GLACIERS

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The Glacier

We stopped, ventured a glance
Down the sad green jaws,
And the strength in our breasts dissolved
Like lost hope. Within him a sad strength sleeps,
And when at night, in the silence
of the moon, he sometimes shrieks and roars,
It is because, in his stone bed,
Huge sluggish dreamer,
He is struggling to turn over and cannot.

Primo Levi
Avigliana, 15 March 1946

Glaciers: Natural Sensors of the Changing Climate

Elisa Palazzi

Glaciers form where soft, light snow that accumulates during the cold, wet winter does not melt completely when the weather turns warm and dry, instead undergoing a series of transformations as the years go by. At first, it accumulates, layer upon layer, gradually growing denser, after which it is transformed into an older, granular, highly compacted form of snow called "firn" and ultimately becomes glacial ice. These processes unfold at high altitude in the mountains in what is known as the glacier's accumulation zone; from there, the ice begins its slow progression towards lower altitudes, moving into what is called the ablation zone, where it can melt. A glacier in motion – slowly flowing from the accumulation to the ablation zone, driven by the force of its weight – is a glacier that is alive. It is alive because it is moving. The transition from the accumulation zone to the ablation zone corresponds to an imaginary line, the equilibrium line; at this point the glacier's mass balance, in other words the relationship between the amount of ice accumulated at higher altitudes and its loss lower down the mountain, is zero.

If a glacier shrinks excessively, for example in this era of global warming, it no longer has the strength to move, to flow, and this often sounds its death knell even before it becomes completely ice-free (different terminology is used to refer to the residual ice, which is known as a glacieret, a transitional form between firn [névé] and a glacier). That is precisely what happened, for example, to the Icelandic glacier Okjökull, whose funeral was held on 18 August 2019. A small patch of ice at the top of the Ok volcano, just 7 per cent of the extent of the ice cover a hundred years earlier, was all that remained of Okjökull in 2019. However, the glacier had already been officially pronounced dead a few years earlier, in 2014, when it had dwindled so dramatically that it was unable to move. At that point the ice no longer had sufficient mass to nourish the glacier's dynamics. Another parameter that indicates a glacier's health is a change in equilibrium-line altitude. That line moves up to higher altitudes in a warmer climate, which means that the overall area where glaciers can grow, nourished by snowfall in the cold season, is becoming smaller.

Let us stop for a moment and consider why glaciers are important, for the climate and for human beings. First of all, they play a significant role in regulating Earth's climate. Thanks to their highly effective reflection of solar radiation, they help ensure that the planet's surface does not grow too hot. They also serve as something akin to water towers for lowland regions: drinking water supplies for two billion people and two-thirds of the world's agriculture under irrigation depend on glaciers. A third, very important aspect, especially for climate scientists like myself, is that glaciers are extremely valuable climate archives. They allow us to reconstruct how the climate evolved in the past, even hundreds of thousands of years ago. If a cylinder of ice – one of those renowned cores – is extracted from a site with abundant ice, such as Antarctica, layers can be identified, corresponding to the accumulation of snow and its compaction year after year. When snow is transformed into ice, air bubbles, organic substances (pollen, plant fragments, insects), and inorganic substances (dust, soot, pollutants) are entrapped within the ice. Years later – even hundreds of thousands of years later – these serve as valuable tools for identifying climate traits from the past. Bubbles, for example, are analysed to determine the concentration of greenhouse gases in fossil air, using specialised dating methods and techniques. These traces of a history of which we can have no other memory make it possible to (re)read today's climate by putting it into perspective and help us understand its specific details, while at the same time serving as a data source to improve the models that underpin projections about future developments.

Glaciers, like the other elements in the cryosphere (everywhere on the planet where water is present in a solid state) are sentinels of climate change. The rapid pace at which glaciers have been melting recently bears witness to the unprecedented rate at which the planet is heating up.[1] A 2021 study showed that the cryosphere has lost around 87,000 square kilometres (an area the size of Portugal) per annum since the 1980s as a consequence of global warming.[2] Large expanses of sea ice have disappeared, along with the ice cover on lakes and rivers, while snow cover has also dwindled

1 Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge and New York, 2023), available online at https://bit. ly/43vHeb5.

2 Peng Xiaoqing, Zhang Tingjun, Oliver W. Frauenfeld, Ran Du, Haodong Jin, and Cuicui Mu, 'A Holistic Assessment of 1979–2016 Global Cryospheric Extent', *Earth's Future* 9, no. 8 (2021), available online at https://bit.ly/4bCF8Iy.

dramatically. Snow is likewise a natural sensor of the changing climate. A warmer world is tantamount to a world with less snow, in which the duration, extent, and thickness of snow cover decreases. If mountain soil is not covered by snow, which acts as a thermal insulator, it is at risk of freezing, leading to an alteration in the nutrient cycle that persists until summer, with knock-on effects for the ecosystem. If there is no snow in the mountains in winter, there is no guaranteed reserve of frozen water that will melt in spring and feed into rivers and streams, bringing water downstream. If there is no snow in winter, glaciers do not have a protective layer over their surface, which helps stop them from melting in the warmer seasons. Studies show that in the Alps the snow water equivalent (SWE: a parameter that indicates the snow's thickness and density and is a helpful measure to determine how much snow has fallen and its water content, potentially available for future use) will fall by between 80 and 90 per cent at around 1,500 metres by late 2100; at higher altitudes the reduction will be smaller, around 10%.[3] A 2020 study published in 2020 addresses the development in the equilibrium line of glaciers in the Alps over a two-century time span, from 1901 to 2100.[4] By 2100, this line could rise by at least 100 metres and at most 600 to 700 metres depending on the greenhouse gas emission scenario, which means that, in the best-case scenario, 69 per cent of the Alpine glaciers that still exist could disappear or, in the worst-case scenario, 92 per cent.

In light of current climate trends, seeking to reduce greenhouse gas emissions through mitigation strategies is only part of the answer. Ingrained mindsets must be abandoned to promote new ways of using and enjoying the mountains, taking the interests of all stake-holders into account and fostering a healthy attitude of respect for this high-altitude realm. This should not happen at the expense of the local populace and should respect the ecosystem of the mountains, in which the world of the glaciers plays such a vital role.

3 Silvia Terzago, Jost von Hardenberg, Elisa Palazzi, and Antonello Provenzale, 'Snow Water Equivalent in the Alps as Seen by Gridded Data Sets, CMIP5 and CORDEX Climate Models', *The Cryosphere* 11, no. 4 (2017), pp. 1625–45, available online at https:// bit.ly/3FhXBhD.

4 Manja Žebre, Renato R. Colucci, Filippo Giorgi, Neil F. Glasser, Adina E. Racoviteanu, and Costanza Del Gobbo, '200 Years of Equilibrium-Line Altitude Variability Across the European Alps (1901–2100)', *Clim Dyn*, no. 56 (2020) pp. 1183—1201, available online at https://bit.ly/4ihltQP.