2021, coinciding with a large ozone hole persisting until December (sections 2g4, 6h). The equatorial stratosphere's quasi-biennial oscillation progressed in 2021 as it usually has for more than half a century: downward-propagating easterly and westerly wind regimes and accompanying temperature variations, with a mean periodicity of somewhat more than two years. This regular downward propagation from the upper to lower stratosphere was interrupted in both 2016 and 2020, but more regular evolution appeared to resume at the end of 2020 with an easterly phase propagating downward from the middle stratosphere (https://acd-ext.gsfc.nasa.gov/Data_services/met/qbo/qbo.html).

c. Cryosphere

1. PERMAFROST TEMPERATURE AND ACTIVE LAYER THICKNESS—J. Noetzli, H. H. Christiansen, M. Guglielmin, F. Hrbáček, K. Isaksen, S. L. Smith, L. Zhao, and D. A. Streletskiy

Permafrost—ground material remaining at or below 0°C for at least two consecutive years—is a key component of the cryosphere in high-latitude and high-altitude regions. Global permafrost temperatures have increased for several decades, with regional variability in magnitude and shorter-term fluctuations related to meteorological variations (Biskaborn et al. 2019; Etzelmueller et al. 2020; Haberkorn et al. 2021). Observed warming rates close to the depth of the zero annual amplitude (DZAA)—where annual temperature fluctuations become negligible—were in the range of a few tenths °C decade^{-1} (Smith et al. 2022). They were largest (0.3°–0.8°C decade^{-1}) at sites in continuous permafrost or at highest elevations with low permafrost temperatures. Warmer and ice-rich permafrost warms more slowly due to latent heat uptake during ice melt (< 0.3°C decade^{-1}). Changes in active layer thickness (ALT)—the thickness of the layer above the permafrost that freezes and thaws annually—relate to annual atmospheric and snow conditions. ALT was greater in 2021 than in 2020 in some polar regions and generally above average of available records for all observed permafrost regions.

Permafrost temperatures in 2021 across the Arctic regions were the highest on record at many sites (see section 5h); however, at some Arctic sites (e.g., northwestern North America, Nordic region, and northern Russia) lower permafrost temperatures than in the previous years were observed, related to lower air temperatures. ALT could not be fully reported for some Arctic regions due to continued COVID-related travel restrictions. In northern Alaska, ALT was below the 2009–18 average, while it was among the largest values on record in Alaska Interior and on average more than 30 cm greater than in 1995. Greenland also reported its greatest ALT since 1995. Northern European Russia and western and eastern Siberia had lower ALT compared to 2020, but was greater than average, while in central Siberia it was greater than 2020.

On James Ross Island, northeastern Antarctic Peninsula, permafrost temperatures in 2021 were the second highest (–5.0°C) since the record began in 2011. The ground temperature at 75 cm increased by 0.9°C over the period 2011–21 (Hrbáček et al. 2021). ALT has increased here by 12 cm decade^{-1} reaching 66 cm in 2021, which was 6 cm above average. At Rothera Point, permafrost temperature below the DZAA has remained stable since 2009.

Mountain permafrost accounts for approximately one-third of the global area underlain by permafrost (Hock et al. 2019). Data are primarily available from the European Alps, the Nordic region, and the Qinghai-Tibetan Plateau (QTP). Ranges of permafrost temperature and warming rates are similar to those observed in the Arctic, but with high spatial variability due to the complex topography. Significant ALT increase by meters were documented at sites in the European Alps over the past two decades (Etzelmueller et al. 2020; Haberkorn et al. 2021; PERMOS 2022), with considerable loss of ground ice (Mollaret et al. 2019). Ground temperatures close to the surface were lower in 2021 than 2020 in the European Alps (PERMOS 2022; Pogliotti et al. 2015; Magnin et al. 2015) due to a long period of snow cover and lower atmospheric temperatures (e.g., MeteoSwiss 2022). This resulted in ALT that were often lower in 2020 and a general decrease in rock glacier velocity (section 2c2). For many sites, permafrost temperatures at 20-m depth—where they react to longer term trends—continued to increase in 2021 and reached record levels (Fig. 2.12). This is also true for the Nordic mainland; on Juvvasshøe in southern Norway, 2021 was the eighth consecutive year (since 2014) with record permafrost temperatures (Noetzli et al. 2021a; Etzelmüller et al. 2020). ALT at sites in the Nordic countries in 2021 were greater than or close to the maximum of 2020. In Svalbard, however, permafrost temperatures at 10-m depth continued to decrease due to cold winters in 2019–21 (Christiansen et al. 2021), but were still above the long-term average (Fig. 2.12). Permafrost temperatures in the QTP in central Asia increased at six sites from 2005 to 2020: 0.45°C decade^{-1} at 10-m depth and 0.24°C decade^{-1} at 20-m depth (Fig. 2.13; Zhao et al. 2020, 2021). Along the Qinghai-Tibet Highway (Kunlun mountain pass), an ALT increase was observed with a mean of 19.4 cm decade^{-1} for the period 1981–2020 (Fig. 2.14).

