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

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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
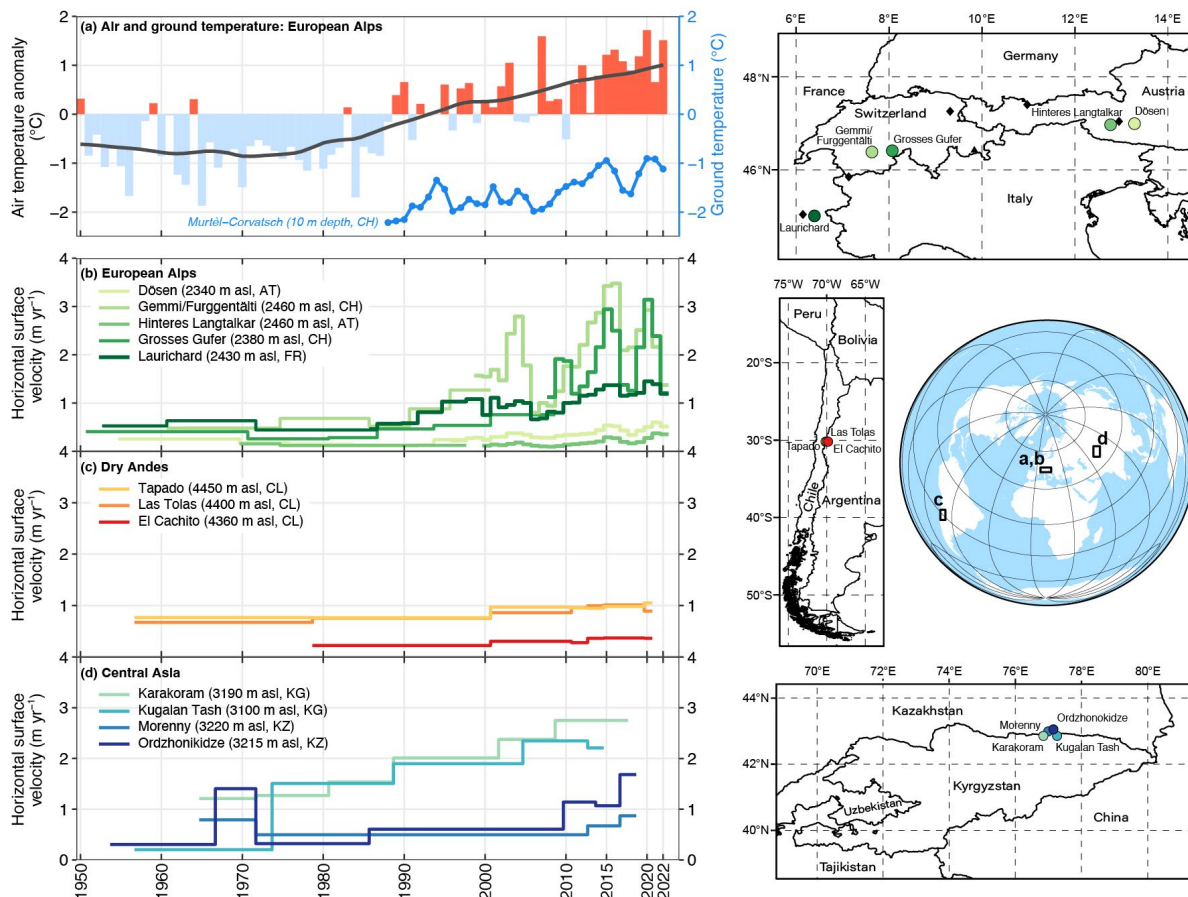

Fig. 2.14. (a) Air and ground temperatures (°C) in the European Alps, (b) rock glacier velocities (m yr⁻¹) at selected sites in the European Alps, (c) the Dry Andes (adapted from Vivero et al. 2021), and (d) Central Asia (adapted from Kääb et al. 2021). Rock glacier velocities are based on in situ geodetic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