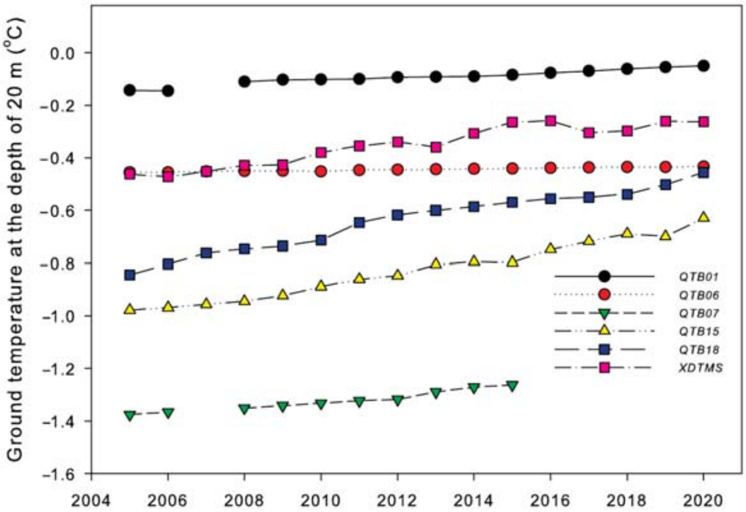

Fig. 2.13. Permafrost temperature (°C) measured in boreholes along the Qinghai-Xizang Highway on the Tibetan Plateau at 2-m depth for the period 2005–20. (Source: Cryosphere Research Station on Qinghai-Xizang Plateau, CAS.)

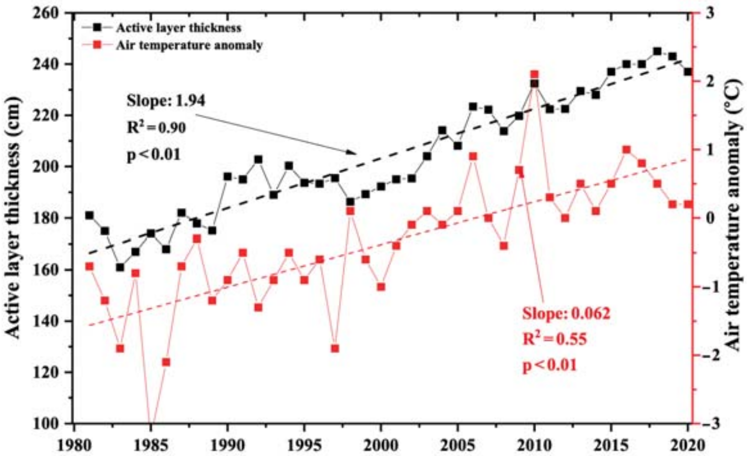

Fig. 2.14. The active layer thickness (cm) and air temperature anomalies (°C) in the permafrost zone along the Qinghai-Tibet Highway during the period 1981–2020. The air temperature anomaly is estimated relative to the base period 1981–2010. (Source: Cryosphere Research Station on Qinghai-Xizang Plateau,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

2021). Regionally, RGVs follow the same interannual behavior despite variable size, morphology, and velocity range (e.g., Delaloye et al. 2010; Kääb et al. 2021; Kellerer-Pirklbauer et al. 2018; PERMOS 2019).

RGVs in the European Alps have increased by a factor of between 2 and 10 from the 1980s to 2021 (Fig. 2.15b). This acceleration was temporarily interrupted at most sites during 2004–06 and 2016–18, coinciding with a decrease in permafrost temperatures, mainly resulting from snow-poor winters, which enabled more efficient ground cooling due to the later onset of an insulating snow cover (Noetzli et al. 2018; PERMOS 2019). Compared to 2020, RGVs decreased in 2021, e.g., at Gemmi/Furggentälti (Switzerland, −26%), Grosses Gufer (Switzerland, −24%), and Laurichard (France, −4%), whereas RGVs increased at Dösen (Austria, +19%) and Hinteres Langtalkar (Austria, +35%) to record values (Fig. 2.15b). The velocity decrease at Swiss and French sites is consistent with lower air temperatures compared to 2020 (Fig. 2.15a) as well as a long-lasting snow cover in spring and a relatively late thickening of the snow cover in autumn, which led to lower ground temperatures (cf. section 2c1). Different behaviors of the rock glaciers between the Western and Eastern Alps in 2021 might be related to differences in precipitation and temperature, particularly in December 2020 (warmer east), January 2021 (drier east), and July 2021 (warmer and less humid east), in addition to the influence of local topo-climatic factors.

