with the anomalous temperatures (Coy et al. 2022; Wang et al. 2022). Low anomalies were largest during SH winter (Fig. 2.11b), with a corresponding equatorward shift of the Antarctic polar vortex and circulation-induced midlatitude ozone losses (Wang et al. 2022). While the HTHH H_2O plume is slowly dispersing throughout the global stratosphere, it is expected to persist for a number of years as H_2O is chemically inert, and the main loss processes are due to transport in the slow overturning stratospheric circulation. Hence the HTHH H_2O anomalies will continue to influence stratospheric temperatures beyond 2022.

The Antarctic polar vortex was strong and characterized by anomalously low temperatures during spring 2022, persisting through December (see section 6b for details). Springtime polar temperatures and vortex persistence are closely linked with springtime polar ozone amounts, due to ozone radiative forcing after the sun returns in October. Springtime polar ozone was also relatively low in 2022 (section 2g4), likely contributing to the observed low temperatures.

The Arctic polar vortex was stable and relatively cold during winter but was disturbed by a major stratospheric warming event in March (Vargin et al. 2022), with polar temperature increases over a few days of about 30K. The vortex did not recover, and this event thus corresponded to the 'final warming' for that winter. The stratospheric QBO in 2022 continued its usual regular progression (as observed since the 1950s) in contrast to the anomalous disruption events of 2016 and 2020 (section 2e3).

c. Cryosphere

1. PERMAFROST TEMPERATURE AND ACTIVE LAYER THICKNESS

—J. Noetzli, H. H. Christiansen, F. Hrbáček, G. Hu, K. Isaksen, F. Magnin, P. Pogliotti, S. L. Smith, L. Zhao, and D. A. Streletskiy

Permafrost is a subsurface phenomenon in polar and high mountain regions and defined as ground with a maximum temperature of 0°C throughout the year. Permafrost temperatures close to the depth where annual fluctuations become minimal (the depth of zero annual amplitude) increased across all permafrost regions in the past decades with rates ranging from below 0.3°C decade^{-1} in warm permafrost (with temperatures close to 0 °C) to above 0.8°C decade^{-1} in cold permafrost (Biskaborn et al. 2019; Smith et al. 2022; Etzelmüller et al. 2020; Zhao et al. 2020; Fig. 2.12; see also section 5i). The thickness of the active layer (ALT), the layer above the permafrost that thaws during summer, increased in the Arctic by a few centimeters per decade in cold continuous permafrost and by more than 10 cm decade^{-1} in discontinuous permafrost. ALT increased by 19.6 cm decade^{-1} over the past 40 years in the Qinghai-Tibet Plateau (Fig. 2.13) and has increased by a few meters in the past 20 years at several sites in the European Alps.

