From ice and permafrost to water and degrading ground: Changes in the cryosphere, as a result of global warming, accelerate the disappearance and thermal transition of cryospheric materials.

Research in Earth's frozen wastelands

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Earth's cryosphere is shrinking. The cryosphere is the frozen part of our planet that is covered by solid water and where ground temperature remains below 0°C for at least some part of the year. From the North to the South Pole, as well as on the highest altitudes, scientists have recently observed the seasonal snow cover decreasing, the permafrost thawing, and the ice retreating.

The cryosphere is not only a unique habitat for life and a key resource of food and freshwater. Snow and ice in glaciers and ice caps help the planet to maintain its energy balance by reflecting 80–90% of the incoming solar radiation. Furthermore, permafrost, defined as ground with temperature below 0°C for at least two years, and which in total underlies an area nearly twice the size of the United States, has acted for millennia as a carbon sink.

Changes in the cryosphere, as a result of global warming, accelerate the disappearance and thermal transition of cryospheric materials. Ice melting creates a greater risk for floods and droughts, posing an existential threat for coastal cities, and thawing permafrost releases microbes that can degrade organic carbon and generate greenhouse gases. But more than a future threat, shifting and cracking permafrost is currently the force behind the crumbling of structures in Arctic cities.

"For countries with a lot of permafrost, such as Russia, US, Canada, China, and Greenland, the geotechnical consequences permafrost thaw has, and its adverse effects on vital infrastructure are a very important concern," said Julian Murton, professor of permafrost science at the University of Sussex. "Permafrost can form in soil, rock, concrete, brick, metal. As ice-rich permafrost warms and thaws, this may cause subsidence that can lead to cracking and collapse of buildings and roads or buckling of pipelines of oil and gas," said Murton. He believes that the engineering implications of permafrost thaw have been downplayed in comparison to the risk it poses as a carbon pool ready to release its CH_4 and CO_2 stock.

Murton's work has focused on the process by which ice breaks up rocks. His results have challenged the conventional understanding that the 9% expansion that takes place when water turns into ice can exert a force strong enough to break rocks apart. "Unless the rock is saturated or nearly saturated with water and frozen very quickly, then the air gaps in the rock take up the expansion force of water that freezes. And if the rock is frozen slowly, then the water migrates towards where the lower temperatures are," said Murton. "So, volumetric expansion mechanism can occur, but only under very unusual circumstances," he added.

Murton and colleagues have shown that the rock fracture process in cold regions commonly occurs near the top of the permafrost by ice that segregates itself from mineral particles. The mechanism is based on tiny lenses of ice, which can draw water, grow, and tear the rock apart. "At rock temperatures above –30°C, there is always some water in the rock, existing as extremely thin films around mineral particles," he said. He and his colleagues have demonstrated experimentally that this water could move slowly—by a combination of gravity and temperature gradient-induced suction—down through the unfrozen active layer, into the frozen rock, augmenting the ice lenses (active layer is the layer of rock that cyclically freezes and thaws each year that sits directly on top of the permafrost).

The scientists also found that a lot of the fracture occurs in simulated summer when the ground above permafrost is thawed. "This is counterintuitive, if one accepts the volumetric expansion mechanism," said Murton, "because in such a case, all the fracture should be occurring when rock freezes, in autumn or winter."

Ice segregation in limestone is very similar to ice segregation in fine-grained silty soil, which geologists have studied for 50 years or more. "We found that the rock we were testing and the silty soil have similar pore properties (for instance, sizes), the basic difference between the two being that the rock was cemented, thus having a greater tensile strength," he added.

The experiments of Murton's team were carried out in a cold room, where blocks of limestone were placed in a metal tank, with a cooling plate at the bottom and insulation around the block to minimize lateral heat flow. Chilled air blown inside the cold room froze the block from the top downward. To simulate summer thawing, the researchers turned on the basal cooling plate to maintain artificial permafrost in the lower half of the block. They then opened the door of the cold room to allow warm air to circulate inside it, resulting in thawing of the upper half of the block.

"We think that the process starts off on a very small scale with microcracks, which over several freeze-thaw cycles propagate and transition into macrocracks, visible to the naked eye," said Murton. To monitor the development of the cracks and identify their 3D location, the researchers installed sensors around the sides of a block that can pinpoint the timing of acoustic emissions. "When a little crack develops in a rock, it sends out elastic waves, just like an earthquake," said Murton. He believes this is the origin of the strongly fractured ice-rich zone that starts to develop at the top of the permafrost and the base of the active layer in places such as northern Canada and Svalbard, a Norwegian archipelago in the Arctic Ocean.

