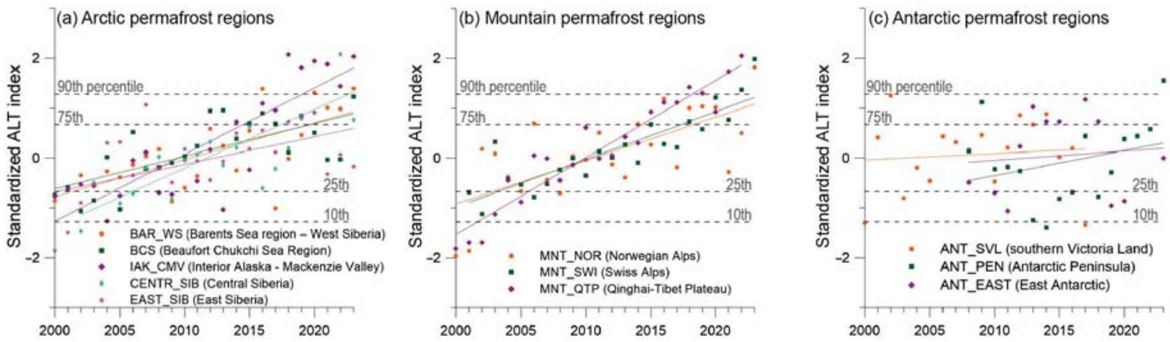

Fig. 2.14. Standardized active-layer thickness (ALT) index relative to 2000–20. (a) Arctic regions: Beaufort Chukchi Sea–Arctic Alaska and Mackenzie Delta region (BCS), Interior Alaska and central Mackenzie Valley, Northwest Territories (IAK_CMV), Barents Sea region–West Siberia (BAR_WS), Central Siberia (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).

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 (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.

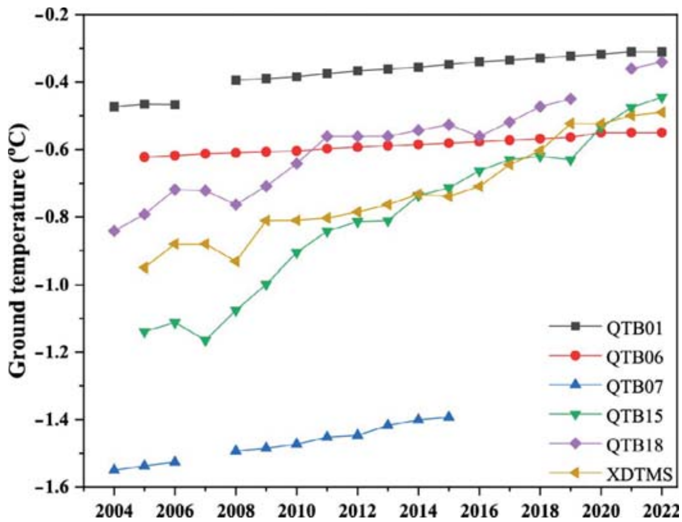

Fig. 2.15. Ground temperatures (°C) measured at 10-m depth in the Qinghai-Tibet Plateau during the period 2005–22. (Source: Cryosphere Research Station on Qinghai-Xizang Plateau, Chinese Academy of Sciences.)

2. ROCK GLACIER VELOCITY

—C. Pellet, X. Bodin, D. Cusicanqui, R. Delaloye, A. Kääb, V. Kaufmann, E. Thibert, S. Vivero, and A. Kellerer-Pirklbauer

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 series of annualized surface velocity values measured/computed on a rock glacier or a part of it (RGIK 2023b). Rock glacier velocities observed in different mountain ranges worldwide have been increasing since the 1950s, with large regional and inter-annual variability. These changes are consistent with the evolution of permafrost temperatures (section 2c1).

Although the hydrological year 2023 (October 2022 to September 2023) was the warmest on record in the European Alps (Fig. 2.16a), RGVs slightly increased in the western part of the Alps and continued to decrease in the east. Compared to 2022, velocity increased in the French Alps (+4% at Laurichard) and western Swiss Alps (+11% at Grosses Gufer and +15% at Gemmi/Furggentälti), whereas velocities continued to decrease in the Austrian Alps (–8% at Dösen and –22% at Hinteres Langtalkar; Fig. 2.16b). These regional evolutions are consistent with different snow conditions, namely exceptionally late onset of the snow cover and low snow depth in the east, which enabled marked cooling of the ground (as confirmed by the permafrost temperature decrease at 10-m depth observed on rock glacier Murtèl-Corvatsch in eastern Switzerland, Fig. 2.16). In the west, slightly later-than-average onset of the snow cover and slightly below-average snow depth were observed (PERMOS 2024). The reported RGV observations in 2023 in the European Alps are part of a general acceleration trend observed at all sites since the 1950s (Cusicanqui et al. 2021; Kellerer-Pirklbauer et al. 2024; PERMOS 2024).

