c. Cryosphere

1. PERMAFROST TEMPERATURE AND ACTIVE-LAYER THICKNESS

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In recent decades, permafrost in cold regions worldwide have undergone widespread and persistent change, but the process is mostly slow and not directly visible. Permafrost is ground material with a maximum temperature of 0°C for at least two consecutive years. Its strongest warming was observed in cold high-latitude and high-elevation permafrost, where decadal rates of permafrost temperature increase by up to 1.0°C decade^{-1} at the depth of zero annual amplitude (DZAA, the depth where annual temperature fluctuations become negligible; e.g., Smith et al. 2023; Noetzli et al. 2021; Smith et al. 2022; Etzelmüller et al. 2023; Magnin et al. 2023; PERMOS 2023). In ice-bearing ground in warmer permafrost regions, latent heat effects due to phase change can significantly reduce temperature changes to below 0.1°C decade^{-1}. The layer above the permafrost that thaws during summer is called the active layer. Its annual thickness (active-layer thickness; ALT) has generally increased in all regions as a result of higher air temperatures. ALT increased by a few centimeters per decade in continuous permafrost in the Arctic in sediments and by decimeters per decade in discontinuous permafrost in bedrock in the Arctic, Antarctica, Scandinavia (e.g., Smith et al. 2022; Noetzli et al. 2023; section 5j), and the Qinghai-Tibet Plateau (QTP, Zhao 2024; Hu 2024). ALT changes of several meters were recorded during the past 20 years in the European Alps in bedrock as well as in degrading permafrost sites in talus slopes (e.g., PERMOS 2023, 2024; Magnin et al. 2023; Pogliotti et al. 2023).

Permafrost temperatures in 2023 were the highest on record for 9 of the 17 Arctic sites and higher than those in 2022 for most sites (see section 5j). However, for six sites in northwestern North America, permafrost temperatures were lower in 2023 compared to those in 2022, resulting from the delayed reaction at depth to the lower air temperatures during 2020–22. Similarly, the effect of higher air temperatures in 2023 is not yet observed at depths of 15 m–20 m. In the cold permafrost in Svalbard, the ground temperatures at 20 m were the fifth highest on record in 2023, based on measurements since 1999. Permafrost temperature at 10 m increased only slightly compared to 2022 and 2021 (Fig. 2.13, Janssonhaugen) and was still above the long-term average.

Active-layer thickness observed in 2023 in the Arctic differs between regions (Fig. 2.14; see section 5j): In high-Arctic Svalbard, record ALTs were documented after the record-warm summer of 2023 (see section 5b) for all sites, with values in bedrock of up to nearly 5 m in extreme cases. In 2023, above-average values were measured in Greenland and at sites from the Barents Sea region to West Siberia. In Central, East Siberia, and Chukotka in the Russian Arctic, in Arctic Alaska, western Alaska, and Northwest Canada (in 2022), ALT was close to the long-term average. In North America, the largest positive ALT anomaly in 2023 was observed in interior Alaska.

Mountain permafrost temperatures near the DZAA in mainland Norway were the highest on record in 2023, meaning reported warming continues (Noetzli et al. 2023; Etzelmüller et al. 2023). In the European Alps, permafrost temperatures at 10-m and 20-m depth were at record levels, particularly for bedrock sites, due to two consecutive hot summers in 2022 and 2023 (as yet, the full effect of the 2023 summer heat cannot be observed at greater depth). In contrast, permafrost temperatures decreased at 10-m depth for several rock glacier stations in

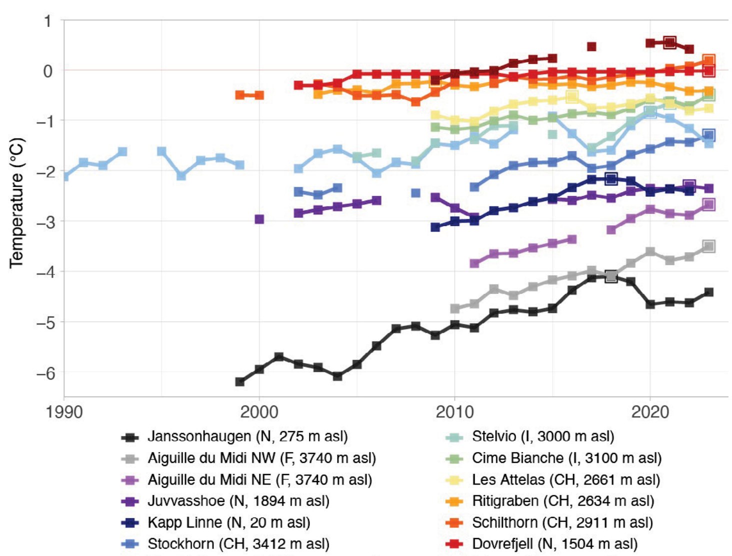

Fig. 2.13. Mean annual ground temperatures (°C) measured in European permafrost boreholes in the Alps, Scandinavia, and Svalbard at a depth of ca. 10 m. Maximum values for each time series are highlighted by a square. (Data sources: Norway: Norwegian Meteorological Institute and the Norwegian Permafrost Database [NORPERM]; Switzerland: Swiss Permafrost Monitoring Network [PERMOS]; France: Magnin et al. 2023; Italy: Pogliotti et al. 2023 and Guglielmin, M. unpublished data.)

