2. ROCK GLACIER VELOCITY

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Rock glaciers are debris landforms generated by the creep of perennially frozen ground (permafrost). Their velocity evolutions are indicative of changes in the thermal state of permafrost and associated ground hydrological characteristics (RGIK 2023a). An overall increasing trend of rock glacier velocity (RGV) has been observed in mountain ranges worldwide since the 1950s (Pellet et al. 2024). In 2024, RGVs consistently increased in the European Alps compared to 2023, and in the Dry Andes, RGVs remained at a high level, with values similar to 2020. RGVs recently compiled in the United States further confirm this general trend of RGV increase (Kääb and Røste 2024), which is consistent with the increase of permafrost temperatures (section 2c1) to which RGV respond more or less synchronously (e.g., Staub et al. 2016).

In the European Alps, 2024 was the second-warmest hydrological year on record based on the average of five high-elevation stations (+1.52°C; Fig. 2.18a) yielding a general increase of RGVs. Compared to 2023, the highest RGV increase occurred in the Swiss Alps (+80.8% at Gemmi/Furggentälti and +80.7% at Grosses Gufer), whereas a +16.9% increase was observed in the French Alps at Laurichard as well as +3.4% and +5.1% increases in the Austrian Alps at Dösen and Hinteres Langtalkar, respectively (Fig. 2.18b). These observations are consistent with the permafrost temperature observations (section 2c1) as confirmed by the increasing temperatures measured in 2024 at 10-m depth on the rock glacier Murtèl in eastern Switzerland (Fig. 2.18a). The regional differences in magnitude of velocity increase is related to landform-specific characteristics combined with the spatial variability of snow conditions, namely early onset and well-above-average snow height throughout the winter in Switzerland and France (preventing any cooling of the ground; PERMOS 2025) as well as early onset followed by below-average snow heights in Austria (enabling limited cooling). The reported RGV observations in 2024 in the European Alps are consistent with the general acceleration trend observed at all sites since the 1950s (Kellerer-Pirklbauer et al. 2024).

In the Dry Andes, RGVs observed during 2023/24 show increases of +13.7% and +1.3% on El Cachito and Las Tolas, respectively, whereas a –15.9% decrease is observed on Tapado compared to 2019/20 (Fig. 2.18c). Velocities reached maximum values at El Cachito and remained at a high level compared to the entire time series on Las Tolas and Tapado. The overall increase observed since the 2000s is further confirmed by a recent study on Largo rock glacier (Fig. 2.18c; Cusicanqui et al. 2024) and is consistent with the slight air temperature increase observed in the region since 1976 (Vivero et al. 2021).

In Central Asia, RGVs observed on four landforms since the 1950s exhibit a general increase, with a marked acceleration in the period 2010–20 (Fig. 2.18d). This evolution is consistent with increasing air temperatures in the region (Azisov et al. 2022; Sorg et al. 2015).

In the United States, RGVs compiled on six rock glaciers show an overall increase since the first available measurements in the 1950s (Fig. 2.18e; Kääb and Røste 2024). This trend is consistent with the strongly increasing air temperature observed in that region (Kääb and Røste 2024).

RGV refers to velocities related to permafrost creep, which has to be understood as a combination of internal deformation of the frozen ground (creep stricto sensu) and shearing in one or more 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 and the shear horizon (Cicoira et al. 2019; Staub et al. 2016). RGV increase and decrease positively correlates with temperature change. Despite differences in size, morphology, topographical, climatic, and geological settings, as well as velocity ranges, consistent regional RGV evolutions have been highlighted in several studies (see Hu et al. 2025). RGV time series are produced using both in situ and optical remote sensing (airborne and spaceborne) measurements. Surface displacements are computed based on matching between images or digital elevation models taken at different times, with the resulting accuracy strongly depending on the characteristics of the input data (Kääb et al. 2021; Vivero et al. 2021). 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). The in situ measurements consist of annually repeated terrestrial geodetic surveys of the positions of selected boulders (10–100 per landform), yielding displacement observation with an average accuracy of mm to cm (Lambiel and Delaloye 2004; Thibert and Bodin 2022).