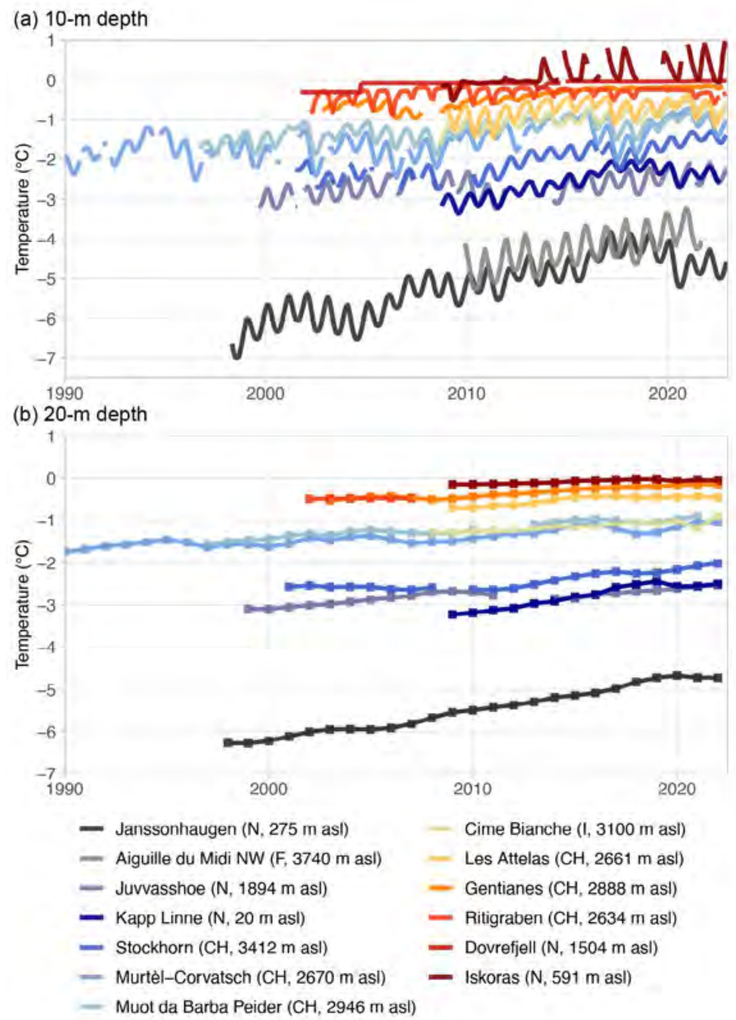

Fig. 2.12. Permafrost temperatures (°C) measured in boreholes in the European Alps and the Nordic countries at a depth of (a) ~10 m (monthly means) and (b) 20 m (annual means). (Sources: Switzerland: Swiss Permafrost Monitoring Network; Norway: Norwegian Meteorological Institute and the Norwegian Permafrost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

Permafrost temperatures in 2022 were the highest on record at 11 of the 25 sites monitored in the Arctic (section 5i), while they were lower than in 2021 in northern Alaska, the northern Mackenzie region in northwestern Canada, and the Canadian high Arctic. This is partly associated with lower air temperatures in those regions over the past two to three years. ALT in Arctic Alaska was one of the lowest since 1995 where most of the sites were established. ALT was lower than 2021 but above the long-term averages in Interior Alaska, northwestern Canada, Greenland, and northern European Russia. ALT in West Siberia was on average 5 cm higher in 2022 than in 2021, while in Central Siberia it was 6 cm lower, but 13 cm higher than average. In East Siberia and Chukotka, ALT was 2 cm–3 cm higher than in 2021, but close to the long-term mean. In high-Arctic Svalbard, permafrost temperatures were the fourth highest on record. ALT was not at maximum due to lower air temperatures in April and early May, and despite record air temperatures in summer 2022 in western and northern Svalbard.

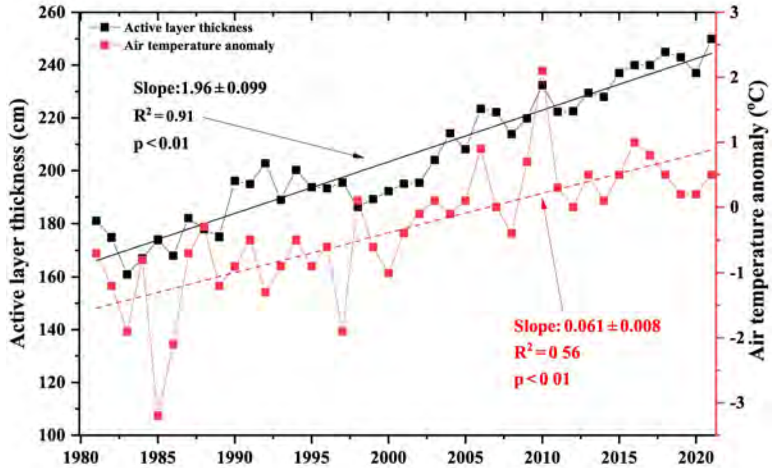

Fig. 2.13. Active layer thickness (cm) and air temperature anomaly (°C; 1991–2020 base period) in the permafrost zone along the Qinghai-Tibet Highway for the period 1981–2021. (Source: Cryosphere Research Station on Qinghai-Xizang Plateau, CAS.)