In the Dry Andes in South America, RGVs reconstructed on three rock glaciers showed low velocities from 1950 to 2000, followed by a steady acceleration since the 2000s (Fig. 2.16c), consistent with the slight air temperature increase observed in the region since 1976 (Vivero et al. 2021). The potential effects of the above-average snow depth and longer snow cover duration in this region, associated with the strong El Niño event in 2023, have yet to be quantified.

Rock glacier velocities observed in Central Asia during the period of around 2018–23 show overall high values. Maximum velocities have been observed at Karakoram and Morenny, and

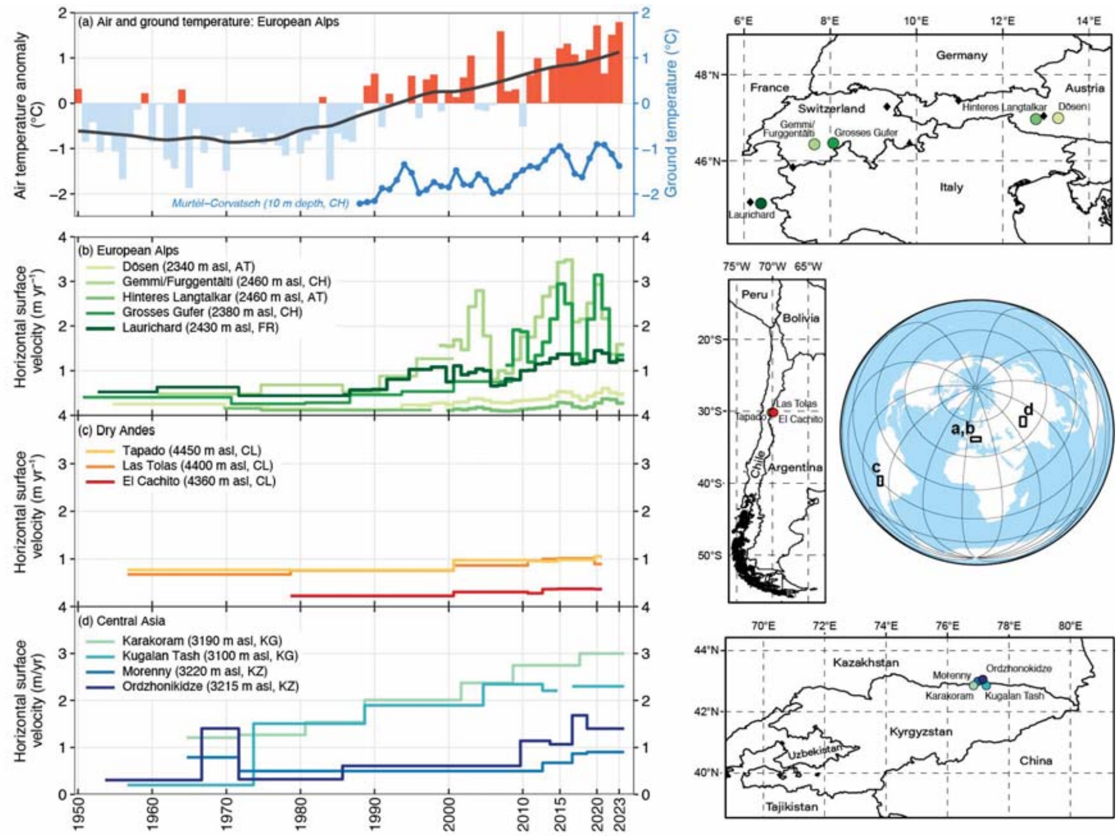

Fig. 2.16. Rock glacier velocity and climate: (a) air and ground temperature (°C) in the European Alps, (b)–(d) rock glacier velocities (m yr^{-1}) at selected sites in the (b) European Alps, (c) Dry Andes (updated from Vivero et al. 2021), and (d) Central Asia (updated from Kääb et al. 2021). Rock glacier 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 base period (bars) and composite 20-year 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 [DWD], MeteoSwiss, GeoSphere Austria, Swiss Permafrost Monitoring Network [PERMOS], University of Fribourg, University of Graz, Graz University of Technology, Université Grenoble Alpes [INRAE], University of Oslo.)

velocities on Kugalan Tash and Ordzhonikidze remain at a high level, although velocity slightly decreased at the latter (Fig. 2.16d; Kääb et al. 2021). This evolution is consistent with increasing air temperatures reported in the region since 1900 (Azisov et al. 2022; Sorg et al. 2015) and with the RGV evolution reported in the European Alps and Dry Andes.

