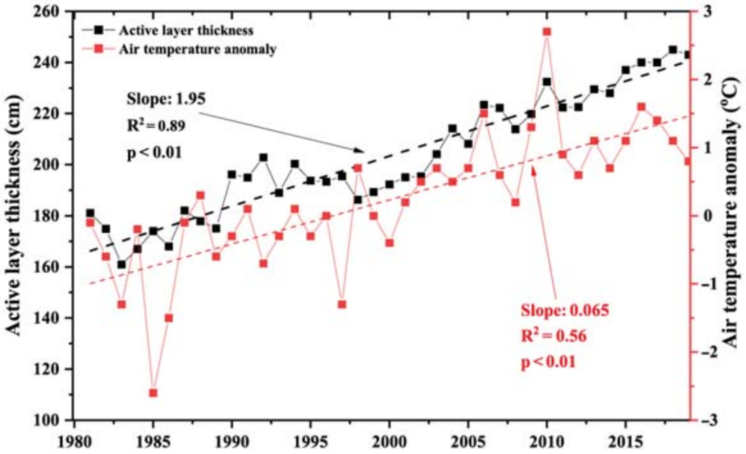

Fig. 2.12. The active layer thickness (cm) and air temperature anomaly (°C) in the permafrost zone along the Qinghai-Tibet Highway during the period 1981–2019. The air temperature anomaly is estimated relative to the climate baseline 1981–2010.

Long-term observation of permafrost relies on field observations of ALT and permafrost temperatures measured in boreholes. International data are collected by the Global Terrestrial Network for Permafrost (GTN-P) as part of the Global Climate Observing System (GCOS). Permafrost temperatures are logged manually or continuously using multi-sensor cables in boreholes reaching at least the depth of the zero annual amplitude. An assessment of the measurement accuracy of permafrost temperatures worldwide varied from 0.01° to 0.25°C, with an assumed overall accuracy of about 0.1°C (Biskaborn et al. 2019; Romanovsky et al. 2010). ALT is determined by mechanical probing where possible and has an accuracy of ~1 cm. Probing is not possible in bedrock or debris material, particularly in mountain regions. Here, ALT is interpolated from temperature sensors in boreholes. The current global coverage of permafrost monitoring sites is sparse; it is particularly limited in regions such as Siberia, central Canada, Antarctica, and the Himalayan and Andes Mountains.

Sidebar 2.2: Rock glacier kinematics—C. PELLET, X. BODIN, R. DELALOYE, V. KAUFMANN, J. NOETZLI, E. THIBERT, AND A. KELLERER-PIRKLBAUER

Rock glaciers are geomorphological indicators of permafrost occurrence in mountain areas and develop in most mountain ranges worldwide. Their kinematics derived from surface displacement measurements typically range from several centimeters up to several meters per year (Kääb and Vollmer 2000). Long-term studies from the European Alps have shown that the velocity of rock glaciers in a specific region responds sensitively and synchronously to interannual and decennial changes in ground temperature (e.g. Bodin et al. 2009; Delaloye et al. 2008, 2010; Kääb et al. 2007; Kellerer-Pirklbauer and Kaufmann 2012, 2018; Staub et al. 2016; Thibert et al. 2018; PERMOS 2019). Measurements of the surface velocity of rock glaciers based on aerial images and geodetic surveys first started in the 1960s in the European Alps (Haeberli 1985). Today, the majority of monitored rock glaciers are in the European Alps, and surface velocity measurements based on repeated terrestrial geodetic surveys have become part of operational permafrost monitoring in several European countries (Austria, France, Switzerland; see PERMOS 2019). In addition to their importance as climate indicators, rock glaciers are highly relevant for natural hazards risk management in mountain regions as well as for land use planning. Active rock glaciers are sediment conveyers and their increasing velocity can lead to a higher frequency of rock fall or debris flows from their frontal parts (e.g., Kummert et al. 2018).

The surface velocity of the majority of the observed rock glaciers in the European Alps behaved similarly during the past decades, despite variable size, morphology, and velocity range (Fig. SB2.4). The surface velocity increased by a factor of 2 to 10 from 1980s to 2015, and a maximum was reached in 2015. The acceleration was temporarily interrupted (i.e., velocity decrease was observed) for most of the landforms between 2004 and 2006, as well as between 2016 and 2018, coinciding with a decrease in ground temperatures (Noetzli et al. 2018; PERMOS 2019). The acceleration resumed in 2018. In 2020, the surface velocity of rock glaciers was close to or even higher than the maximum observed in 2015, which corresponds to the high ground temperatures observed (see section 2c1). Compared to the values of 2019, the surface velocity increase spans from +17% (Dösen [Austria] and Gemmi/Furggentälti [Switzerland]) to +45% (Grosses Gufer [Switzerland] and Hinteres Langtalkar [Austria]), which is in the same range as the acceleration observed between 2014 and 2015.

Long-term in situ measurements of rock glacier kinematics are scarcely available from other regions of the world. However, the increasing emergence of open-access and high-resolution satellite data (e.g., optical and Synthetic Aperture Radar [SAR]) facilitates the setup of regional surveys worldwide (e.g., Strozzi et al. 2020). Recent studies in northern Norway (Eriksen et al. 2018) and in the Tien Shan Mountains (Kääb et al. 2020) found an overall increase of the rock glaciers' surface velocity from the 1950s on. These observations are consistent with the results obtained in the European Alps.

