, air masses quickly lose the characteristic signature of previous physical states, leaving no detectable trace of past weather conditions.

Devastating winds associated with a hurricane, fuelled by an oceanic heat source, dissipate quickly as the air mass moves over land. Within several weeks, we can no longer accurately trace the storm's trajectory or reconstruct its prior temperature, wind speed, or other properties. The destruction brought on by a storm will thus last far longer than that storm's physical presence within the climate system. We can understand longer-term weather patterns from the statistical average of many individual events, but predicating a single weather perturbation eludes us. For this reason, we can make projections about the average frequency and intensity of hurricanes on a warming planet over years and decades, but we can't accurately forecast the trajectory and characteristics of a storm more than a few weeks into the future.

Earth's climate system may have a fickle short-term memory, but its long-term climate history has been recorded and stored in multiple ways. During the last glacial period, about twenty thousand years ago, Earth's climate bore little resemblance to what we experience today. Average global temperatures were five degrees Celsius colder, and enormous ice sheets covered Canada and Scandinavia. These large ice masses, up to four kilometres thick in some places, modified the shape of the planet as they pressed down on Earth's surface with their enormous weight. After the glaciers retreated, about ten thousand years ago, Earth's surface began to rebound back towards its original shape, much like a foam mattress after the weight of a body has been removed from it. This isostatic rebound is ongoing today and can be measured accurately, with rates exceeding one centimetre per year in extreme cases. This process helps explain the complex patterns observed in sea level changes across the planet. There is no doubt that global average sea level is now rising approximately three millimetres per year because of global warming, which causes the thermal expansion of sea water and the melting of mountain glaciers and ice sheets in Greenland and Antarctica. But we can't understand the actual patterns of sea level change in any particular location without taking into account traces of Earth's history as a glaciated planet. For example, the sea level along the US East Coast has risen significantly faster than the global average, while other regions in the tropical Indian and Pacific Oceans exhibit lower than average rates of sea level rise. In areas close to former ice sheets, including Hudson Bay and the Baltic Sea, sea levels are actually decreasing because of the isostatic rebound of the land surface, providing a detectable physical memory of past glaciation.

Earth retains memories of its distant past in more direct ways. Atmospheric temperature variations affect surface ocean temperatures, which are then transferred into the deep sea by the vertical mixing of water masses and large-scale ocean currents. It can take up to two millennia for surface water to reach the bottom of the north Pacific, and over this long period the temperature of a water mass will remain largely unchanged. This means that the present-day temperature of the deep Pacific Ocean reflects atmospheric conditions during the early days of the Roman Empire. Ancient ice sheets likewise hold memories of past atmospheric temperatures. Precise measurements in the Greenland ice sheet have shown that evidence of the cold atmospheric temperatures of the last glacial period still resides about two kilometres beneath the surface. This temperature memory is slowly diffusing away but, assuming that climate stays stable, it will take tens of millennia for the ice at these depths to reach thermal equilibrium with the overlying atmosphere.

The history of Earth's climate is thus written all around us, in deep ocean waters, in sediments, and in glaciers. The challenge is learning how to read this memory, to understand its implications for the present and to preserve the record for the future. Unfortunately, we haven't been collecting observations for long. Atmospheric temperature measurements go back only to the eighteenth century. Data for oceanic temperatures and sea level reach back no farther than the nineteenth century. And these data are strongly biased towards Europe and North America. In some cases, scientific measurements can be supplemented by Indigenous oral histories, but they too are geographically limited and only go back about ten thousand years, at best. We need a longer history.

To go back farther in time, and to improve the geographic range of observations, climate scientists have developed paleoclimatic indicators – so-called climate proxies – that can be measured in a wide variety of natural archives, including glaciers and ice sheets, groundwater, sediments, stalagmites, fossil corals, and ancient trees. To establish a link between a proxy measurement and a climate fact, scientists apply what they know about chemical thermodynamics or the biological adaptations of various organisms, whose remains may be preserved in the geological archive. The science of geochemistry and biology can help us interpret the ancient signatures we find in various Earth system archives. Admittedly less precise than instrumental data, climate proxies can nevertheless generate valuable information about the past when applied with care. They are the only means at our disposal to recover historical climate features and examine the Earth system's deep memory.

Like other forms of memory, the information held in climate proxies can disappear or be distorted over geologic time. Paleoclimate studies must therefore be highly redundant, and scientists typically measure several proxies in the same archive and use different archives to reconstruct a local climate record. Like a jury in a criminal trial, we must arrive at our best guess of the truth by reconstructing multiple lines of evidence from different sources and sites. As an example, consider the use of isotopic thermometers in polar ice caps, which are based on measuring small changes in the relative abundance of different isotopic forms of oxygen and hydrogen in the water molecules of different ice layers. These signatures reflect atmospheric temperatures around the time when snow accumulated on the ice cap, building up each successive layer of ice laid down in a chronological sequence.

In the early 1990s, Europeans and Americans raced to drill adjacent sites on the summit of the Greenland ice sheet. Within the top three kilometres of the ice core, the two isotopic temperature records were nearly identical, showing abrupt and repeated climate shifts over the past hundred thousand years of Earth history. Below this depth, however, the two climate records, each from a slightly different site, diverged significantly, particularly in the oldest sections of ice. In hindsight, we know that these disparities reflected local melting of the deep ice, influenced by geothermal heating, that led to complex folding and mixing within the ice sheet. This physical distortion of the ice core record significantly complicates how we interpret the various proxies and must be taken into account if we are to arrive at a correct understanding of past climate history. And other examples of memory distortion reside in various climate archives. Sediments can be mixed, homogenized, and transported, disturbing the natural layering that we use to infer a chronology; minerals can be dissolved and then reformed, altering the chemical composition from which we derive the climate record.

An extreme example of geological memory loss and distortion has unfolded over the past few decades. The ice of low and mid-latitude mountain glaciers, such as those on Mount Kilimanjaro in Tanzania and in the South American Andes, houses a significant repository of climate memory. In the last half of the twentieth century, these glaciers began to rapidly disappear, and it's highly probable that most will be gone before the end of this century, taking with them the climate history encapsulated in their frozen archives. The international Ice Memory project, launched by French and Italian scientists in March 2017, aims to create the world's first library of archived glacier ice as a "scientific heritage for generations to come." The project has already collected ice cores on Mont Blanc in the French Alps and on Mount Illimani in the Bolivian Andes. These cores will be shipped to central Antarctica, where they can be maintained indefinitely, frozen without electricity or other significant infrastructure, thereby creating an archive of Earth's climate history.

Science can help us supplement, store, and restore our failing memories about Earth's climate. It allows us to identify the climatic causes of events that affect human societies such as food shortages, large-scale epidemics, or even wars. We need to document and understand past environmental changes as they are remembered in the materials of the Earth, working against our human tendency to either not notice or simply forget.