Several countries in Europe recorded extremely dry and warm conditions in summer 2022 (see section 7f; sections 2b4, 2d11; Copernicus 2023). In northern Norway, the permafrost degradation continued, with permafrost thaw down to 20-m depth at Iskoras, and in southern Norway the permafrost temperature was the highest on record at Juvvasshøe (Fig. 2.12). Nearby, on Dovrefjell, since 2021 the active layer has not completely frozen down to the underlying permafrost during winter, resulting in a talik (unfrozen zone; Isaksen et al. 2022). In the European Alps, mean annual ground surface temperature increased in 2022 by more than 1°C compared to 2021 at the majority of the 30 Swiss sites due to higher air temperatures and early snow melt (section 2c5; MeteoSwiss 2023; Pielmeier et al. 2023). The active layer was the thickest on record at most monitoring sites in the Swiss, French, and Italian Alps. In contrast, permafrost temperatures at 10-m depth decreased in 2022 at many sites (update from the Swiss Permafrost Monitoring Network [PERMOS] 2022; Pogliotti et al. 2015; Magnin et al. 2015; Fig. 2.12) reflecting the colder conditions of 2021 (Noetzli et al. 2022). Permafrost temperatures at 20-m depth—where they react to longer-term trends—continued to increase in 2022 at most sites and were close to record levels.

Permafrost temperatures in the Qinghai-Tibet Plateau continued to increase from 2005 to 2021 at 10- and 20-m depth at six sites, with stronger warming in colder permafrost. At the 10 ALT sites along the Qinghai-Tibet Highway (Kunlun mountain pass), ALT increased from the start of the measurements in 1981 to a new maximum of 250 cm in 2021 (the latest value available; Fig. 2.12).

On James Ross Island in the northern Antarctic Peninsula, 2022 was the warmest of the instrumental records since 2004. The mean annual near-surface temperature (–3.2°C) was 2.2°C above the 2011–20 mean (reference site AWS-JGM), leading to a mean annual temperature at the permafrost table (i.e., the top of permafrost) 1.6°C above average. The ALT was 71 cm in 2022 and 22 cm above the mean during 2011–20 (Kaplan-Pastirikova et al. 2023). ALT has been increasing at all Antarctic Peninsula monitoring sites since 2015, whereas it has remained stable in the other regions of Antarctica.

International field data of ALT, permafrost temperatures, and rock glacier velocity (Streletskiy et al. 2021; section 2c2) are collected by the Global Terrestrial Network for Permafrost (GTN-P). Permafrost temperatures are manually recorded or continuously logged in boreholes with a measurement accuracy of ~0.1°C (Biskaborn et al. 2019; Noetzli et al. 2021; Streletskiy et al. 2021). ALT is either determined by mechanical probing (with an accuracy of ~1 cm) or interpolated from borehole temperature measurements. The global coverage of permafrost monitoring sites is sparse and biased to the Northern Hemisphere. Permafrost data are particularly limited in regions such as Siberia, central Canada, Antarctica, and the Himalayan and Andes Mountains.

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) whose velocity changes are indicative of changes in the thermal state of permafrost (RGIK 2022a,b). Rock glacier velocities (RGV) observed in different mountain ranges worldwide have been increasing since the 1950s, with large regional and inter-annual variability. In 2022, RGVs in the European Alps decreased at all monitoring sites. For some rock glaciers this was the second consecutive year of decreasing velocities. These changes are consistent with the evolution of permafrost temperatures (section 2c1) to which rock glacier surface velocities respond synchronously (e.g., Kenner et al. 2017; Staub et al. 2016).

Although summer was marked by exceptionally high air temperatures (Fig. 2.14a; section 2b4), RGVs in the European Alps decreased at all sites in 2022, which contrasts with the general

