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

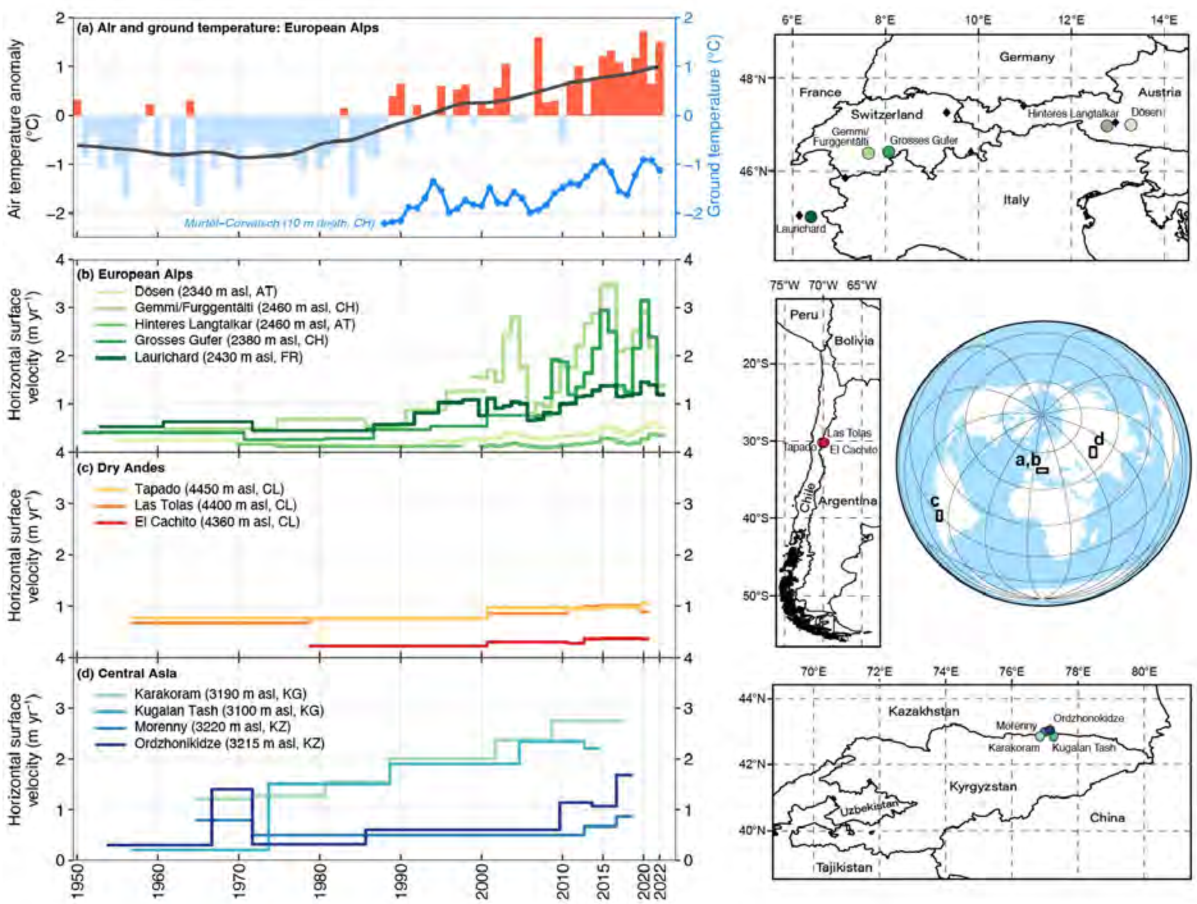

Fig. 2.14. (a) Air and ground temperatures (°C) in the European Alps, (b) rock glacier velocities (m yr⁻¹) at selected sites in the European Alps, (c) the Dry Andes (adapted from Vivero et al. 2021), and (d) Central Asia (adapted from Kääb et al. 2021). Rock glacier velocities are based on in situ geodetic 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.)

acceleration trend observed since the 1950s (Pellet et al. 2022; PERMOS 2022). Maximum velocity decrease compared to 2021 was observed in the Swiss Alps (e.g., Grosses Gufer: –49% and Gemmi/Furggentälti: –37%), whereas a smaller decrease was reported in the French (e.g., Laurichard: –14%) and Austrian (e.g., Dösen: –15% and Hinteres Langtalkar: –5%) Alps (Fig. 2.14b). The velocity decrease is consistent with a decrease in permafrost temperatures observed at 10-m depth (section 2c1), which reflects the comparatively cold year of 2021. The relatively dry winter of 2021/22 and dry and warm spring and summer of 2022 affected the geohydrological conditions at all sites (i.e., reduced the amount of water available in the terrain) and also contributed to velocity decrease (i.e., reduced shearing due to reduced pore water pressure; see Cicoira et al. 2019)

There are only a few long-term in situ RGV measurements outside of the European Alps. However, RGVs have been increasingly observed and reconstructed using (archival) aerial photographs and high-resolution satellite data (e.g., Cusicanqui et al. 2021; Eriksen et al. 2018). In the Dry Andes, RGVs reconstructed on three rock glaciers show low velocities from 1950 to 2000, followed by a steady acceleration since the 2000s (Fig. 2.14c), consistent with the climatic conditions in the region (Vivero et al. 2021).