In Svalbard, the dramatic rise of the temperature has put in danger the Global Seed Vault, a facility buried deep in an abandoned

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coal mine, surrounded by permafrost to keep the world's crops and plants frozen and safeguard them for future generations. However, since a flooding event due to thawing permafrost in 2017, it now needs extra cooling capabilities.

Apart from seeds, Svalbard also hosts several international research stations, which offer unique opportunities for studying the Arctic climate and phenomena, such as iceberg calving, a process that takes place at a glacier's front, where big chunks of ice break off and fall into the water.

Andreas Köhler, a geophysicist at the University of Oslo until 2019, now working at the research foundation NORSAR, uses seismic records from ice quakes to monitor glacier activity. Ice quakes are seismic signals that are emitted by glaciers during dynamic processes. Köhler is part of an interdisciplinary team of experts who have focused on the well-studied and fast-flowing glacier, Kronebreen, in northwestern Svalbard. His first goal was to analyze the spatial-temporal distribution and characteristic frequencies of ice quake signals in Svalbard and to distinguish them from tectonic earthquakes. He discovered that the majority of signals were generated by iceberg calving events.

Northwestern Svalbard, where Andreas Köhler and his colleagues set up their station. Credit: Andreas Köhler.

Köhler said that using seismological methods has huge potential for monitoring and studying iceberg calving with high temporal resolution. "If you want to quantify and make projections on how much ice the glacier will lose in the future and how much this will affect the sea level, this is an important step to better understand the calving process," said Köhler.

Using seismic calving observations to physically quantify ice loss through calving means to translate seismic signal properties to ice volumes. For this, Köhler and his colleagues combined seismic data, from permanent seismometers and from field experiments, with ice-loss observations from satellite images and, on a smaller scale, seismic data with data they collected at the glacier front with a laser scanner.

Another seismic method, which was applied to the same data sets, makes use of ambient seismic noise to measure materials properties. This method could potentially monitor changes in permafrost, though it is still in an experimental stage. Köhler used seismometers installed on frozen ground in Svalbard to see if he could detect changes in permafrost between summer and winter. "In summer, seismic waves travel through frozen and thawed material with different speeds. The change of speed of the seismic waves is quite big, with reductions of more than 75%," he said.

Before calving occurs, smaller cracks and fractures in glacier ice propagate into larger crevasses. In 2012, a team of researchers led by Markus Buehler, of the Massachusetts Institute of Technology, suggested that increased concentrations of CO_2 cause ice to become more brittle and therefore more prone to cracking. "This suggests that the chemical composition of the atmosphere can be critical in mediating the motion and/or melting of large volumes of ice, beyond the effect of global temperature. In some sense, the fracture of ice due to carbon dioxide is similar to the breakdown of materials due to corrosion," explained Buehler.

Buehler and his team showed specifically that the partial negative charge of oxygen atoms in CO_2 are attracted to the partial positive charge of hydrogen atoms of the water. This results in broken hydrogen bonds between the ice water molecules. Simulations showed that CO_2 molecules, attached to the surface of a crack, moved toward the crack tip, breaking hydrogen bonds between water molecules as they went. "If ice caps and glaciers were to continue to crack and break into pieces, the surface area that is exposed to air would be significantly increased, which could lead to accelerated melting and a much reduced coverage area on the Earth," said Buehler.

"A whiter planet tends to reflect more sunlight and remains cooler, as opposed to a more blue and green planet that heats itself up," said David Holland, professor at the New York University in New York and Abu Dhabi. He combines field observations with state-of-the-art global climate models to understand climate change.

He currently focuses his efforts on the instability of the West Antarctic marine ice sheet (ice grounded to the sea floor). "It will take more than 1000 years for the atmosphere to considerably melt a lot of land ice and change the sea level. But if the ocean invades and destroys the West Antarctic marine ice, then sea level will rise by several meters," said Holland.

It takes longer to melt surface ice by warm air than by warm water; if cold water at the freezing point remains around the edge of Antarctica, the ice is safe. But models have shown that the area is unstable, and if warm water attacks, it will destroy it. "There is one place where we have discovered warm water under Antarctica, Thwaites Glacier. And we can see from satellites the area is falling apart, dropping by several meters every year," said Holland. This can lift the sea level around the world.

The big challenge is to determine whether this area will remain stable. "People understand the material properties of an ice cube. What we do not understand are the properties when the scale is really big, like in the case of ice in glaciers," said Holland.

"In the heart of the problem, something that people don't know is that physically and mathematically, the description is missing. To get the description, you have to go to the field, and that is very difficult," said Holland.

Hopefully, scientists will soon be able to derive equations that will explain the observations and understand the complex phenomena behind glaciers, permafrost soil, and other cryospheric materials in Earth's frozen wastelands. □