Connectedness: an incomplete encyclopedia of anthropocene
views, thoughts, considerations, insights, images, notes & remarks
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An Incomplete Encyclopedia of the Anthropocene

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A mechanical memory of past climates

The aim of ice-core research is to document the past, understand the present, and predict the future. Current interest is focused on the development of methods for ice-core dating and synchronization, as well as the analysis of climate and isotope records from a wide variety of ice cores. The research is based on the assumption that scientists have taken advantage of this nature archive of snowfall. With a method originally conceived by Danish physicist Willi Dansgaard, Danish-Icelandic physicist Sigfus Johnsen, and their colleagues at the University of Copenhagen, Denmark, scientists drill through the kilometre-thick ice sheet and retrieve a cylindrical rod of ice, an ice core, and perform measurements that reveal past climate conditions. Subtle variations in the ratio between the isotopes of the hydrogen and oxygen atoms that make up the ice molecules reflect past atmospheric temperatures around the ice-core site and document climatic changes on all scales: at the surface, the differences between winters and summers are clearly detectable, and half-way to the base of the ice sheet, the isotope-based temperature reconstructions show how the Greenland climate changed from glacial to interglacial conditions 11,700 years ago. Ice sheets are among the cleanest reserves of water on Earth, but still the ice contains miniscule traces of volcanic eruptions, forest fires, dust storms and other processes that pollute the atmosphere with tiny particles that end up in the snow. While the isotopes of the ice itself reveal past temperatures and the minute impurities in the ice can tell their story, the ice also acts as a sample container for the tiny bubbles of air that were once formed from the ambient air during the transformation of snow to ice. By melting or crushing the ice samples in the laboratory, this air is released and analysed to reveal how the atmosphere’s composition has changed across the wide range of climatic conditions of the past. Ice cores from different regions have different times particularly well, and by piecing these records together carefully, scientists have re-constructed climatic variations year by year 60,000 years back through our current interglacial period, the Holocene, and halfway into the glacial. Even when the annual layers are no longer discernible, the ice cores still document climatic changes in outstanding resolution. The longest Greenland records go back 128,000 years, while the cores from Central Antarctica reach even further back and cover many glacial-interglacial cycles due to the very sparse snowfall on the East Antarctic Plateau. When tied together by layers of tiny volcanic glass particles found in several ice cores and variations of methane in the bubbles that are common to all ice cores (because the bubbles were formed from the same atmosphere), the ice cores form a comprehensive set of records of both greenhouse-gas concentrations and past climate changes as manifested in the high southern and northern latitudes over more than a full glacial cycle.

The records from the Greenland and Antarctic ice cores allow us to place the recent changes in climate and greenhouse-gas concentrations into a perspective that reaches far beyond historical records. Continuous monitoring of the atmospheric composition only commenced about six decades ago, and accurate thermometer measurements go back at best a couple of centuries. Further back, climate-relevant information can be inferred from historical records, which document local and regional climate variations, sometimes with large impact on past societies. The ice cores paint a picture of more radical climate change, with the last major global shift taking place 18,000 to 11,000 years ago, more than twice as far back in time as the earliest written records of any civilization on Earth. To find the ice in the Greenland Ice Sheet that originated from snow that fell on the surface 18,000 years ago, we would have to drill to more than a kilometre and a half below the surface, and each annual layer would have thinned to just a centimetre or two. However, the layering is intact, and from the isotope ratios in each layer we can extract an

**An ice-core perspective**

Snow falls, flake by flake, on the vast, flat, cold and empty surface of the Greenland Ice Sheet. On a clear summer day, some flakes turn back into vapour and escape back into the atmosphere, and winds may move the uppermost snow around, but most of the snow settles and is covered by another layer of snow. Layer by layer, year after year, the snow is gently but relentlessly compressed by the burden of the younger snow. The snow crystals are first rounded and then start to grow together, and meanwhile most of the air between the crystals is squeezed out. Two hundred years after the snow originally settled on the surface, the snow is buried under 58 metres of layers of later snowfall, and the compression has reduced the volume of the original snow to less than a fifth. One cubic metre now weighs 800 kilograms, and in the space between ice crystals, atmospheric air is enclosed and forms tiny bubbles that will remain unaltered as the ice is compressed further and makes its way into the deep, cold interior of the ice sheet. A snowflake falling near the crest of the Greenland Ice Sheet may continue its journey towards the bedrock in ever-thinning layers for hundreds of thousands of years, or it may end up flowing slowly towards the edge of the ice sheet, just to return to the ocean as meltwater or in an iceberg.