Long-term observation of permafrost relies on field observations of ALT, permafrost temperatures, and, since 2021, on rock glacier velocity (Streletskiy et al. 2021; Pellet et al. 2021). International data are collected by the Global Terrestrial Network for Permafrost (GTN-P) as part of the Global Climate Observing System (GCOS). Permafrost temperatures are logged in boreholes reaching at least the DZAA, with a measurement accuracy assumed to be 0.1°C (Biskaborn et al. 2019; Noetzli et al. 2021b; Streletskiy et al. 2021). ALT is determined by mechanical probing where possible (accuracy of ~1 cm) and otherwise interpolated from borehole temperature measurements. The global coverage of permafrost monitoring sites is sparse and particularly limited in regions such as Siberia, central Canada, Antarctica, and the Himalayan and Andes Mountains.

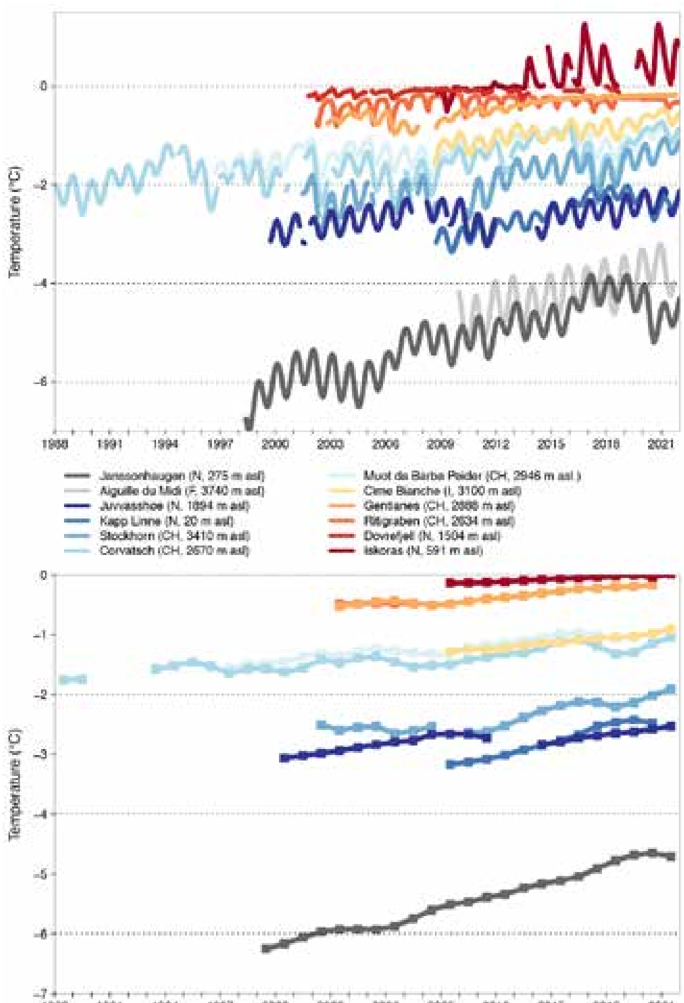

Fig. 2.12. Permafrost temperature (°C) measured in boreholes in the European Alps and the Nordic countries at a depth of (a) ca. 10 m (monthly means) and (b) 20 m (annual means). (Data sources: Switzerland: Swiss Permafrost Monitoring Network PERMOS; Norway: Norwegian Meteorological Institute and the Norwegian Permafrost Database NORPERM; France: updated from Magnin et al. 2015; Italy: updated from Pogliotti et al. 2015.)