Rock glacier velocity refers to velocities related to permafrost creep, which is a generic term referring to the combination of both internal deformation within the crystalline structure of the frozen ground (creep stricto sensu) and shearing in one or more discrete layers at depth (shear horizon; RGIK 2023b). RGVs are mostly related to the evolution of ground temperature and liquid water content between the upper surface of permafrost (i.e., permafrost table) and the layer at depth of the shear horizon (Cicoira et al. 2019; Frauenfelder et al. 2003; Kenner et al. 2017; Staub et al. 2016). Despite variable size, morphology, topographical and geological settings, and velocity ranges, consistent regional RGV evolutions have been highlighted in several studies (e.g., Pellet et al. 2023; Kellerer-Pirklbauer et al. 2024). Multi-annual long-term RGV time series are reconstructed using repeated aerial or optical satellite images. Horizontal displacements are computed based on cross-correlation feature tracking on multi-temporal ortho-images or digital elevation model matching (Kääb et al. 2021; Vivero et al. 2021). The resulting accuracy strongly depends on the spatial resolution of the images and on the image quality (i.e., presence of snow and shadows). Surface displacements are averaged for a cluster of points/pixels selected within areas considered as representative of the downslope movement of the rock glacier (RGIK 2023b). Annual rock glacier velocities are commonly measured using terrestrial geodetic surveys performed each year at the same time (usually at the end of summer). The positions of selected boulders (10–100 per landform) are measured with an average accuracy in the range of mm to cm (Lambiel and Delaloye 2004; Kellerer-Pirklbauer et al. 2024; PERMOS 2024; Thibert and Bodin 2022).

3. ALPINE GLACIERS

—M. S. Pelto

Mountain-region (i.e., alpine) glacier annual mass balance (sum of accumulation and ablation) observations are reported to the World Glacier Monitoring Service (WGMS). The WGMS reference glaciers each have at least 30 continuous years of mass balance observation, and benchmark glaciers have at least a 10-year mass balance record and are in regions that lack sufficient reference glaciers. In 2023, all 35 reporting reference glaciers had a negative balance, along with all 18 benchmark glaciers. This is the first year that all reference glaciers have had a negative balance. The 2023 dataset includes 109 glaciers from six continents, with 108 having a negative balance and 1 glacier reporting a positive mass balance. This makes 2023 the 36th consecutive year with a global alpine glacier mass balance loss, the 15th consecutive year with a mean global mass balance below –500 mm water equivalent (w.e.), and the year with the highest ratio of negative-to-positive mass balance observations of any year in the record (Fig. 2.17).

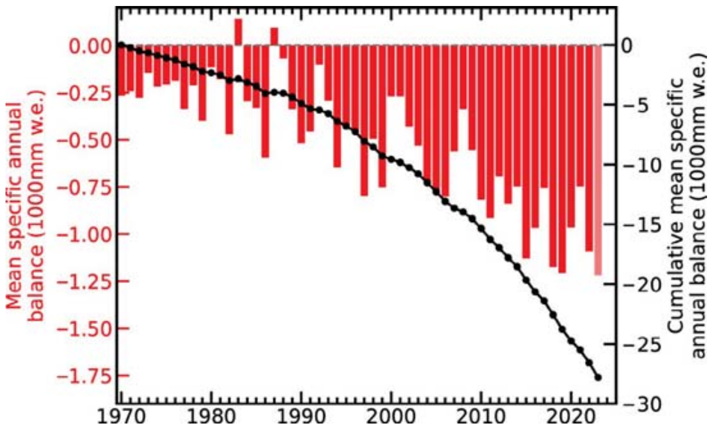

Fig. 2.17. Time series of global mean annual glacier mass balance (mm w.e.) of alpine glaciers from 1970 to 2023 as determined by the World Glacier Monitoring Service, using 19 regional averages from 53 glaciers in total.

The combination of benchmark and reference glaciers is used to generate regional averages (WGMS 2023). Global values are calculated using a single averaged value for each of 19 mountain regions, limiting bias towards well-observed regions (WGMS 2023). In 2023, the mean annual mass balance of the 35 reference glaciers was –1568 mm w.e., and –1590 mm w.e. for all 109 reporting glaciers regardless of record length. In a similar result, 2022 mean annual mass balance was –1475 mm w.e. for 37 reporting reference glaciers and –1568 mm w.e. for all 116 reporting glaciers. The regionally averaged global mass balance was –1090 mm w.e. in 2022; a final value for 2023 has not yet been determined, but the preliminary value is –1219 mm w.e.

The result of the melt in several regions has been an increasing complete loss of glaciers (see below; Huss and Fischer 2016; Fountain et al. 2023). This led to the Global Land Ice Measurements