Sune Olander Rasmussen (born 1974, located in Copenhagen, DK) is an associate professor at the Niels Bohr Institute, University of Copenhagen. He holds a PhD in Geophysics and works with ice-core research. He is mainly interested in the development of methods for ice-core dating and synchronization, as well as the analysis of climate records from a wide variety of palaeoclimate archives with the aim of understanding the governing mechanisms of past abrupt climate changes.
Despite the obvious differences between cores show regional variations, and in particular show that the polar regions warmed more than average, Earth as a whole reacted to small and slow changes in the amount and distribution of energy from the Sun and warmed by somewhere around 6 °C on average. This change was not likely initiated by CO₂, but the ice cores show how CO₂ concentrations rose together with – or were slightly lacking after – the temperature over many thousands of years and was most likely closely tied to temperature via positive feedbacks, involving, among other processes, the exchange of CO₂ between the atmosphere and ocean. The impact was dramatic: the large ice sheet that covered North America all the way down to the Great Lakes melted back and eventually disappeared, and ice caps covering the British Isles, Scandinavia and northern Siberia all decayed and left nothing more than a few mountain glaciers.

The global ocean rose on average 120 metres due to the meltwater from these immense amounts of ice, and even today Earth's crust is still adjusting to the removal of the enormous load of the now-vanished ice sheets. Despite the obvious differences to today's situation, the observed climate change since the onset of the Industrial Revolution shares essential features with the glacial-to-interglacial transition: the changes were gradual and relatively smooth in most places, the CO₂ concentration changes were of a similar magnitude, and because the greenhouse-gas concentrations played such a large role, no region on Earth was unaffected.

Drilling a few hundred metres deeper into the Greenland ice, we find repeated evidence of climate change of a radically different nature. During most of the glacial period, which lasted about 100,000 years, Greenland did not experience stable glacial climate conditions for more than a few millennia at a time. Instead, the same pattern of climate change interrupted the cold glacial conditions about 30 times, and although the duration of these interruptions varies widely, they share so many features that they have been given a common label: the Dansgaard-Oeschger events. Each event starts with an abrupt warming of typically around 10–15 °C in Greenland and takes place over a few decades, after which the temperature drops more slowly for a while before returning abruptly to the cold glacial level. The Greenland ice cores do not provide many direct hints about the reason for these extreme changes, but when compared to similar records from Antarctica, a persistent pattern emerges: within a century or two after the abrupt warming sets in over Greenland, Antarctica starts cooling gradually, and conversely Antarctica starts warming slowly after Greenland has returned to its cold state. Records of the ocean circulation from ocean-floor sediment cores show variations that to the best of our knowledge appear contemporaneous with the changes observed in the polar regions, and climate models suggest that the climate of the hemispheres was coupled via the ocean heat transport. This interpretation is known as the ‘bipolar seesaw’, as it involves a seesaw between the North and South Atlantic. When the northward heat transport in the Atlantic is strong, heat is drawn away from the South Atlantic and exported to the high-latitude North Atlantic by oceanic and atmospheric currents, causing Greenland to experience relatively warm conditions while the interior of the Earth's other oceans and the southern hemisphere slowly is losing heat, leading to gradual cooling in and around Antarctica. When the ocean heat transport is relatively weak, the opposite scenario occurs, which again is in full agreement with the ice-core evidence. What causes the ocean circulation to change strength abruptly is still not fully understood, although it seems clear that the amount of fresh water added to the ocean, sea-ice dynamics and variability in both wind and ocean currents play important roles. Greenhouse gases, on the other hand, do not vary enough, and especially not fast enough to play a main role for these changes. While the exact mechanisms behind the changes are still not fully known, it is thus clear that the Dansgaard-Oeschger events represent a different type of climate change than the gradual climate change of the glacial transition and the current warming: the main mechanism of the Dansgaard-Oeschger events was an abrupt change in the redistribution of heat that occurred when the climate system reached a threshold that allowed it to shift from one mode to another.

What is the relevance of Dansgaard-Oeschger events for the current and future climate situation? Although Dansgaard-Oeschger events proper were a glacial phenomenon, they are indirectly relevant to us because they demonstrate a type of variability that has occurred naturally and thus serves as a training ground for climate scientists and the computer models used to describe the most important physical processes in the climate system. They also directly exemplify that when Earth's climate is in a state that is prone to change, it does not take much forcing to initiate a sequence of events that leads to dramatic climate changes, potentially with regionally highly heterogeneous manifestations.

During the Dansgaard-Oeschger events, particularly Greenland and Northern Europe experienced climate change on a scale that would probably have rendered all human adaptation strategies except migration infeasible. It does not seem likely that we will see Dansgaard-Oeschger events in the foreseeable future, but the physical governing mechanisms of the events can also lead to changes on smaller scales, and there are other elements of the climate system that are able to exhibit abrupt changes and could be triggered by humanity's alterations of Earth's surface and atmospheric composition. I therefore find it worth considering if just a small increase in the risk of large-scale abrupt climate change is not just as worrying and thus merits just as much action as the gradual and relatively well-understood climate changes that we are already observing and must expect based on projections of future climate.
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