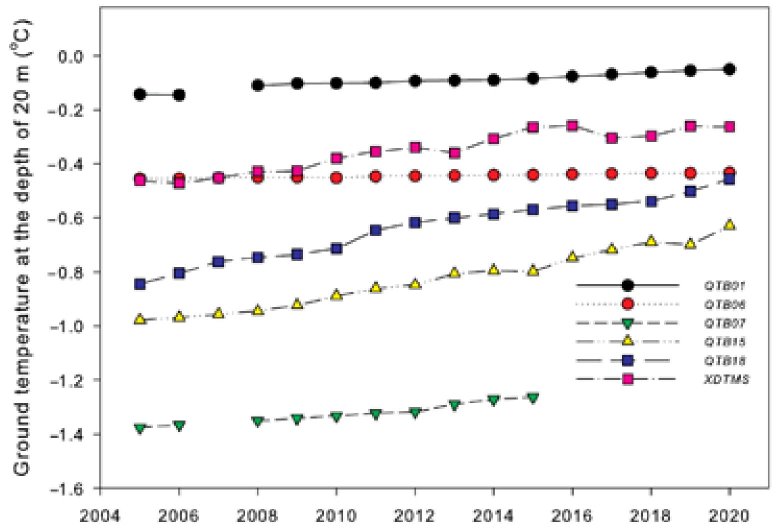

Fig. 2.13. Permafrost temperature (°C) measured in boreholes along the Qinghai-Xizang Highway on the Tibetan Plateau at 2-m depth for the period 2005–20. (Source: Cryosphere Research Station on Qinghai-Xizang Plateau, CAS.)

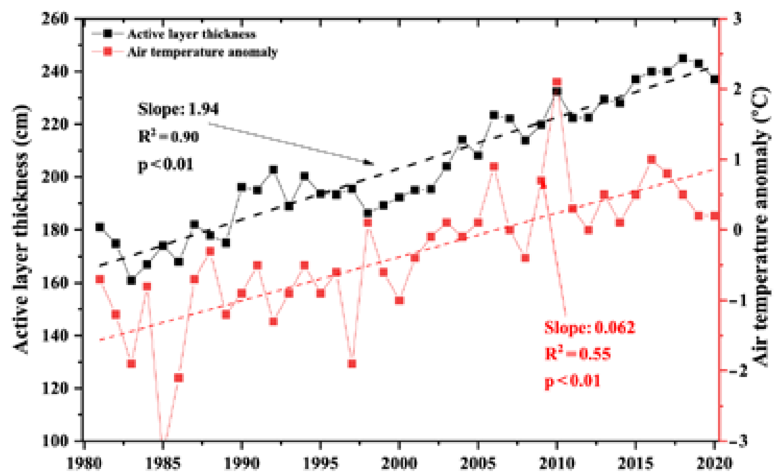

Fig. 2.14. The active layer thickness (cm) and air temperature anomalies (°C) in the permafrost zone along the Qinghai-Tibet Highway during the period 1981–2020. The air temperature anomaly is estimated relative to the base period 1981–2010. (Source: Cryosphere Research Station on Qinghai-Xizang Plateau, CAS.)

2. ROCK GLACIER VELOCITY—C. Pellet, X. Bodin, D. Cusicanqui, R. Delaloye, A. Kääb, V. Kaufmann, J. Noetzli, E. Thibert, S. Vivero, and A. Kellerer-Pirklbauer

Rock glaciers are debris landforms generated by the creep of frozen ground (permafrost) found in most mountain ranges worldwide (RGIK 2021). Changes in their velocities are mostly related to the evolution of ground temperature and liquid water content between the permafrost table and the shearing horizon at depth: the closer to 0°C, the faster the rock glacier is able to move (Cicoira et al. 2019; Frauenfelder et al. 2003; Staub et al. 2016). In 2021, the variable rock glacier velocity (RGV) was adopted as a new associated product to the essential climate variable (ECV) permafrost by GCOS and the Global Terrestrial Network for Permafrost (GTN-P, Streletskiy et al. 2021), given the global occurrence of active rock glaciers and their sensitivity to changes in ground temperature.

RGVs, observed in several mountain ranges across the globe, have been increasing since the 1950s, with regional variability in magnitude and marked interannual variability. Observed rates of increase are largest since 2010 and record high velocities have been recorded since 2015. These changes are consistent with interannual variations of permafrost temperatures (cf. section 2c1), to which rock glacier velocities have been shown to respond synchronously (Cusicanqui et al. 2021; Kääb et al. 2007; Kellerer-Pirklbauer and Kaufmann 2012; Staub et al. 2016; Vivero et al.