RGVs observed in Central Asia have increased overall since the first available measurements in the 1950s, although their inter-annual evolution differs (Fig. 2.14d; Kääb et al. 2021). This general trend is consistent with increasing air temperatures in the region and with the acceleration reported in the European Alps and Dry Andes.

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 where most of the deformation occurs (the so-called 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., Delaloye et al. 2010; Kääb et al. 2021; Kellerer-Pirklbauer et al. 2018). Given the global occurrence of rock glaciers and the sensitivity of their surface velocity to ground temperatures and, by extension, to climate change, RGV was adopted in 2021 as a new associated product to the essential climate variable permafrost by the Global Climate Observing System (GCOS 2022a,b) and the GTN-P (Streletskiy et al. 2021). 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., snow-free and shadows). Surface displacements are averaged for a cluster of points/pixels selected within areas representative of the downslope movement of the rock glacier (RGIK 2022a). 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 of selected boulders (10–100 per landform) are measured with an average accuracy in the range of mm to cm (Delaloye et al. 2008; Kellerer-Pirklbauer and Kaufmann. 2012; PERMOS 2022; Thibert and Bodin 2022).

3. ALPINE GLACIERS

—M. S. Pelto

In 2022 heat events in the European Alps, Svalbard, High Mountain Asia, and the central Andes of Argentina and Chile resulted in a global mean annual mass balance of –1433 mm w.e. (water equivalent) for all 108 reporting alpine (mountain-region) glaciers, with data reported from 20 nations on five continents. In the hydrological year 2021/22, the preliminary regionally averaged annual mass balance based on the World Glacier Monitoring Service (WGMS 2021) reference glaciers was –1179 mm w.e. compared to the 1970–2020 average of −490 mm w.e. This makes 2022 the 35th consecutive year with a global alpine mass balance loss and the 14th consecutive year with a mean global mass balance below −500 mm w.e. (Fig. 2.15). This acceleration in mass loss from global alpine glaciers in the twenty-first century matches the findings of Huggenot et al. (2021). Since the start of the record in 1970, 9 of the 10 most negative mass balances have occurred since 2013.

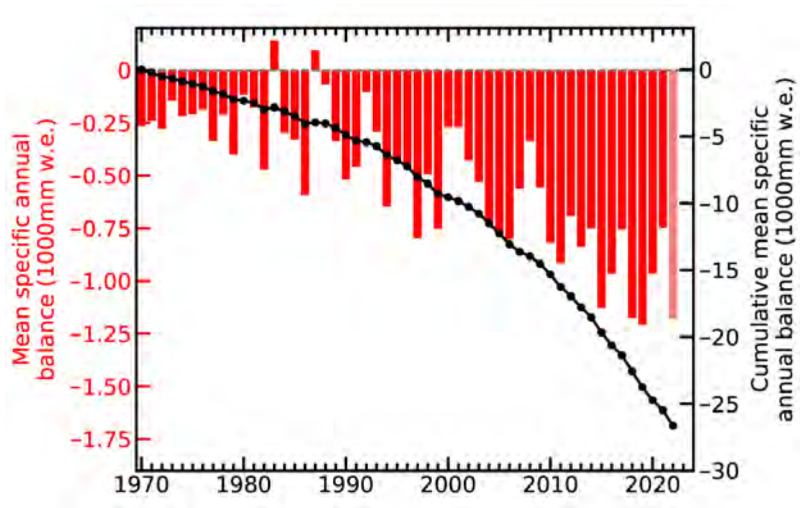

Fig. 2.15. Global average annual (left axis, red bars) and cumulative (right axis, black line) mass balance (1000 mm w.e.) of alpine glaciers for the period 1970–2022. (Source: WGMS regionally averaged reference glacier network.)

In 2022, a negative annual mass balance was reported from 34 of the 37 reference glaciers reported to WGMS. The mean annual mass balance of the 37 reference glaciers was –1547 mm w.e. Reference glaciers each with at least 30 continuous years of observation are used to generate regional averages. Global values are calculated using a single value (averaged) for each of 19 mountain regions in order to avoid a bias toward well-observed regions.

More frequent and intense heatwaves impacting glaciated ranges continued to take a toll on alpine glaciers in 2022. Heatwaves reduce snow cover extent earlier in the melt season, exposing ice surfaces earlier and enhancing surface darkening, both of which cause higher melt rates on alpine glaciers (Shaw et al. 2021; Pelto et al. 2022; Cremona et al. 2023).