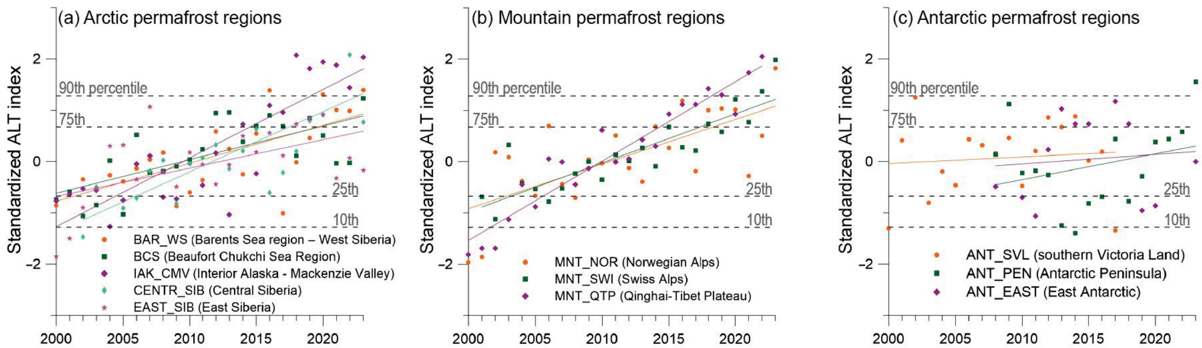

Fig. 2.14. Standardized active-layer thickness (ALT) index relative to 2000–20. (a) Arctic regions: Beaufort Chukchi Sea–Arctic Alaska and Mackenzie Delta region (BCS), Interior Alaska and central Mackenzie Valley, Northwest Territories (IAK_CMV), Barents Sea region–West Siberia (BAR_WS), Central Siberia (CENT_SIB), East Siberia (EAST_SIB); (b) Mountain regions: Norwegian mountains (MNT_NOR), Swiss Alps (MNT_SWI), Qinghai-Tibet Plateau (MNT_QTP); and (c) Antarctic: southern Victoria Land (ANT_SVL), Antarctic Peninsula (ANT_PEN), East Antarctic (ANT_EAST). (Source: Circumpolar Active Layer Monitoring [CALM].)

2023 after a snow-poor winter (Fig. 2.13; PERMOS 2024). The ALT for 2023 at the majority of sites in the Norwegian mountains and in the European Alps were at or close to their previous maximum, or set a new maximum (Fig. 2.14). Degraded permafrost in the upper part of the ground can be observed at several sites in Europe, e.g., by talik formation or active layers that no longer freeze during winter (Etzelmüller 2023; PERMOS 2023, 2024).

Permafrost temperatures at depths of 10 m and 20 m at six sites in the QTP in central Asia (Kunlun mountain pass to Liangdaohe) warmed significantly between 2005 and 2022, with many record values observed in 2021 (Fig. 2.15). For ALT in this region, a large increase was observed at 10 sites from 1981 to 2022 (Fig. 2.14), associated with a significant increase in air temperature.

Active-layer thickness in the Antarctic Peninsula region has increased since 2014, with the 2023 value being the maximum for 2006–23 (Fig. 2.14). Permafrost temperatures at DZAA at Rothera Station and Signy Island have remained stable since 2013 (Grifoni et al., accepted). In East Antarctica and Victoria Land, ALT remains relatively stable without clear detectable trends (Hrbáček et al. 2023).

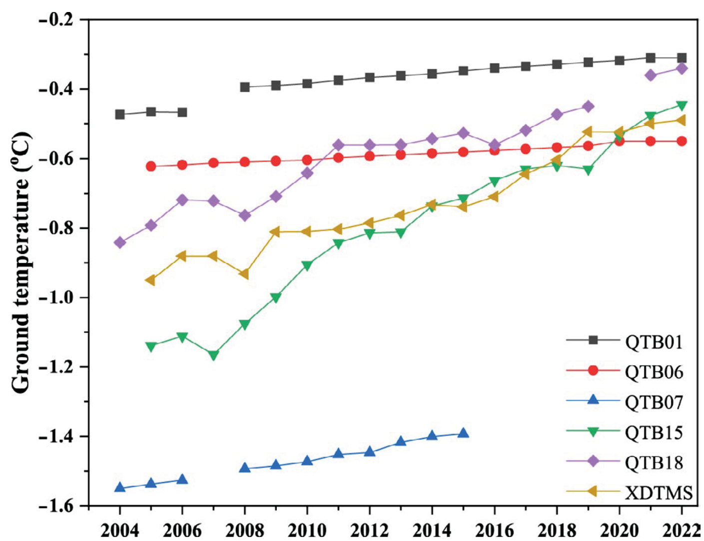

Fig. 2.15. Ground temperatures (°C) measured at 10-m depth in the Qinghai-Tibet Plateau during the period 2005–22. (Source: Cryosphere Research Station on Qinghai-Xizang Plateau, Chinese Academy of Sciences.)

Permafrost observation relies on field measurements at the national or institutional level and is globally collected in the framework of the Global Terrestrial Network for Permafrost (GTN-P; Streletskiy et al. 2021) as an essential climate variable of the Global Climate Observation System. The global coverage of permafrost monitoring sites is sparse and is mainly available in the Northern Hemisphere. Coverage is particularly limited in regions such as Siberia, central Canada, Antarctica, and the mountains in Central Asia, the Himalayas, and the Andes.

2. ROCK GLACIER VELOCITY

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Rock glaciers are debris landforms generated by the creep of perennially frozen ground (permafrost) whose velocity changes are indicative of changes in the thermal state of permafrost and associated ground hydrological changes (i.e., increasing temperatures lead to increase in velocity and vice-versa; RGIK 2023a; Staub et al. 2016). Rock glacier velocity (RGV) is a time