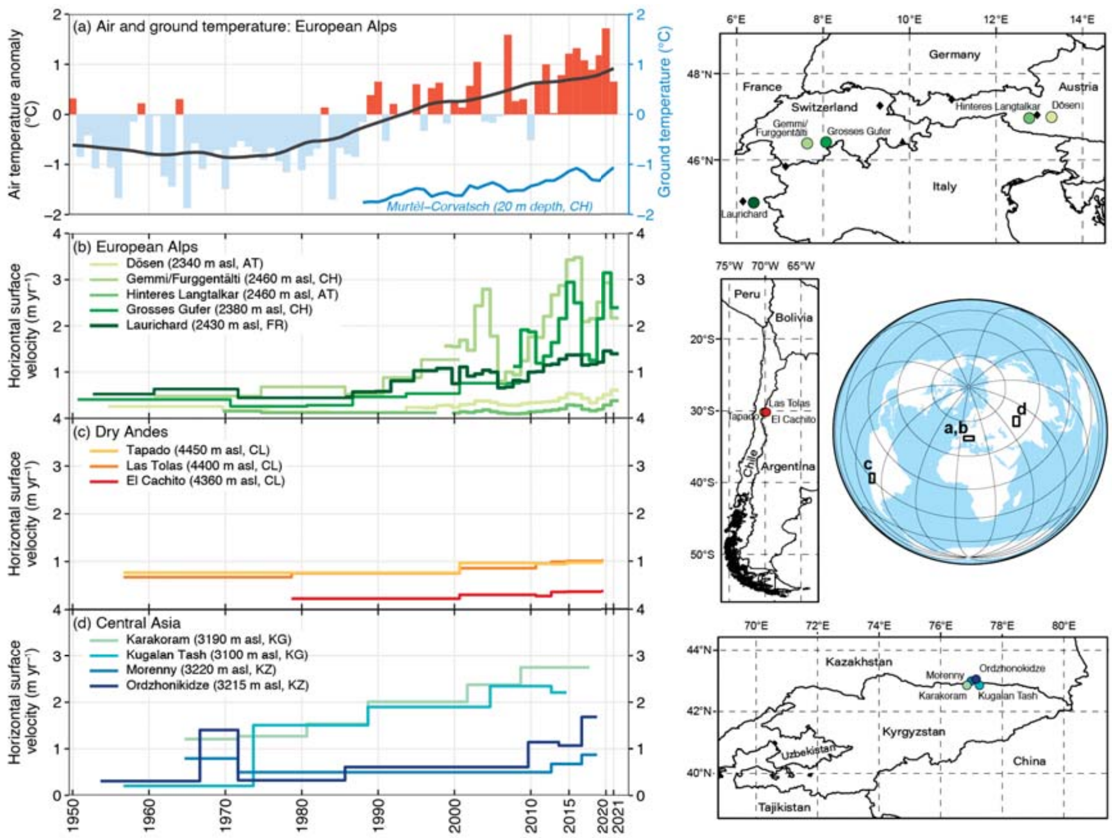

Fig. 2.15. (a) Rock glacier velocity and climate: air and ground temperature (°C) in the European Alps. Rock glacier velocities (m yr^{-1}) at selected sites in (b) the European Alps, (c) the Dry Andes (adapted from Vivero et al. 2021), and (d) central Asia (adapted from Kääb et al. 2021). Rock glacier velocities based on in situ geodetic surveys or photogrammetry in the context of long-term monitoring. In-situ permafrost temperature measured at 20-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-year running mean (solid line) at Besse (FR), Grand Saint-Bernard (CH), Saentis (CH), Sonnblick (AT), and Zugspitze (D, black diamonds on Europe map). (Data sources: Météo France, Deutscher Wetterdienst [DWD], MeteoSwiss, Zentralanstalt für Meteorologie und Geodynamik [ZAMG], Swiss Permafrost Monitoring Network [PERMOS], University of Fribourg, University of Graz, Graz University of Technology, Université Grenoble Alpes [INRAE], University of Oslo.)