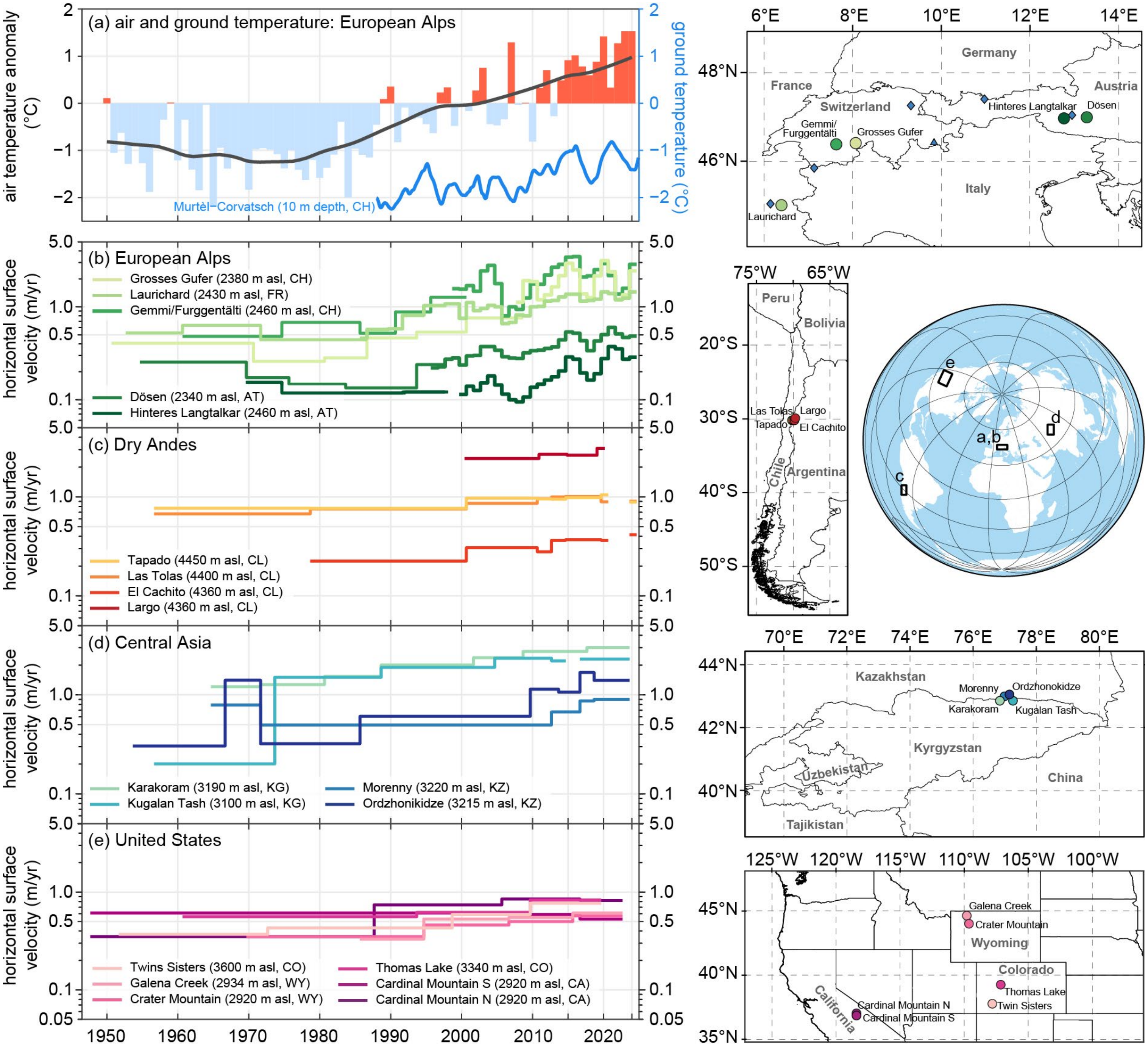

Fig. 2.18. Rock glacier velocity and climate: (a) air temperature in the European Alps and ground temperature in the Swiss Alps (°C), (b)–(e) rock glacier velocities (m yr⁻¹) at selected sites in the (b) European Alps, (c) Dry Andes (updated from Vivero et al. 2021 and Cusicanqui et al. 2024), (d) Central Asia (updated from Kääb et al. 2021), and (e) United States (adapted from Kääb and Røste 2024). Rock glacier velocities are based on in situ geodetic surveys ([b], since 2000s) or photogrammetry ([b]–[e]) in the context of long-term monitoring. In situ hydrological mean annual permafrost temperature measured at 10-m depth (blue line) at Murtèl Corvatsch (blue triangle on Europe map) and air temperature: composite anomaly to the 1991–2020 base period (bars) and composite 20-year running mean (solid line) at Besse (France [FR]), Grand Saint-Bernard (Switzerland [CH]), Saentis (CH), Sonnblick (Austria [AT]), and Zugspitze (Germany [D], blue 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 National Institute of Agricultural Research [INRAE], University of Oslo).