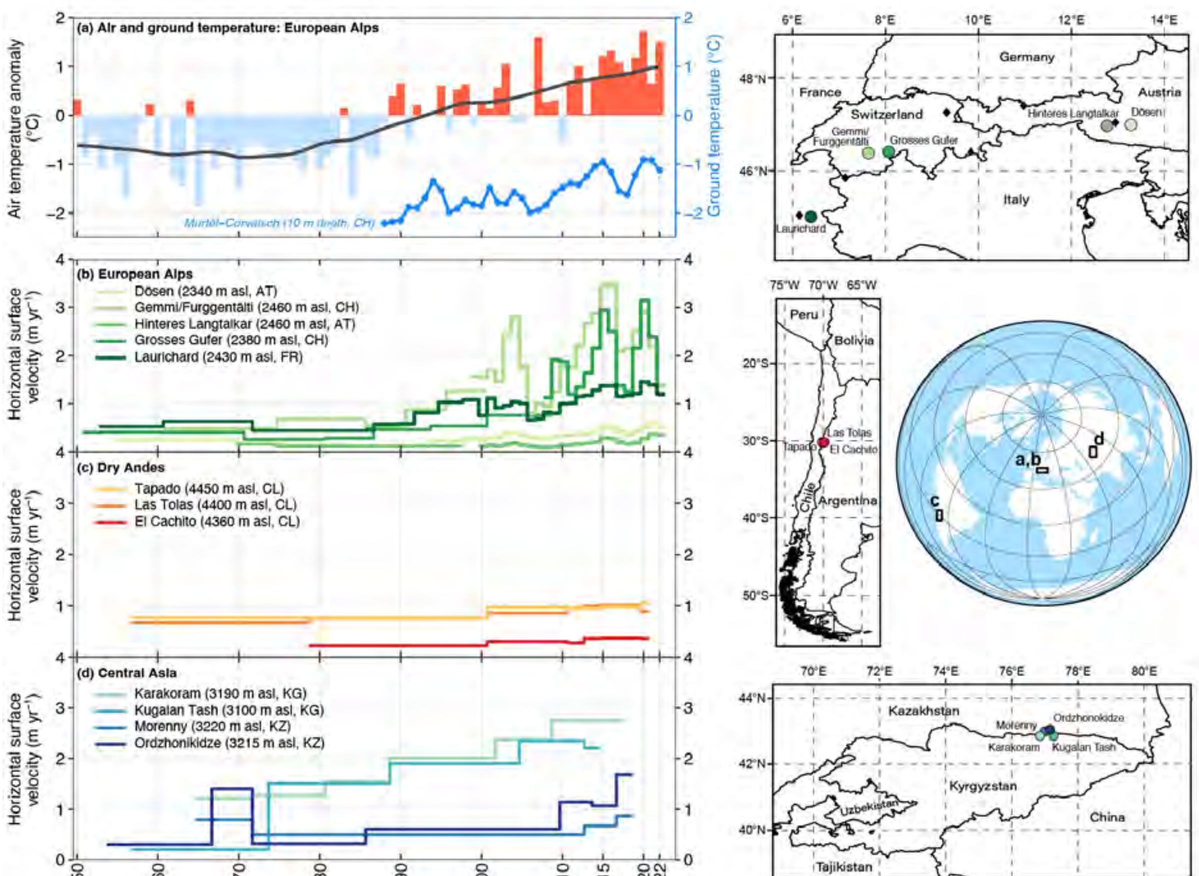

Fig. 2.14. (a) Air and ground temperatures (°C) in the European Alps, (b) rock glacier velocities (m yr⁻¹) at selected sites in the European Alps, (c) the Dry Andes (adapted from Vivero et al. 2021), and (d) Central Asia (adapted from Kääb et al. 2021). Rock glacier velocities are based on in situ geodetic surveys or photogrammetry in the context of long-term monitoring. In situ hydrological mean annual permafrost temperature measured at 10-m depth (blue line) at Murtèl Corvatsch (black triangle on Europe map) and air temperature: composite anomaly to the 1981–2010 average (bars) and composite 20-yr running mean (solid line) at Besse (FR), Grand Saint-Bernard (CH), Saentis (CH), Sonnblick (AT), and Zugspitze (D, black diamonds on Europe map). (Sources: Météo France, Deutscher Wetterdienst, MeteoSwiss, GeoSphere Austria, Swiss Permafrost Monitoring Network, University of Fribourg, University of Graz, Graz University of Technology, Université Grenoble Alpes, University of Oslo.)