All 32 reporting glaciers in the Alps, Pyrenees, and Caucasus Mountains had a negative mass balance averaging –3100 mm w.e. in 2022. In the European Alps, the combination of low winter snowpack and several summer heatwaves generated unprecedented mass loss (sections 2b4, 7f3). In Switzerland, the 25 days of heatwaves in 2022 are estimated to have melted 1.27±0.10 km^3 w.e., equivalent to 35% of the overall glacier mass loss that occurred during the summer, a period that led to a 6.2% overall glacier volume loss (Cremona et al. 2023).

In Norway and Sweden, the average balance of 11 reporting glaciers was −443 mm w.e., with three glaciers in Norway having a positive balance. Iceland completed surveys of nine glaciers; five had a positive balance and four a negative balance, with a mean mass balance of –7 mm w.e., close to equilibrium.

On Svalbard, the mean loss of the four reporting glaciers was –1102 mm w.e. The negative mass balances were due to several summer heat events (see section 5b, Sidebar 5.1), which led to many glaciers and ice caps losing all or most of their snow cover, further accelerating mass loss (Fig. 2.16).

In Alberta and British Columbia, Canada, and in Alaska and Washington, United States, 19 glaciers had a negative mass balance, averaging –965 mm w.e. The Alberta, British Columbia, and Washington regions experienced several prolonged heatwaves as they did in 2021. Daily glacier ablation in this region was noted as increasing by 30%–40% during heatwave periods (Pelto et al. 2022).

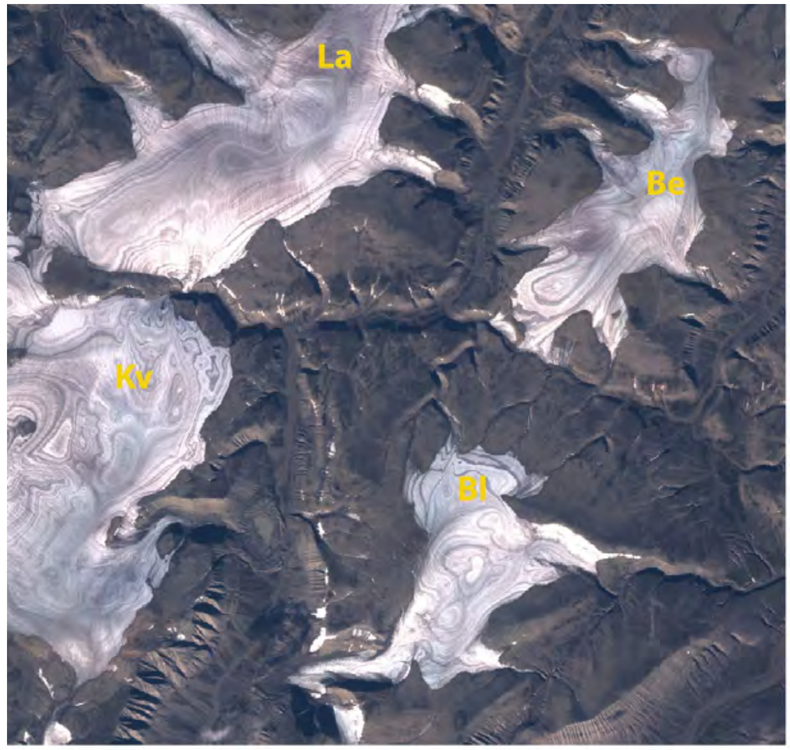

Fig. 2.16. Langjokulen (La), Kvitisen (Kv), Bergfonna (Be), and Blaisen (Bl) ice caps on the northeastern island of Edgeøya, Svalbard, in Copernicus Sentinel-2 MSI image (RGB) on 20 Aug 2022 illustrating the lack of snow cover, limited firn areas, and numerous annual layers. This pattern of annual layers due to glaciers being stripped of snow cover is becoming increasingly frequent.

In South America, mass balance data, reported from five Andean glaciers in Ecuador, Argentina, and Chile were negative, with a mean of –1465 mm w.e. The combination of drought and heat events left many central Andean glaciers snow free by mid-summer in early 2022. Shaw et al. (2021) noted a significant decline in surface albedo (section 2h1) due to decreased fractional snow cover that further enhances melt.

In High Mountain Asia, mass balance measurements were completed on glaciers in China, Kazakhstan, Kyrgyzstan, Russia, and Tajikistan. All 20 glaciers reported negative balances, with an average of –1040 mm w.e. The negative balances were driven by above-average melting during the May–July period.

In New Zealand, the mass balance assessed on Brewster and Rolleston Glaciers were strongly negative at –1125 mm and –1065 mm w.e., respectively. The end of year snowline observations on 50 glaciers was one of the five highest of the last 45 years.

Annual mass balance is reported in mm water equivalent (w.e.). A value of –1000 m 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}.