According to in situ measurement (e.g., Arenson et al. 2002; Buchli et al. 2018) and modeling approaches (e.g., Kannan and Rajagopal 2013), the displacement at the surface of rock glaciers mainly results from shearing within a layer of several decimeters to a few meters thickness, which typically lies between 15- and 30-m depth. The changes in rock glacier kinematics are mostly related to the evolution of ground temperature and liquid water content between the permafrost table and the main shearing horizon at depth: the closer to 0°C the temperature is, the faster the rock glacier is moving (Cicoira et al. 2019; Frauenfelder et al. 2003; Staub et al. 2016). A time lag of around 1 to 2 years has been observed between high air temperatures and the resulting acceleration (Kellerer-Pirklbauer and Kaufmann 2012; Staub et al. 2016).

The consistent regional evolution of rock glacier velocity and its sensitivity to changes in ground temperature, together with their global presence, make rock glaciers ideal climate indicators. An Action Group of the International Permafrost Association (IPA; see Delaloye et al. 2018) aims to internationally harmonize and coordinate measurements of rock glacier kinematics (RGK). Based on their recommendation, the Global Terrestrial Network for Permafrost (GTN-P) is proposing to include RGK as a new product of the GCOS essential climate variable (ECV) permafrost, in addition to the thermal state of permafrost and active layer thickness. RGK measurements are based on repeated terrestrial geodetic surveys or determined photogrammetrically using aerial images. Geodetic surveys are performed annually at the same time of the season (usually at the end of the summer). The coordinates and elevation are measured for a number of selected boulders (10–100 per landform) with an average accuracy in the range of millimeters to centimeters (Delaloye et al. 2008; PERMOS 2019). Multi-temporal aerial images are compared with each other to obtain rock glacier-wide movement information. Typically, horizontal displacement metrics are computed based on 2D ortho-image matching algorithms or digital elevation model matching. The accuracy of the photogrammetrically derived displacements strongly depends on the spatial resolution of the aerial images and on the image quality (e.g., sharpness, contrast, and so forth).

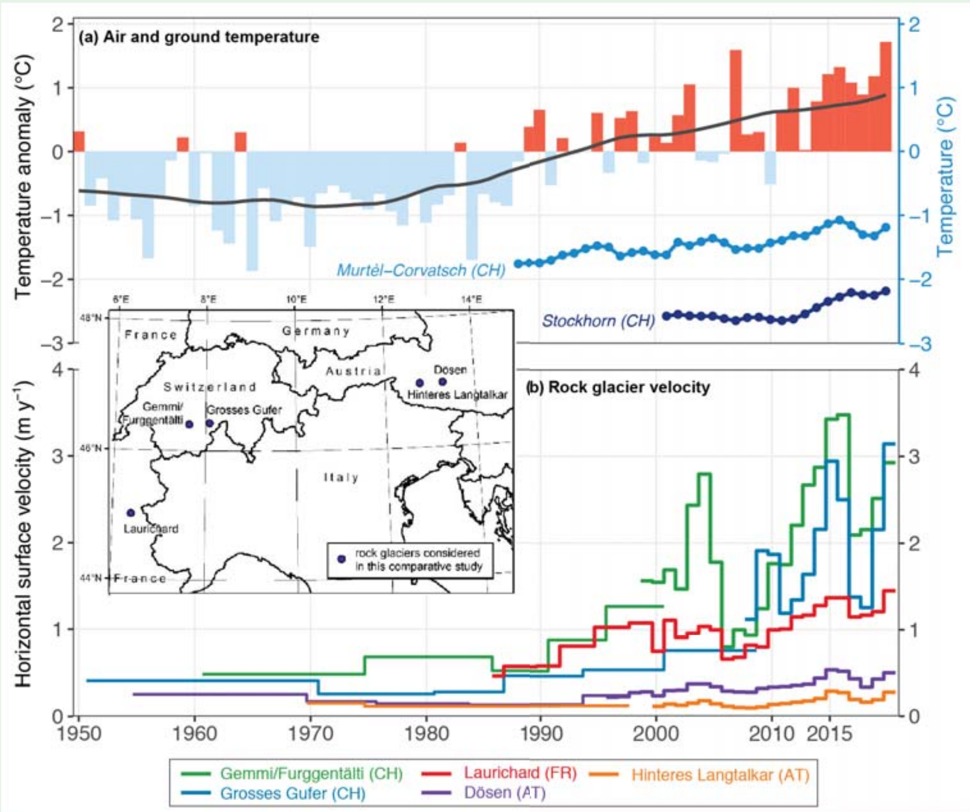

Fig. SB2.4. (a) Long-term in situ permafrost temperature measured at 20-m depth [blue lines]) and air temperature measurements (composite anomaly to the 1981–2010 norm [red and blue bars]) and composite 20-year running mean (solid line) at five selected sites in the European Alps (Switzerland, France, Austria): Besse France, Grand Saint-Bernard Switzerland, Sonnblick Austria and Zugspitze Germany. (b) Rock glacier surface velocities (m yr^{-1}) measured using in situ geodetic surveys and photogrammetrics. (Sources: Météo France, Deutscher Wetterdienst DWD, MeteoSwiss, Zentralanstalt für Meteorologie und Geodynamik ZAMG, Swiss Permafrost Monitoring Network, University of Fribourg, University of Graz, Graz University of Technology, Université Grenoble Alpes [INRAE].)