There are few long-term in situ measurements of RGVs outside of the European Alps. However, an increasing number of studies exploit the potential of archival aerial photographs and high-resolution satellite data to reconstruct RGVs (e.g., Cusicanqui et al. 2021; Eriksen et al. 2018). The velocities of three rock glaciers observed in the Dry Andes in South America showed slow velocities from 1950 to 2000, followed by a steady acceleration since the 2000s (Fig. 2.15c), consistent with the climatic conditions observed in the region (Vivero et al. 2021).

RGVs observed in Central Asia since the 1950s do not show a uniform picture (Fig. 2.15d; Kääb et al. 2021). The Karakoram and Kugalan Tash (Kyrgyzstan) RGVs steadily increased since the 1960s, whereas at Ordzhonikidze and Morenny (Kazakhstan) high velocities were observed during the second half of the 1960s, then low velocities until 2010, and increasing velocities in recent years. All RGVs have increased since the start of the observations and accelerated since 2010, which is consistent with increasing air temperatures and with the acceleration reported in the European Alps and Dry Andes.

Long-term RGV time series are reconstructed using multi-temporal aerial or optical satellite images. Horizontal displacements are computed based on feature tracking, 2D ortho-image matching algorithms or digital elevation model matching. The resulting accuracy strongly depends on the spatial resolution of the aerial images and on the image quality. Surface displacements are averaged for a cluster of points selected within areas, representative of the flow field and indicative of the downslope movement of the rock glacier (RGIK 2022). Annual rock glacier velocities are measured using terrestrial geodetic surveys performed each year at the same time (usually at the end of summer). The positions are measured for a number of selected boulders (10–100 per landform) with an average accuracy in the range of mm to cm (Delaloye et al. 2008; PERMOS 2019).

3. ALPINE GLACIERS—M. Pelto

In the hydrological year 2020/21, observed World Glacier Monitoring Service (WGMS) reference glaciers experienced a mass balance loss of –900 mm water equivalent (mm w.e.), compared to –700 mm w.e. in 2019/20. From 1970 to 2021 the eight most negative mass balance years were all recorded after 2010. A value of –1000 mm w.e. per year represents a mass loss of 1000 kg m^{-2} of ice, or an annual glacier-wide thickness loss of about 1100 mm yr^{-1}.

Figure 2.16 illustrates glacier mass balance for the WGMS global reference glaciers with more than 30 years of data for the period 1970 to 2020. Global values are calculated using a single value (averaged) for each of 19 mountain regions in order to avoid a bias to well observed regions. In 2021, a negative annual mass balance was reported from 31 of the 32 reference glaciers reported to the WGMS as of 1 June 2022. The mean annual mass balance of the 32 reference glaciers reporting

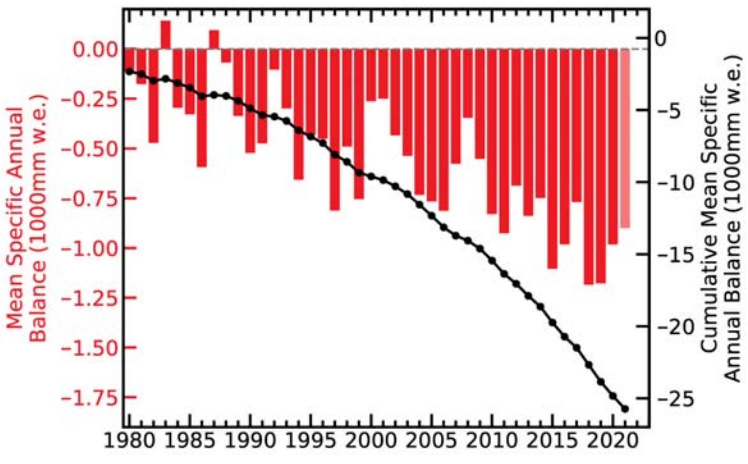

Fig. 2.16. Global annual glacier mass balance of WGMS reference glacier network in mm water equivalent (w.e.), with annual values (red bars, left axis) and cumulative amounts since 1979 (black dots, right axis). Lighter shading for 2021 is used as the final values for that year were not yet available at time of publication.